Microalgae as a Feedstock for Biofuels

Abstract This review explains the potential use of the so-called "green coal" for biofuel production. A comparison between microalgae and other crops is given, and their advantages are highlighted. The production of biofuels from microalgae biomass is described, such as the use of algae extracts (e.g. biodiesel from oil, bioethanol from starch), processing the whole biomass (e.g. biogas from anaerobic digestion, supercritical fluid, bio-oil by pyrolysis, syngas by gasification, biohydrogen, jet fuel), as well as the direct production (e.g. alcohols, alkanes). Microalgal biomass production systems are also mentioned, including production rates and production/processing costs. Algae cultivation strategy and the main culture parameters are point out as well as biomass harvesting technologies and cell disruption. The CO_2 sequestration is emphasised due to it's undoubted interest in cleaning our earth. Life cycle analysis is also discussed. The algal biorefinery strategy, which can integrate several different conversion technologies to produce biofuel is highlighted for a cost-effective and environmentally sustainable production of biofuels. The author explains some of the challenges that need to be overcome to ensure the viability of biofuel production from microalgae. This includes the author's own research, the use of microorganism fuel cells, genetic modification of microalgae, the use of alternative energies for biomass production, dewatering, drying and processing. The conclusion of the manuscript is the author's view on the potential of microalgae to produce biofuels; the drawbacks and what should be done in terms of research to solve them; which technologies seem to be more viable to produce energy from algae; and which improvements in terms of microalgae, systems, and technologies should take place to enable the algae to fuels concept a reality.

Keywords Bioenergy production · Biofuels · Biorefinery concept · CO_2 sequestration · Environmental sustainability · Green coal · Life cycle analysis of microalgae · Microalgae · Microalgal biomass production systems · Photobioreactors

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1 Introduction

Fuels make up a large share of global energy demand ($\sim$66%). The development of CO_2-neutral fuels is one of the most urgent challenges facing in our society, to reduce gaseous emissions and their consequential climatic changes, greenhouse and global warming effects. Biofuel production is expected to offer new opportunities to diversify income and fuel supply sources and can help to reduce the adverse effects of the frequent oil supply crisis, as well as developing long-term replacement of fossil fuels, helping non-fossil–fuel-producing countries to reduce energy dependence. This will in turn promote employment in rural areas, reduce greenhouse gas (GHG) emissions, boost the decarburization of transportation fuels, increase the security of energy supply and promote environmental sustainability.

However, to achieve environmental and economic sustainability, production of fuels should require them to be not only renewable, but also capable of sequestering atmospheric CO_2.

2 Microalgae and Biofuels Production

Microalgae are microscopic photosynthetic organisms that are found in both marine and fresh water environments. Their photosynthetic mechanism is similar to land-based plants, due to a simple cellular structure, and the fact that they are submerged in an aqueous environment, where they have efficient access to water, CO_2 and other nutrients, they are generally more efficient in converting solar energy into biomass. The absence of non-photosynthetic supporting structures (roots, stems, etc.) also favours the microalgae in aquaculture (John et al. 2010).

Microalgae appear to represent the only current renewable way to generate biofuels (Chisti 2007; Schenk et al. 2008). Microalgae biofuels are also likely to have a much lower impact on the environment and on the world's food supply than conventional biofuel-producing crops. When Compared with plants biofuel, microalgal biomass has a high caloric value, low viscosity and low density, properties that make microalgae more suitable for biofuel than lignocellulosic materials (Miao et al. 2004), as well as due their inherently high-lipid content, semi-steady-state production, and suitability in a variety of climates (Clarens et al. 2010).

One unique aspect of algae as compared to other advanced feedstocks is the spectrum of species available for amenability for biofuel production. Various species may be selected to optimize the production of different biofuels. Algae offer a diverse spectrum of valuable products and pollution solutions, such as food, nutritional compounds, omega-3 fatty acids, animal feed, energy sources (including jet fuel, aviation gas, biodiesel, gasoline, and bioethanol), organic fertilizers, biodegradable plastics, recombinant proteins, pigments, medicines, pharmaceuticals, and vaccines (Pulz 2004; Pienkos and Darzins 2009).

Microalgae may soon be one of the Earth's most important renewable fuel crops (Campbell 1997). The main advantages of microalgae are (Campbell 1997; Chisti 2007; Huntley and Redalje 2007; Schenk et al. 2008; Li et al. 2008; Rodolfi et al. 2009; Khan et al. 2009):

- a higher photon conversion efficiency (approximately 3–8% against 0.5% for terrestrial plants), which represents higher biomass yields per hectare) and grow at high rates (e.g. 1–3 doublings/day)
- a higher CO_2 sequestration capacity
- it is able to grow in a liquid medium, with better handling, and can utilize salt and waste water streams (saline/brackish water/coastal seawater), thereby reducing freshwater use
- it utilizes nitrogen and phosphorous from a variety of wastewater sources (e.g. agricultural run-off, concentrated animal feed operations and industrial and municipal wastewaters) providing the additional benefit of wastewater bioremediation
- it uses marginal areas unsuitable for agricultural purposes (e.g. desert and seashore lands) and thereby does not compete with arable land for food production
- production is not seasonal and can be harvested batch-wise nearly all-year-round
- cultures can be induced to produce a high concentration of feedstock (oil, starch, biomass)
- algal biomass production systems can be easily adapted to various levels of operational and technological skills
- it can be cultured without the use of fertilizers and pesticides, resulting in less waste and pollution
- the nitrous oxide released can be minimized when microalgae are used for biofuel production (Li et al. 2008)
- they have minimal environmental impact such as deforestation
- the conversion of light to chemical energy can be responsible for a wide range of fuel synthesis: protons and electrons (for biohydrogen), sugars and starch (for bioethanol), oils (for biodiesel) and biomass (for BTL and biomethane) (Fig. 1), via biochemical, thermochemical, chemical and direct combustion processes (Fig. 2)
- they produce value-added co-products or by-products (e.g. proteins, polysaccharides, pigments, biopolymers, animal feed, fertilizers…).

Photosynthesis drives the first step in the conversion of light to chemical energy and is, therefore, ultimately responsible for the production of feedstock required for all biofuels: synthesis of protons and electrons (for Bio-H_2), sugars and starch (for Bio-ethanol), oils (for Biodiesel) and biomass (for BTL products and Biomethane) (Hankamer et al. 2007; Costa and Morais 2011).

In the international market, the most technically feasible and commercialised alternative renewable fuel sources are biodiesel and bioethanol. These, respectively, can both replace diesel and gasoline in today's cars with not much or no

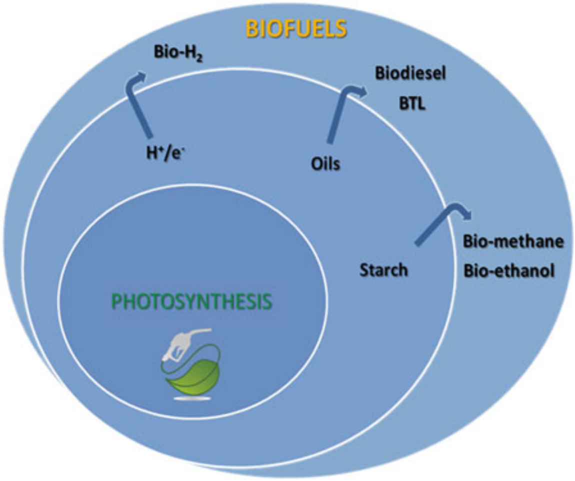

Fig. 1 The rule of photosynthesis in biofuel production

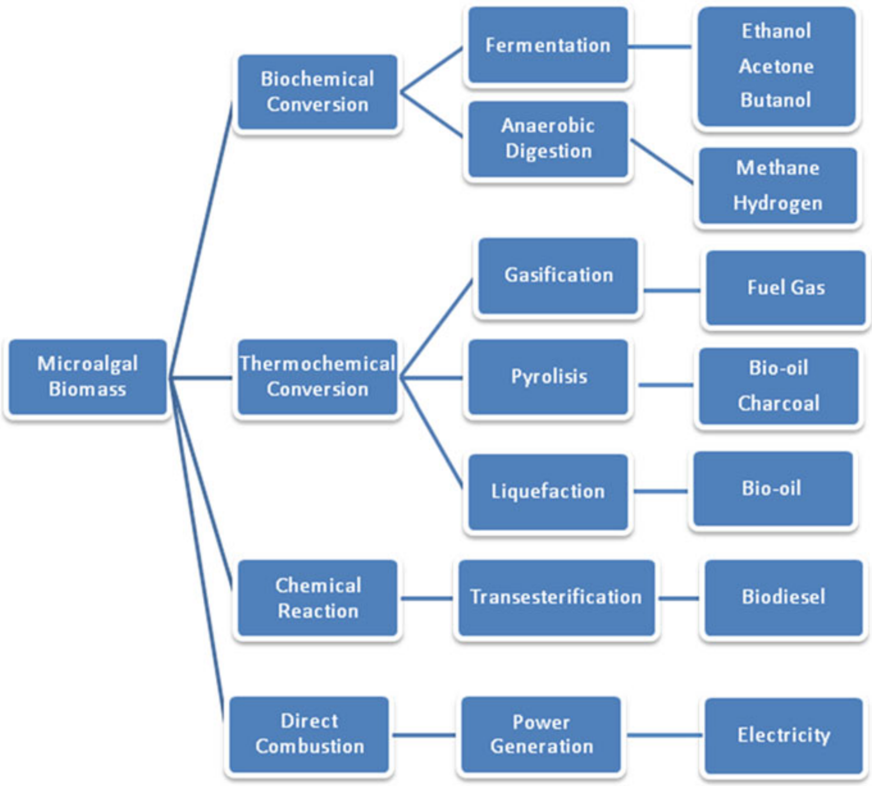

Fig. 2 Energy production by microalgal biomass conversion using biochemical, thermochemical, chemical and direct combustion processes (Wang et al. 2008)

modifications to vehicle engines. They can be produced using existing technologies and can be distributed through the available and existing distribution systems.

When terrestrial biofuels are to replace mineral oil-derived transport fuels, large areas of good agricultural land are needed: about 5×10^8 ha in the case of biofuels from sugar cane or oil palm, and at least $1.8–3.6 \times 10^9$ ha in the case of ethanol from wheat, corn or sugar beet, as produced in industrialized countries (Reijnders 2009).

The overall solar energy conversion efficiency determines net energy yield/ha and this in turn determines land requirements for fossil fuel displacement. In the case of ethanol from sugarcane, the overall solar energy conversion energy efficiency is currently ~0.16% (Kheshgi et al. 2000) and in the case of biodiesel from palm oil ~0.15% (Reijnders and Huijbregts 2009). These percentages are much higher than those for transport biofuels from European wheat and rapeseed (Reijnders 2009).

Both fuels (Biodiesel and Bioethanol) are being produced in increasing amounts as renewable biofuels, but their production in large quantities is not sustainable (Chisti 2007, 2008a, b).

Currently, about 1% (14 million hectares) of the world's available arable land is used for the production of biofuels providing 1% of global transport fuels. Clearly, increasing the share, it will be impractical due to the severe impact on the world's food supply and the large areas of production land required (IEA 2006).

A large number of potential pathways exist for the conversion from algal biomass to fuels. The pathways can be classified into the following three general categories: (1) those that process algal extracts (e.g., lipids, carbohydrates) to yield fuel molecules (e.g. biodiesel, bio-ethanol); (2) those that process whole algal biomass to yield fuel molecules; and (3) those that focus on the direct algal production of recoverable fuel molecules (e.g. ethanol, hydrogen, methane, alkanes) from algae without the need for extraction.

Nevertheless, microalgae that have been pointed as the next feedstock for biofuels due to their very high productivities when compared with the conventional energy crops, many constraints related with harvesting, drying and extraction of oils have delayed the industrial production of microalgal biofuels.

2.1 Algal Extracts

2.1.1 Oils to Biodiesel

Biodiesel is developing into one of the most important near-market biofuels as virtually all industrial vehicles used for farming, transport and trade are diesel based. In the past decade, the biodiesel industry has seen massive growth globally, more than doubling in production every 2 years (Oilworld 2009). Biodiesel represents the highest contribution to the total amount of liquid biofuels produced in the EU with a market share, in 2004, of 79.5%. In Indonesia, Malaysia and

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