Renewable and Sustainable Energy Reviews xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Algal Green Energy – R & D and technological perspectives for biodiesel production

Rajesh P. Rastogi[a,*], Ashok Pandey[b], Christian Larroche[c], Datta Madamwar[d,*]

[a] Ministry of Environment, Forest and Climate Change, Indira Paryavaran Bhawan, Jor Bagh Road, New Delhi 110003, India
[b] CSIR-Indian Institute of Toxicology Research, Lucknow 226 001, India
[c] Polytech Clermont-Ferrand, Universite Clermont Auvergne, Clermont Ferrand, France
[d] Post-Graduate Department of Biosciences, UGC-Centre of Advanced Study, Sardar Patel University, Vadtal Road, Satellite Campus, Bakrol, Anand, Gujarat 388315, India

ARTICLE INFO

Keywords:
Algae
Biofuels
Biodiesel
Green energy
Photo-bioreactor
Triacylglycerol

ABSTRACT

Energy is the utmost requirement for driving the organization and maintenance of entire ecosystem. Our continued dependency on fossil fuels such as coal, petroleum and natural gas as the prime source of energy has led to serious concerns about the future energy supply and security. Furthermore, over-consumption of carbon-based fossil energy sources raises serious environmental issues of global warming and climate change. To overcome the global energy demand and to enable economic as well as ecological development in a sustainable manner, technological progress for the utilization of renewable natural energy are essential to protect the environment and save energy in today's increasingly competitive world. To this end, algal biofuels are being claimed as an apt alternative energy source and in recent past, several taxonomic groups of algae have been studied and reported as an alternative to fossil fuels. It is envisaged that algal biomass could be readily processed into the raw material to make cost-effective biofuels and is being explored as an emergent and renewable green energy crops for the production of biofuels, especially biodiesel. Development of astonishing technological innovations in the field of algal genetic engineering has triggered remarkable output across the global energy sector for better biofuels. Several new techniques are being adopted for large-scale farming of microalgae intended for biofuel production. However, there are certain constraints for commercial-scale energy production from algae. The present review discusses the technological development and current information on the cultivation and process of biodiesel production form algae. Also, discussed are the technological development and genomic insights into the algal biomass and triacylglycerol accumulation for enhanced biodiesel production.

1. Introduction

Since ancient times, fossil fuels have been used as an efficient and ideal source of energy. In the last few decades, urbanization and industrialization has led to substantial extraction and consumption of fossil fuels such as coal, petroleum and natural gas for various purposes. Moreover, fossil fuels are carbon-based energy sources which pose serious environmental health issues due to emission of incredible amount of gaseous pollutants such as carbon dioxide (CO_2), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), etc., upon combustion [1]. The harmful environmental impacts and global crisis of fossil fuels due to their over-consumption, and limited source in the nature has seriously impelled worldwide interest in search of alternative renewable energy sources [2–4]. Besides various natural energy sources, such as solar/wind power and hydroelectricity, different types of biomass are being used in various energy sector for power generation to meet the global fuel demand [5]. Conversion of renewable biomass to biofuels could be exceedingly feasible from ecological as well as economical view point, as fossil fuels are progressively becoming scarce and costly.

Algae including cyanobacteria (or blue-green algae) are major photosynthetic primary producers, maintaining the trophic energy dynamics and display a substantial role in sustainable development of aquatic or terrestrial ecosystems. Existence of different algae and cyanobacteria in diverse ecological niches even under adverse growth conditions compelled them to synthesize a range of valuable secondary biomolecules such as lipids or oils, carbohydrates, proteins, and several other feedstocks that can be used in production of biofuels and other co-

* Corresponding authors.
E-mail addresses: raj_rastogi@rediffmail.com (R.P. Rastogi), ashok.pandey1@iitr.res.in (A. Pandey), christian.larroche@univ-bpclermont.fr (C. Larroche), datta_madamwar@yahoo.com (D. Madamwar).

http://dx.doi.org/10.1016/j.rser.2017.10.038
Received 14 April 2017; Received in revised form 13 August 2017; Accepted 26 October 2017
1364-0321/

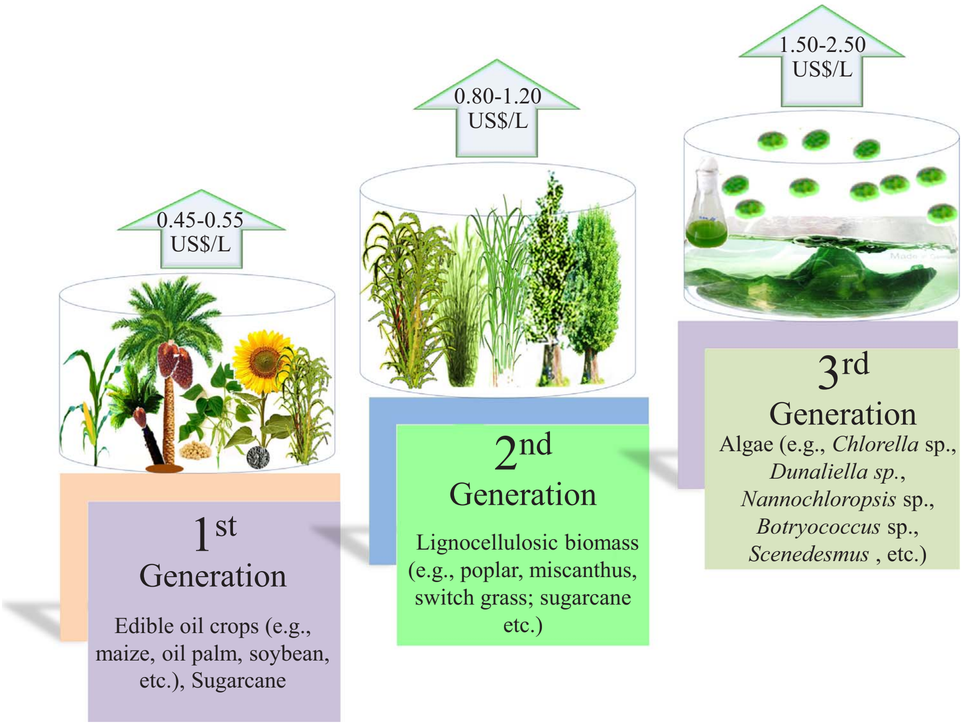

Fig. 1. The utilization of various natural resources for the production of first, second and third generation biofuels as the suitable alternatives to exhausting fossil fuels. As shown in Fig. 1, the production of biofuels from algae is quite higher than 1st or 2nd generation crops; however, the current cost of algal biofuel is comparatively higher (shown by arrow) (for details see [11,12].

products [6–10]. Algae can be employed as a very promising renewable energy sources due to their inherent capacity to fix the atmospheric CO_2 by the light-driven phenomena photosynthesis [11]. Moreover, algae can replace the first-generation feedstock such as edible crops (due to their food values), and second-generation lignocellulosic energy crops for the production of biofuels (Fig. 1) [6].

The net algal biomass yield per unit area is often higher than those of higher energy crops [12]. It has been shown that about 13.1 kg dry weight m^{-2} (over seven months) of brown algae was obtained under cultured conditions compared to about 6.1–9.5 kg fresh weight $m^{-2}yr^{-1}$ for sugarcane [13]. In comparison to higher energy crop, algae could be a potent biofuel feedstock due to their fast growth rate and per hectare productivity, cultivation on unproductive bare land using fresh/saltwater along with nutrients from waste water, and low cost downstream processing [14,15]. It has been speculated that around 200 barrels of oil can be achieved by growing the photosynthetic algae per hectare of land. The above estimated yield from algae is supposed to be several hundred times higher than that of a commonly used energy (biodiesel) crop (soybean) [7] (Fig. 2).

Usually, microalgae have far more extensively been used as a lipid-based biorefinery for biodiesel production than macroalgae due to their higher per hectare yield (158 t) than those of later 60–100 t) [14]. However, macroalgae offer ease of harvesting and comprising high content of carbohydrates, which can be processed into bioethanol. Macroalgae can produce a net energy of 11,000 MJ/t dry biomass compared to 9500 MJ/t by microalgae by gasification [16]. Algal biomass can be converted into different forms of biofuels such as bioethanol, biodiesel, bio-oil, and biogas (e.g., biohydrogen and biomethane) using different conversion techniques such as fermentation, transesterification, liquefaction, anaerobic digestion, and pyrolysis [6,17]. Some other strategies, including heterogeneous catalytic processes could also be employed for the transformation of algal biomass. Several catalysts are used for the conversion of various biomass-derived molecules such as levulinic acid [18] and/or gamma-valerolactone [19] for the production of value-added chemicals and transportation fuels. Recently, Yan et al. [20] have reviewed the use of layered double hydroxides (LDH) and its derived metal oxides (DMO) catalysts for the conversion of biomass-derived molecules.

Biofuel production from algae, including cyanobacteria is at developing stage and needs efficient and economically viable technological solutions for commercial-scale processes. Several pilot projects have been established worldwide to facilitate the mass production of algae and algal biofuels. Besides open pond cultivation, different kinds of photobioreactors have been explored for maximum algae production [21]. Development in genetic engineering has resulted into genetically engineered algae as a potent biofuel feedstock. However, there are several issues regarding the algal farming for biofuels, which needs to be addressed to advance the algae-based biofuel industry at commercial scale. There are concerns that algal farming at large-scale may cause exposure of harmful phycotoxins to both aquatic and terrestrial ecosystems [22,23]. Production of different algal toxins and other allergens or carcinogens may pose a serious threat to global public health as well as fundamental ecological processes due to their potential carcinogenicity. Thus, the safety concerns must be addressed before their production at commercial scale, in particular for genetically modified cultures.

2. Algal biomass: production and processing

Algae are ubiquitous in fresh or marine water habitats and are major biomass producers both in aquatic and terrestrial ecosystems. They exist in unicellular or large multicellular forms. Since ancient times, algae serve as potent multipurpose cellular factories for high-value products [24]. Besides the immense source of several valuable natural products, some species of algae are considered an excellent source of biofuels as a renewable source of green energy [25]. To reach a maximum output of any products, fast growth rate and high production of biomass is crucially required. Light, CO_2 and water are the prime factors for efficient growth of algae, including cyanobacteria; however, several other parameters such as temperature, pH, aeration, and nutrient availability also affect their growth and development. To compete with fossil fuels, cost-effective cultivation of algae at large scale is