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Perspectives of microalgal biofuels as a renewable source of energy

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ABSTRACT

Excessive use of fossil fuels to satisfy our rapidly increasing energy demand has created severe environmental problems, such as air pollution, acid rain and global warming. Biofuels are a potential alternative to fossil fuels. First- and second-generation biofuels face criticism due to food security and biodiversity issues. Third-generation biofuels, based on microalgae, seem to be a plausible solution to the current energy crisis, as their oil-producing capability is many times higher than that of various oil crops. Microalgae are the fastest-growing plants and can serve as a sustainable energy source for the production of biodiesel and several other biofuels by conversion of sunlight into chemical energy. Biofuels produced from microalgae are renewable, non-toxic, biodegradable and environment friendly. Microalgae can be grown in open pond systems or closed photobioreactors. Microalgal biofuels are a potential means to keep the development of human activities in synchronization with the environment. The integration of wastewater treatment with biofuel production using microalgae has made microalgal biofuels more attractive and cost effective. A biorefinery approach can also be used to improve the economics of biofuel production, in which all components of microalgal biomass (i.e., proteins, lipids and carbohydrates) are used to produce useful products. The integration of various processes for maximum economic and environmental benefits minimizes the amount of waste produced and the pollution level. This paper presents an overview of various aspects associated with biofuel production from microalgae, including the selection and isolation of microalgal species, various cultivation and harvesting techniques as well as methods for their subsequent conversion into biofuels.

1. Introduction

Global energy demand is increasing at a very fast rate due to rapid population and industrialization growth, affecting the usage of fossil fuels. In the last two decades, global energy consumption has increased approximately 44% from 355QBTU in 1990 to 510QBTU in 2010 (Energy Information Administration, USA). The use of fossil fuels to meet our energy demands is inadvisable, as it accelerates the accumulation of greenhouse gases (GHG), causes air pollution and is responsible for acid rain. However, fossil fuels have been in great demand because they provide high energy density, are ease to use and transport and, importantly, have yet to be challenged by any other alternative fuel in terms of cost. Even today, more than 80% of the annual global energy demand is realized through the burning of fossil fuels such as petroleum, natural gas and coal. The EIA further reports that global energy consumption will increase by approximately 60% in the next 20 years [1]. Fossil fuel consumption is not a sustainable solution in the long run due to rapidly depleting resources [2]. In the recent years, research has focused on the identification of new renewable fuels sources that can maintain economic sustainability [3–6]. Renewable fuels are clean and environmentally safe solutions with negligible GHG emissions compared to fossil fuels [7]. Among the various renewable fuels, microalgal biofuels have attracted surprisingly strong interest in the last decade; they possess many characteristics similar to fossil fuels and are currently seen as a viable replacement for petroleum fuels. Their successful use in various fields (power generation, transportation etc.) would increase energy security and help abate the severe issues associated with the use of fossil fuel i.e., global warming and environmental pollution.

This paper highlights the potential of microalgae as a sustainable source for biofuel production. Various microalgal biofuels have been covered, but biodiesel has received intense focus due to its diversified use and superior financial viability. Hence, the various steps involved in biodiesel production from microalgae have been discussed: microalgae cultivation, harvesting and conversion.

2. Biofuel classification

Biofuels are renewable fuels obtained from biological materials (such as plants, animals and microorganisms, including

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microalgae). They can be used directly/indirectly as transportation fuel with little/no modification to the existing engine or as a fuel in various other applications. Biofuels are still more expensive than conventional fuels, but exhaustive research being conducted worldwide is expected to decrease production costs and make these fuels competitive with conventional fossil fuels. Moreover, government bodies globally are providing financial incentives for both the processing and use of biofuels. This financial assistance is expected to encourage further cost reduction through large-scale production. Currently, biofuels are produced from numerous raw materials, and the most commonly used raw material varies by country depending on geographical location and social constraints. For example, biodiesel is produced mainly from maize and sugarcane in Brazil and the USA, sugar beet and cereals in Europe [8] and non-edible plants in Asian countries. Other potential sources for biofuel production include industrial [9], agricultural [10], forestry and household [11,12] waste.

Based on their phase, biofuels can be classified as solid, liquid or gaseous. Solid biofuels include straw, wood, sawdust, shells and cakes of oil-rich plant species. Liquid biofuels are mainly used as transportation fuel. The two main types of liquid biofuels are bioalcohol and biodiesel. Bioalcohol is mainly produced by the fermentation of crops rich in sugars and starch, although recent interest has shifted towards cellulosic biomass for the production of bioalcohol. Biodiesel is produced by transesterification, hydrogenation, etc. Gaseous biofuel, also known as biogas, is formed mainly through the anaerobic fermentation of agricultural waste, animal manure or farmyard manure [13,14]. Another well-known classification divides biofuels into first-, second- and third-generation biofuels.

2.1. First-generation biofuels

First-generation biofuels are also called conventional biofuels and are mainly made from food/oil crops (rapeseed oil, sugarcane, barley, maize, sugar beet, wheat, etc.) and animal fats [15]. They are converted into biofuels using fermentation or esterification techniques. Biofuel production using these types of biomass has increased rapidly in the last decade. However, many concerns are associated with their use, such as competition with food and fiber production, the large fresh water requirement, the large input of fertilizer and biodiversity conservation. Importantly, their excessive use for biofuel production will place an undesirable burden on food prices [3,11].

2.2. Second-generation biofuels

The motivation behind second-generation biofuels was to utilize waste residues (waste from the wood-processing industry, fruit skins, etc. [16,17]) and barren land for growing biomass. These biofuels can be produced from non-edible oil plants, which can grow even on marginal areas and can survive on salted water (e.g., *Jatropha, Pongamia*) [18–20]. However, their sustainability also comes under scrutiny because of their competition with food crops for fertile land and deforestation [21]. Such limitations have led to the use of lignocellulosic feedstocks as second-generation biofuels. Sims et al. [22] reported that significant progress is necessary to overcome the technical and economic challenges associated with second-generation biofuels.

2.3. Third-generation fuels

Third-generation biofuel production is mainly based on microalgae, which contain a higher oil mass fraction than other microorganisms (viz. bacteria, fungi and yeast). Microalgae seem to have the capacity to replace large volumes of crude oil. For example, India has a demand for 120 million tonnes of oil per year. Fulfilling this demand through oil crops such as soybean or palm would require quite large cultivation areas [23]. In contrast, only 2–3% of all Indian cropland would be sufficient for the production of the required crude oil using microalgae. Hence, microalgae can be a better option for the production of cost-effective biofuels with low investment.

Microalgae provide the following advantages over higher plants in relation to biofuel production [3,24–27]:

(1) Carbon dioxide sequestration from flue gases emitted from thermal power plants, thereby reducing emissions of a major greenhouse gas, CO_2 (1 kg of dry microalgal biomass utilizes approximately 1.83 kg of CO_2).
(2) Bioremediation of wastewater by the removal of NH_4^+, NO_3^-, PO_4^{3-} and heavy metals from agricultural run-off as well as industrial, municipal and other wastewater.
(3) Accumulation of large quantities of neutral lipids and rapid biomass production (e.g., doubling of biomass 1–3 times per day).
(4) Year-round production, exceeding the oil yield per unit area of other oilseed crops.
(5) Ability to grow under extreme environmental conditions and low nutritional requirements.
(6) Lower water requirement than terrestrial crops, reducing the load on freshwater resources.
(7) No requirement of herbicides or pesticides.
(8) Ability to be cultivated in saline/coastal seawater and non-arable land.
(9) No interference with food security issues.
(10) Other compounds may also be extracted, such as polyunsaturated fatty acids, natural dyes, polysaccharides, pigments, antioxidants and proteins.

Table 1 compares the oil content and yield from first-, second- and third-generation biofuels [24,28–31]. It is clear that third-generation biofuels are far superior to first- and second-generation biofuels. Under proper growth conditions, microalgae can produce oils in quantities many times higher than any other plant system [32,33]. Nonetheless, the superiority of microalgae as biofuel feedstock has only been established in research facilities. To date, the commercial-scale sustainability of microalgal biofuels has yet to be demonstrated due to the unavailability of publicly accessible data. Presently, many research groups and various production companies are placing intense focus on microalgae-based fuels. Conversely, due to various challenges in microalgal biofuel production and processing, slow progress has been observed toward commercial-scale achievements.

3. Algaculture

Algae include diverse groups of aquatic and photosynthetic organisms categorized as microalgae and macroalgae. Microalgae are eukaryotic or prokaryotic photosynthetic microorganisms having a unicellular or simple multicellular structure. Eukaryotic microalgae include green algae (Chlorophyceae) and diatoms (Bacillariophyceae), whereas prokaryotic microalgae include cyanobacteria (Cyanophyceae). Eukaryotic organisms possess a high degree of internal organization with a membrane-bound nucleus containing genetic material and several other organelles surrounded by membranes, whereas prokaryoteslack a distinct nucleus. Macroalgae, or seaweeds, are multicellular algae having defined tissues with specialized cells. Diatoms (silicon-rich algae) and prokaryotic cyanobacteria offer various opportunities for metabolic engineering and biotechnology.