**Microalgae: A sustainable Source of Bioenergy**

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**I. Introduction**

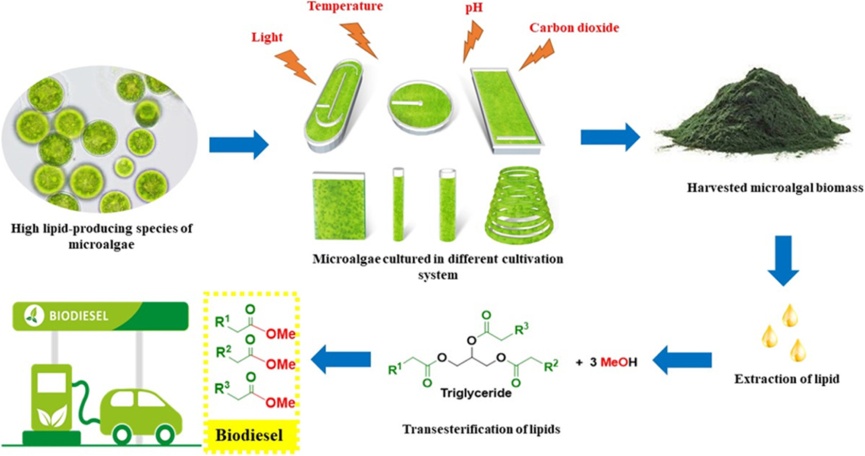
Due to increasing population and environmental deterioration, any nation can face the challenge of sustainable development. To sustain population’s growth and advancement, it is critical that renewable sources of energy must be found. While it is important for energy to be produced without harmful emissions and long-term damage to the environment [1]. The world's population has more than doubled in the last 50 years, expected to improve living standards and steadily increase economic output. This has led to a significant increase in primary energy demand, mainly from fossil fuels. This upward trend in energy consumption is likely to continue as the world population is projected to grow by 1.4 billion by 2030 and global real incomes are projected to grow by 100% [2]. The globe currently consumes about 15 terawatts of energy annually, of which renewable energy accounts for about 7.8%. Nevertheless, the total amount of sunlight that hits the earth's surface each year is about 85,000 terawatts. The steadily increasing global demand for fuels for motors and power generation, combined with environmental concerns related to greenhouse gases (GHGs), has led scientists and engineers to consider a variety of alternative energy sources [3]. As a result, there is growing interest in sustainable alternatives, such as bioenergy production, that reduce reliance on fossil fuels and reduce greenhouse gas emissions [4]. In recent years, emphasis has been placed on investigating the potential use of algae as a source of bio-oils and bio-gases for energy utilization. [5].

Algae as energy crops have potential due to their adaptability to growing conditions, their ability to grow in fresh or saltwater, and their ability to avoid land use. Moreover, since water covers two-thirds of the earth's surface, algae would be a truly renewable solution with great potential to meet the world's energy needs [6,7]. Therefore, microalgae for biofuels have been studied for many years for production of hydrogen, methane, vegetable oils (triglycerides, for biodiesel), hydrocarbons and ethanol. Methane was the focus of the earliest studies on microalgae biofuel production, and microalgae were primarily considered for wastewater treatment applications [5]. A bioreactor that uses microalgae to capture CO2 and NO2 is currently being developed in the United States on an industrial scale. In modern Mexico, microalgae were used as a dietary supplement. Microalgae, which are rich in proteins and lipids, may one day prove to be a viable alternative to petroleum. The National Renewable Energy Laboratory (NREL) and Department of Energy (DOE) have been collaborating to develop commercially viable fuels from microalgae rich in algae [6].

**II. Microalgae an emerging source of biofuel**

Microalgae are microscopic plants that are major syntheses of organic matter in the aquatic environment. They have a high surface area-to-volume ratio, fast uptake of nutrients and carbon dioxide (CO2), and significantly faster cell growth than land plants [7]. Microalgae are found worldwide and have evolved to withstand a variety of environmental conditions, including heat, cold, drought, salinity, photo-oxidation, anaerobic life, osmotic pressure and UV exposure. Microalgae do not require arable land to grow, can grow on seawater or residual nutrients, are highly productive in area, are rich in oils, proteins and carbohydrates, and can be fractionated into bioenergy and food by biorefineries [8]. The use of algal biomass as a bioenergy source is becoming increasingly popular. Although it is estimated that there are 50,000 species of algae in the world, only about 30,000 have been identified and studied to date [9]. Algae most commonly used for biofuel production include green algae such as *Chlorella, Spirulina, Scenedesmus obliquus, Chlorella vulgaris, Tetraspora* sp., *Chlamydomonas reinhardtii, Botryococcus braunii* [10].Microalgae that contain at least 30% lipids within the microalgae cells can be used for biofuel production. Through photosynthesis, microalgae can absorb large amounts of CO2 and produce sugars and oxygen. Sugars are then converted into lipids, proteins, carbohydrates, and like materials into biofuels [9]**.** The photosynthetic reaction formula is as follows. The representation of utilizing microalgae in the biodiesel production is depicted in the Figure 1.

6CO2 + 6H2O + sunlight energy →C6H12O6 (sugars) + 6O2



**Figure 1: Utilization of Microalgae in the biodiesel production [26].**

**III. Classification of Biofuels**

Biofuels are fuels made from living organisms or metabolic by-products. Many sources have been considered for producing biofuels. To be classified as a biofuel, a fuel must contain at least 80% renewable raw materials. Biofuels are classified as:

**A. First generation algal biofuels**

First-generation biofuels are derived from edible biomass, primarily corn and soybeans in the United States and sugar cane in Brazil. These biofuels have many problems. First, there is not enough arable land to meet more than about 10% of liquid fuel demand in developing countries. Also, the use of first-generation biofuels makes animal feed more expensive and ultimately increases the cost of food. Bioethanol is currently made from corn and sugar cane, while biodiesel is made from palm oil, soybean oil and canola [11].

**B. Second generation algal biofuels**

Second generation biofuels are based on non-edible plant parts such as straw, wood and waste streams. However, for woody lignocellulosic substrates, second-generation biofuel technologies can be as energy-intensive as first-generation biofuels. Lignocellulosic material may require a pretreatment step such as steam blasting prior to the biofuel production stage. Therefore, the energy demands of second-generation biofuel processes are likely to be greater than those of first-generation processes [12]. The advantage of second-generation biofuels is that they are abundant and do not interfere with food production. Most of these energy crops can be grown on marginal land that would otherwise not be used for cultivation[11].

**C. Third generation algal biofuels**

Third generation biofuels do not require agricultural land for production. Third-generation biofuels are typically based on algae, which are said to require less land than terrestrial crops such as corn, oilseed rape, and switch grass. According to Oncel [13] microalgae are more productive per hectare compared to crops. Currently, only biodiesel and bioethanol are produced on an industrial scale[14]. Microalgae use photosynthetic processes similar to higher plants and can go through an entire growth cycle every few days. In fact, the biomass doubling time of microalgae during exponential growth is only 3.5 hours [15].

**IV. Types of biofuel production from microalgae**

**A. Biodiesel from Microalgae:**

Microalgae are considered a potential source for biodiesel production due to their higher growth rates than terrestrial plants. However, large-scale application of algal biodiesel is limited by the downstream costs of lipid extraction and the availability of water, CO2, and nutrients [9]. Biodiesel has engine performance comparable to petroleum diesel fuel while reducing sulfur and particulate matter emissions. Biodiesel is a biodegradable alternative fuel derived from renewable resources and is inherently non-toxic. Presently, biodiesel has come to mean a very specific chemical modification of natural oils [16]**.** One of the biggest advantages of biodiesel compared to many other alternative transportation fuels is that it can be used in existing diesel engines without modification, and its suitability for blending in at any ratio with petroleum diesel. Biodiesel from algae can be obtained directly from transesterification of algal biomass. Alternatively, they can be produced by a two-step process in which the lipids are first extracted and transesterified later, but both processes involve lipid extraction with solvents such as methanol, isopropanol, petroleum ether, and alcohols. The direct transesterification process is a fast and inexpensive technique[17].

Microalgal lipids are mostly neutral lipids with lower degree of unsaturation. This makes microalgal lipids a potential replacement for fossil fuel. The main limitation of microalgae oil is the unsaturated fatty acid content. Excess unsaturated fatty acid levels are a major problem for biodiesel production, because they may induce cross linking of fatty acid chains, causing tar formation. The levels of unsaturated fatty acids in microalgae are sometimes very high (up to 30% of fatty acids) [18].

**Table 1: Comparison of some sources of biodiesel** [12]

|  |  |  |
| --- | --- | --- |
| **Crop** | **Oil yield (L/ha)** | **Land area required (M ha)** |
| Corn | 172 | 1540 |
| Soyabean | 446 | 594 |
| Canola | 1190 | 223 |
| Jatropa | 1892 | 140 |
| Coconut | 2689 | 99 |
| Oil palm | 5950 | 45 |
| Microalgaea | 136,900 | 2 |
| Microalgaeb | 58,700 | 4.5 |

**B. Bioethanol**

The recent attempts for producing ethanol are focusing on microalgae as a feedstock for fermentation process. Microalgae are rich in carbohydrates and proteins that can be used as carbon sources for fermentation. The amount of carbohydrates and protein varies or algal species. Bacteria, yeast or fungi are microorganisms used to ferment carbohydrates to produce ethanol under anaerobic conditions. In addition to ethanolas main products, CO2 and water are also formed as by-products. Microalgae are also being studied for bioethanol production. Green algae including *Spirogyra* species and *Chlorococum* sp. have been shown to accumulate high levels of polysaccharides both in their complex cell walls and as starch. This starch accumulation can be used in the production of bioethanol. Harun et al. have shown that the green algae *Chlorococum* sp. Produces60% higher ethanol concentrations for samples that are pre-extracted for lipids versus those that remain as dried intact cells. This indicates that microalgae can be used for the production of both lipid-based biofuels (Fig.3) and for ethanol biofuels from the same biomass as a means to increase their overall economic value [2].

In general, two methods are normally adopted for production of bioethanol from biomass. The first one is biochemical process, i.e. fermentation and other is by thermo-chemical process orgasification. The primary problem being the high-value for food applications and requires large quantities of land to be produced for both kinds of feedstocks. Thus, both of these compete with food chain as well as land use, which pose a constraint to expand production of these biofuels [19].

Microalgae fermentation is two stage processes. In the first stage, microalgae undergo fermentation in anaerobic and dark environment and ethanol is produced. Then the ethanol thus produced can be purified to be used as fuel. TheCO2 produced in the fermentation process was recycled to algal cultivation ponds as a nutrient to grow microalgae. The second stage involved the utilization of remaining algal biomass slurry left after fermentation, which may be used in anaerobic digestion process while keeping the pH in the range of 6–9. This process produced methane which can further be converted to produce electricity. Although, a number of advantages in the production of bioethanol from algae, fermentation process involves less intake of energy and the process is much simple in comparison of biodiesel production system. In addition, CO2 produced as by-product from fermentation process can be recycled as carbon sources for microalgae cultivation, thus reducing the greenhouse gases emissions as well [20].

**C. Biomethane**

The bioethanol production by fermentation is also useful for simultaneous production of biogas. Therefore, the application of methane fermentation technology to algae to produce valuable by-products such as biogas. Biogas produced from anaerobic microorganisms by anaerobic digestion mainly consists of a mixture of methane (55–75%) and CO2 (25–45%). Methane from anaerobic digestion can be used as fuel gas and also be converted to generate electricity. Residual biomass from anaerobic digestion also can further be reprocessed to make fertilizers. In addition to being renewable and sustainable, this would encourage sustainable agricultural practices in providing greater efficiencies and reduce algae production costs. Due to absence of lignin and lower cellulose, microalgae exhibit good process stability and high conversion efficiency for anaerobic digestion [21].

**Table: 2 Methane yield from the different algal strains.**

|  |  |
| --- | --- |
| **Biomass** | **Methane yield (m**3**kg**- 1**)** |
| *Laminaria* sp. | 0.26–0.28 |
| *Gracilaria* sp. | 0.28–0.4 |
| *Macrocystis* | 0.39–0.41 |
| *L. digitata* | 0.5 |
| *Ulva* sp. | 0.2 |

Methane yield from different algae species (as feedstock) depends biogas production from this anaerobic digestion process is primarily affected by its organic loadings, pH, temperatures, and retention time in reactors. Mainly long solid retention time and high organic loading rate give significant results in high methane yield. In addition, anaerobic digestion can operate in either mesophilic (35o C) or thermophilic (55o C) conditions. Used constant temperature, mesophilic for anaerobic digestion of *Ulva sp*. and found 180 ml/g (volatile solid based) of methane yield. On the other hand, the mesophilic condition promoted slower breakdown of organic compounds in anaerobic digestion process. However, it was reported that production cost of methane from microalgae was higher compared to other biomass, grass and wood. The integrated processes that combine algal cultivation and wastewater treatment system for methane production can be most suitable approach to reduce production cost and make it more profitable [22]**.**

**D. Bio-hydrogen**

Biohydrogen is an important fuel with wide applications in fuel cells, liquefaction of coal, and upgrading of heavy oils (e.g., bitumen). Hydrogen can be produced biologically by a variety of means, including the steam reformation of bio-oils, dark and photo fermentation of organic materials, and photolysis of water catalyzed by special microalgal species [23].

**V. Microalgae cultivation systems for biofuel production**

There are several approaches for producing microalgae biomass, which strongly differ from each other in terms of construction, efficiency and economy. Principally microalgae mass cultivation systems can be divided into outdoor and indoor systems; outdoor systems are more economic because of the utilization of sunlight. Biomass productivity by area differs widely across the various cultivation systems: opensystems achieve a productivity rate of 10 – 25 g m-² d-1, closed systems 35 – 40 g m-² d-1 and thin-film systems80-100 g m-² d-1[12].

**A. Open Cultivation Systems**

Cultivation of algae in open ponds has been extensively studied in the past few years. Open ponds can be categorized into natural waters (lakes, lagoons, ponds) and artificial ponds or containers. The most commonly used systems include shallow big ponds, tanks, circular ponds and raceway ponds. One of the major advantages of open ponds is that they are easier to construct and operate than most closed systems. However, major limitations in open ponds include poor light utilization by the cells, evaporative losses, diffusion of CO2 to the atmosphere, and requirement of large areas of land [24].Open systems have several drawbacks (Table-3), such as, insufficient monitoring and control options for parameters such as pH, temperature, mixing and light availability. SpargedCO2 has a very short residence time, resulting in high losses and poor solubility. Furthermore, seasonal variations contribute to reduced reproducibility of data**.**[25, 12].In spite of all these negative aspects, the advantages of open systems can still outweigh disadvantages. The large benefit of open cultivation systems is their cheap and simple maintenance. Since this is also the case for construction of raceway ponds, up scaling is easy. Therefore, they are more often applied in large scale approaches [12]. In order to overcome the problems with open ponds, much attention is now focused on development of suitable closed systems such as flat-plate, tubular, vertical-column and internally-illuminated photobioreactors [25].

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**A B**

A. *H. pluvialis* production in raceway paddle wheel mixed ponds (Parry *Nutraceuticals,* India).

B. *Chlorella* production in circular ponds (Weissman, J.C.; Goebel, R.P. 1987).

**Figure 3: Commercial open pond production systems.**

**B. Closed Cultivation Systems (Photobioreactors)**

Among the closed systems several types of PBRsexist (Fig.4). Algal culture systems can be illuminated by artificial light, solar light or by both. Naturally illuminated algal culture systems with large illumination surface areas include open ponds, flat-plate, horizontal/serpentine tubular airlift, and inclined tubular photobioreactors. Some of these photobioreactors include bubble column, airlift column, stirred-tank, helical tubular, conical, torus, and seaweed type photobioreactors. Photobioreactors require much more energy for building and during processing compared to the increase in productivity. Assuming that the photosynthesis potential of a pond is equivalent to a5-cm depth photobioreactor, growth-rates (expressed inday-1) for photobioreactor lead to productivity rate between 20 and 30 g ·m-2· day-1, which are in the range of usual performances of open raceways. Nutrient and CO2 supply to produce 1 kg of algae are determined for both culture methods and from culture conditions [25].



**Figure 4: Closed pilot-scale cultivation systems for cultivation of microalgae.**

**VI. Microalgae harvesting methods**

Efficient harvesting of microalgae is one of the major factors to be overcome in order for them to be used as a fuel source. Basically, there are four methods to harvest microalgae: sedimentation, filtration, flocculation and centrifugation [7].

**A. Sedimentation**

The simple sedimentation system is suitable for microalgae which have naturally high sedimentation rates. This is performed in thickeners or clarifiers, standard processes in water treatment plants. If the strain has poor sedimentation properties, a flocculation agent can help. The appropriate choice of flocculation and harvesting combination is mainly an economic consideration [7].

**B. Flocculation**

Flocculation is one of the famous chemical technologies in the microalgae harvesting. Because the particular sizes of microalgae cells are very small, by using flocculation, microalgae are gathered into larger size particles, thereafter by the effect of gravity, there will be sedimentation of them. Alum and ferric chloride as chemical flocculants are used to feed into the harvesting microalgae process [9]. These chemicals can be added to modify the surface tension of particles in order to increase bubble attachment. Compared to sedimentation the flotation process is very fast. It only requires a few minutes instead of hours for sedimentation. Capital and operating costs are low. Biomass is collected at the surface of the pond[7].

**C. Centrifugation**

Centrifugation is a process by using centrifuge to sediment mixture by centrifugal force. Currently, centrifugation is the most widely used harvesting method in microalgae production [9]. Centrifugation is an accelerated sedimentation process. It can operate with rotating walls (the most common type) or with fixed walls in systems called hydro cyclones. Capital and operation costs are usually high, but efficiency compared to natural sedimentation is much higher [7, 9].

**D. Filtration**

Filtration is a very common practice in industry. This process can range from simple screening or microstrainers to dewatering up to complex vacuum or pressure filtration systems. The more complex the system is, the more it costs. The main limitation of filtration is plugging. To solve this, vibrating screens are used ortangential filtrations. Deep bed filtration is also commonly used to avoid plugging, but it requires mixing the solution with sand. Some combined systems use pressing and screening belts, having the advantage of continuous operation[9].

**VII. Conclusion**

The idea of using microalgae as a source of biofuel is not new, but in recent decades it is been taken seriously because of the rise in price of petroleum products and more significantly, the emerging concern about global warming that is associated with burning of fossil fuels. Microalgae have the potential to be a significant source of bioenergy and functional foods. Through various conversion processes, microalgae can be used to produce many kinds of biofuels, such as biohydrogen, biodiesel, and bio-ethanol. Moreover, the large number of existing species of microalgae constitutes a unique reservoir of biodiversity, which supports potential commercial exploitation of many novel products. Microalgal farming can be coupled with flue gas CO2 mitigation and wastewater treatment. It can also be carried out with seawater as the medium, given that marine microalgal species are adopted, providing a feasible alternative for biofuel production to populous and dry coastal regions.

The development of technologies that lower prices while improving yields still need more advancements. Technological advances, such as those in photobioreactor design, microalgal biomass harvesting, drying, and other downstream processing technologies, are significant areas that may result in improved cost-effectiveness and, as a result, the successful commercial implementation of the biofuel from microalgae strategy. Therefore, microalgae biofuels are a sustainable source of energy; the issue will be production economics. A few businesses are already working to produce microalgal biofuels on a commercial basis.

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