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Microalgae biomass production for a biorefinery system: Recent advances and the way towards sustainability

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ABSTRACT

Microalgae are an important source of oils and other molecules that can be used as feedstocks to produce biofuels and high-value products, having the potential of becoming a significant renewable energy source. However, large scale production of microalgal biofuels faces numerous technical challenges, which makes the current growth and development of the microalgae biorefinery industry, still economically unviable. This study reviewed the recently released information regarding the upstream methodologies involved in an algae-based biofuels production system. The better understanding of the conversion of light to biomass, the analysis of the productivities of the most recent culture systems, the use of waste waters as alternative sources of nutrients, and the co-location of the algae biomass production process to an industry are among the approaches that have been proposed to track the challenges in the development of a biorefinery system based on microalgae; these have been analyzed critically in this work.

1. Introduction

Biofuels are considered the most likely sources of energy that can replace an important proportion of fossil fuels. Third-generation biofuel production is mainly based on microalgae. Microalgae are photosynthetic prokaryotic or eukaryotic microorganisms that grow rapidly and have the ability to live in different environments due to their unicellular or simple multicellular structure and their simple growth needs [1]. The interest for these organisms lies in their potential to produce biomass for food, feed and fine chemicals but mainly for the possibility of synthetizing biofuels from the microalgae biomass.

Microalgae can produce lipids, proteins and carbohydrates that can be processed into both biofuels and valuable co-products with the capacity to replace large volumes of crude oil and to supply demands in food supplements, animal feed, colorants, enzymes, and several other valuable chemicals.

The production of the biomass can be achieved in closed and open systems, following several different configurations. The open systems, even when having the disadvantage of low control contamination from predators, are the more economic systems, whilst photobioreactors (PBR) provide a favourable system to control nutrients and cultivation parameters such as temperature, dissolved CO_2, pH and lighting. This, at a high initial cost. The kind of system to be utilized is determined by the intended use of the biomass, and driven by the environmental conditions of the production location.

Despite the several advantages associated to microalgae over higher plants (such as soybean, sunflower, sugar cane and palm oil) with regard to biofuel production, the production of biofuels from microalgae biomass still do not represent a significant share in worldwide liquid fuel supply as there are many challenges still standing in front of the deployment of algal biofuels and hinder the achievement of a sustainable biofuel production from microalgae that competes with petroleum (Table 1). Efforts are being made by the academic, industrial and governmental sectors to overcome these challenges which had resulted in a constant flow of new information in terms of innovative technologies for bioreactors, new sources of nutrients, and cultivation strategies.

This new trends and information regarding the biorefinery systems from microalgae as feedstock need to be analyzed with the aim to find research gaps, and the future directions in this area.

This paper brings together the latest released information related to the production systems for microalgae biomass as feedstock for a biorefinery system; with a focus on the literature analysis on the recent

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Table 1
Advantages and challenges of the use of microalgae biomass as a feedstock to produce biofuels and co-products compared with higher plants.

Advantages	Challenges
Higher growth and photosynthetic rates and higher oil productivities for their all-year production capability [2].	Better understanding of the trade-offs between lipid and co-products accumulation and productivity [5].
Growth under extreme environmental conditions and lower nutritional and water requirements. Ability to be cultivated in saline water and no requirements of herbicides or pesticides [2].	Designing of more efficient strategies to improve the light-to-biomass conversion efficiencies of the microalgae cultivation [6].
Contribution to CO_2 sequestration and to wastewaters bioremediation [3].	Attaining of higher effectiveness of the biomass production systems to reduce evaporation, and capture CO_2 from the flue gases having a complex composition, while still maintaining high volumetric microalgal productivity [7].
Valuable co-products such as proteins and pigments, could also be obtained from microalgal biomass with the possibility to modulate the biomass composition by modifying the nutritional requirements and growth conditions [4].	Accomplishment of more positive energy balances after accounting for requirements in water pumping, CO_2 transfer, and the harvesting, extraction and conversion processes [8].

advances, the state of the art on the currently operating plants of biomass, biofuels and co-products at a large scale and the way-to-go to overcome the challenges of a sustainable microalgae-based biofuels industry.

2. Products obtained from microalgae

Microalgae are microscopic organisms that photosynthesize light and can grow rapidly and live in several environments such as in freshwater, waste water, and marine water due to their unicellular or simple multicellular structure. Microalgae are present in all existing earth ecosystems, either terrestrial or aquatic environments. Depending on the species, microalgae are capable to produce varying amounts of lipid, polyunsaturated fatty acid, natural dye, carotenoid, antioxidant, enzyme polymer, peptide, toxin and sterols, with valuable applications in different industrial sectors (biofuels, cosmetics, pharmaceuticals, nutrition and food additives, aquaculture and pollution prevention).

2.1. Biofuel production

One of the main interest in growing microalgae is because of the ability of these microorganisms to produce and accumulate energy molecules in their cells. Different types of microalgal species accumulate significant quantities of lipids, a valuable component for the production of biodiesel, renewable diesel, and biocrude. Species such as *Botryococcus braunii, Desmodesmus, sp., Nannochloropsis sp., Scenedesmus* SDEC-8, *Nannochloropsis sp. and Sorokiniana* FCG IITG, have been reported for having the highest lipid content ranging between 45% and 64% of dry weight, these can be converted potentially to biofuel [9–16].

Table 2 summarizes some of the most recent works on the lipid content and productivities for different species of algae.

The lipid fraction in microalgae biomass can be transformed into energy products via a thermochemical conversion to produce renewable diesel or biodiesel.

Biodiesel is a mixture of the mono alkyl esters of long-carbon-chain fatty acids derived from renewable lipid feedstock. The biodiesel production process includes a cell disruption to release the lipids, a solvent-assisted lipid extraction, and a transesterification step to produce the biodiesel. The drying step of the biomass is one of the most energy consuming unit operations in biodiesel production [17]. However, novel approaches have been shown to have higher productivities by a direct conversion of wet microalgae biomass into biodiesel with a microwave-assisted transesterification [18].

On the other hand, renewable diesel, also known as green diesel, is a term used to classify a hydro treated vegetable oil (HVO) produced from soybean, palm, canola or rapeseed oil; animal tallow; or vegetable oil waste and can be used alone or blended with petroleum. Neste Corporation, the current largest producer and distributor of renewable diesel in the world has initiated a partnership with Cellana, Inc. a leading developer of algae-based Bioproducts, for a commercial-scale quantities of Cellana's ReNew™ Fuel algae oil feedstock for biofuel applications.

Bio oil production is performed from the pyrolyzation of free fatty acids from microalgae lipids either in the presence of nitrogen or air, or in the presence of hydrogen (hydro pyrolysis). The production of hydropyrolysis oil requires the use of catalyzers to improve the quality of the oil as it is still very viscous, acidic, unstable and has poor miscibility with refinery feedstocks [20]. These processes convey higher cost for the energy inputs needed and the possible necessity of a previous lipid extraction step, which places them in a disadvantageous

Table 2
Lipid yields and productivities of different microalgae species.

Strain	Culture conditions	Total lipid extracted (DW %)	Comments	Reference
Desmodesmus, sp.	Continuous illumination at 700 μmol/m^2 s, 35 °C, CO_2 flow rate of 0.2 vvm	64.1	38.9% saturated, 33.1% mono unsaturated and 22.6% poly unsaturated fatty acids in the lipid fraction	[10]
Chlorella sp. PCH90	16 W/m^2, on a 16:8 light: dark photoperiod, 22 °C, pH of 6.8	36	Novel microalga native to Quebec with the ability to grow at low temperature (10 °C) and to produce high concentration of lipid.	[19]
Botryococcus braunii	35 μmol/m^2 s on a 16:8 h light: dark cycle, 56 days culture	57.1	Dried biomass with 52.6% of crude hydrocarbon and 55 KJ/g of energy value after 28 days.	[16]
Botryococcus braunii	100 μmol/m^2 s, 10 days attached cultivation	51	Hydrocarbon content and productivity of 32% and 1.06 g/m^2 d respectively	[9]
Desmodesmus sp	Batch Fed-batch Semi-continuous	64.1 49.2 45.6	72% saturated and monounsaturated fatty acids in the lipid fraction.	[11]
Nannochloropsis oceanica IMET1	100 μmol/m^2 s, CO_2 flow rate of 1.6 mL/min, 25 °C, 22 days culture	52.9	Promising feedstock for microalgal biodiesel production for the favourable fatty acid profiles and suitable biodiesel properties	[13]