Bioresource Technology 145 (2013) 134–141

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

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

Algal biofuels: Challenges and opportunities

Gustavo B. Leite, Ahmed E.M. Abdelaziz, Patrick C. Hallenbeck *

Département de microbiologie et immunologie, Université de Montréal, CP 6128, Centre-ville, Montréal, Canada PQ H3C 3J7

HIGHLIGHTS

- Algae are promising for biofuels production.
- Higher productivity and lipid content than plants.
- Open ponds are better than PBRs for biofuels.
- Technical hurdles include harvesting and oil extraction.

ARTICLE INFO

Article history:
Available online 9 February 2013

Keywords:
Biofuels
Algal biodiesel
Photobioreactors
Oil extraction

ABSTRACT

Biodiesel production using microalgae is attractive in a number of respects. Here a number of pros and cons to using microalgae for biofuels production are reviewed. Algal cultivation can be carried out using non-arable land and non-potable water with simple nutrient supply. In addition, algal biomass productivities are much higher than those of vascular plants and the extractable content of lipids that can be usefully converted to biodiesel, triacylglycerols (TAGs) can be much higher than that of the oil seeds now used for first generation biodiesel. On the other hand, practical, cost-effective production of biofuels from microalgae requires that a number of obstacles be overcome. These include the development of low-cost, effective growth systems, efficient and energy saving harvesting techniques, and methods for oil extraction and conversion that are environmentally benign and cost-effective. Promising recent advances in these areas are highlighted.

1. Introduction

The transportation sector plays a major role in the production of greenhouse gas (GHG) emissions, as well as being responsible for 28% of total world primary energy consumption, mainly consisting of fossil fuels, and for 71% of the total crude oil used (Energy, 2004; Pienkos and Darzins, 2009). Transportation fuels can be divided into three groups related to use: private vehicles (gasoline); commercial vehicles and stationary engines (diesel); or jet fuels (kerosene). World consumption of diesel was nearly 1460 trillion liters in 2011 (OPEC). Fuel demand in the transportation sector is projected to increase by 40% over the period 2010–2040 (ExxonMobil, 2013). Most of this demand is driven by the commercial sector with heavy duty vehicle (diesel) fuel use increasing by 65%. Although the number of light-duty vehicles (cars) could double, the increased fuel demand might be largely offset by increased fuel efficiency and the switch to hybrid technologies (ExxonMobil, 2013).

Any plan to lower GHG emissions will require the substitution of at least part of the petroleum-based fuels used for transportation. Today we “*borrow land from the past*” (Wackernagel and Yount, 1998), by using carbon which was fixed in another era. Even at present prices, crude oil is cheap, easily extracted and easy to use since it just needs to be taken from its natural reservoir and distilled into products. However, its use reintroduces into the atmosphere carbon trapped millions of years ago. In addition to the role of fossil fuel combustion in climate change due to the increased concentration of CO_2 in the atmosphere, a well established mathematical model used to calculate crude oil field reserves and production capabilities predicts peak oil within the next few decades (Nashawi et al., 2009).

After a hundred years of intensive use, humanity has become strongly dependent on fossil fuels, we are addicted to oil. The world’s economy relies on the very efficient system of production, distribution and use that has been developed. Any transition to a new fuel will have to be “painless”, using the technology and infrastructure of the existing system as much as possible. The first generation of biofuels fit this model as bioethanol and biodiesel require minimal or no adjustment of regular internal combustion engines, and can generally be distributed, stored and pumped like conventional crude oil-derived fuels. The major drawback to the use of these alternative fuels is that arable land is used to farm the corn, sugar cane or oil seed

* Corresponding author. Tel.: +1 514 343 6278; fax: +1 514 343 5701.
E-mail address: patrick.hallenbeck@umontreal.ca (P.C. Hallenbeck).

0960-8524/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2013.02.007

crops needed to produce these fuels. In addition, it would be impossible to produce the quantity of biofuels that would be necessary to meet present fuel demands using first generation technology. In 2010, the US consumed nearly 220 trillion liters of diesel (Energy Information Administration, 2012). To produce this volume of fuel using soybeans for example (average yield of 600 liter per hectare), would require 367 million hectares, in contrast with the only 178 million hectares that is currently available for cropland and the 930 million hectares of total US land area (EIA, 2012). In addition, the commodities used for first generation biofuels production have other possible markets as sugar, animal feed or cooking oil. A farmer will negotiate the selling price of his product in order to profit as much as possible, enhancing even more the competition between food and fuel and creating a complex fluctuation of food prices linked to fuel demand. With actual world production of biofuels at 109 trillion liters per year (86.6 trillion liters bioethanol, 24.4 trillion liters of biodiesel) (EIA, 2012), there has been a great deal of speculation as to whether or not this is already happening. Thus it is clear that although production of first generation biofuels was an important step, it is however only a palliative solution and is untenable in the long term.

2. Microalgae

The call for advanced biofuels demands "drop in" fuels able to be used with the existing infrastructure for storage and distribution, from manufacture to the final customer, but with a production system able to be scaled up without competing with food crops for land. Microalgal biodiesel has been proposed as the most obvious choice. Microalgae are oxygen producing microorganisms containing chlorophyll "a", mostly autotrophs, using atmospheric CO_2 as primary carbon source whereas some can grow mixotrophically, facultatively using an organic source of carbon in addition to CO_2, or even heterotrophically, using only previously fixed carbon as a carbon source. Some are obligate heterotrophs, unable to perform photosynthesis due to a defective plastid. Thus, microalgae can be pictured as single or associated cells floating in oceans, rivers or lakes and using sunlight to produce and store fixed carbon. Thousands of prokaryotic (cyanobacterial) and eukaryotic species match this description; they are the primary producers in oceans, supporting three-fourths of the planetary food chain. The ancestors of microalgae go all the way back to the origin of life and have been directly linked to past events of climate change, transforming the composition of the Earth's atmosphere by the production of O_2, and mitigating CO_2 by sinking fixed carbon deep in the ocean (Buesseler, 2012).

By the above definition, the term "algae" is an artificial way to group tens of thousands species which are in fact taxonomically distributed over several kingdoms; Protista, Chromista, and Plantae (Woese et al., 1990; Cavalier-Smith, 2004; Guiry and Guiry, 2012). These organisms inhabit the most divergent environments, with some species colonizing the Earth's poles and others causing blooms in the tropics (de Morais and Costa, 2007; Cellamare et al., 2010; Mutanda et al., 2011; Pereira et al., 2011). They are found in hyper-saline to fresh water environments, over a broad range of pHs, and even relatively dry environments such as soil and rocks. Microalgae are adapted to inhabit almost any place with enough humidity, and many are also able to enter into a dormant state until there is enough moisture to resume metabolism. They are taxonomically rooted with the ancestor of land plants, an organism formed by the endosymbiosis between a heterotrophic eukaryotic host cell and a cyanobacterium, which formed the plastid. This event is thought to have happened 1.5 billion years ago (Yoon, 2004) and subsequent differentiation and further endosymbiotic events gave rise to branches such as the green algae and the red algae.

Table 1
Conventional diesel cost as of August 2012 (retail price US-$1.05/L) {EIAUSEnergyInfo:tm}.

Diesel fuel cost	Share (%)	Value (US-$)
Taxes	12	0.126
Distribution and marketing	14	0.147
Refining	14	0.147
Crude oil	60	0.630

3. Algal biofuels

Any organism dependent on sunlight as its primary energy source needs to store energy-rich compounds to avoid starvation when light is not available. Vascular plants synthesize a variety of energy rich molecules to save enough energy from the sunlight period for a rainy day (or night). A Canadian example would be the maple tree and the phloem with its high sugar content (Maple Syrup). Vascular plants often produce oil as a carbon reserve for germination. To increase embryo viability, some plants accumulate part of the energy in the seed as TAGs (triacylglycerols), which is historically accessed by press extraction (e.g. olive oil). Microalgae are capable of the synthesis and accumulation of a variety of high energy molecules, including fatty acids (FA) and TAGs, the major feedstock for biodiesel production.

However, species with a high lipid content are not phylogenetically related, occurring in different kingdoms, Protista (e.g. Dinoflagellates), Chromista (e.g. Diatoms) and Plantae (e.g. Chlorophytes). TAG content varies among strains of the same species in quantity and quality (Leite and Hallenbeck, 2012). Nevertheless, lipid content higher than 50% is frequently described in many species, which represents one of the advantages of using microalgae instead of vascular plants for biodiesel production. Only the seeds of a vascular plant are used when making plant-derived biodiesel, with the rest of the biomass usually considered waste. Consequently, the aerial production yield of lipids from microalgae has the potential to be many times higher than that of the already developed technology of oil seed crops, with the advantage of not requiring arable land. Another key factor for choosing microalgae as a system for biodiesel production is their potentially minimal nutritional requirements. Microalgae can be grown on fresh or marine water, on marginal lands, and even in association with wastewater treatment plants or industrial parks where their cultivation offers the additional benefit of bioremediation. After the extraction of hydrocarbon for biodiesel production, the biomass can be processed in an anaerobic digester for methane production, a secondary source of energy, with the digester effluent fed back into the algae cultivation system as a source of nutrients. Even though production with such a system may not completely satisfy local fuel demands, it will evidently lower the importation of fuel, creating a decentralization of production (Table 1), improving the local economy and helping the environment.

4. Cultivation

Two basic alternatives for microalgae cultivation exist and their relative merits are the basis of ongoing debate. Some of the factors involved are listed in Table 2.

4.1. Photobioreactors

These are systems where the cultures are enclosed in some transparent recipient. Photobioreactors (PBR) can have different sizes and shapes: plastic bags, flat panels, tubes, fermenter like and others. Vertical tubes are among the most popular system