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Integrated biodiesel and biogas production from microalgae: Towards a sustainable closed loop through nutrient recycling

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A B S T R A C T

The sustainable, efficient production of biofuel can lead to reductions in greenhouse gas emissions, lowered climate change impact and increased security owing to the fulfilment of global energy demands. Microalgae have been shown as an attractive feedstock for renewable fuel production, such as biodiesel and biogas. To date, more effort has been put towards the production of biodiesel using the lipid contents in algal cells, while less attention has been placed on biogas production through anaerobic digestion. However, anaerobic digestion has the potential to generate energy from waste residues and to mobilize nutrients enabling subsequent recovery and/or recycling. Therefore, anaerobic digestion is an area with strong potential for novel research focusing on the development of a sustainable integrated system of biodiesel and biogas production. The result is essentially a solar power plant, producing fuel with minimal inputs and a closed nutrient loop, a necessity for sustainable and cost-efficient production of biofuel. In this review we discuss relevant studies on biodiesel and biomethane production, including the potential improvements and advantages when using an integrated approach for biodiesel and biogas production with special focus on nutrient recycling.

1. Introduction

Biofuels have been considered a promising sustainable alternative for energy production, potentially decreasing the emission of greenhouse gasses. Currently, liquid biofuels are mainly produced in the forms of bioethanol and biodiesel from different agricultural feedstocks, including oil crops such as oil palm, soybean and rapeseed, and sugar and starch crops such as sugarcane and corn [1,2]. These biofuels (named first generation biofuels) have been shown to be unsustainable and insufficient to meet the increasing energy demands, due to uncertain/poor energy balances, high water demands and high nutrient requirements, as well as competition for arable lands and thus with food crops [3–7]. Second generation biofuels seem to be an interesting alternative since they are produced from non-food biomass, including agricultural wastes and ligno-cellulosic feedstock such as wood, grasses and forest residues [4,8]. However, their potential to sustainably satisfy world energy demands is a matter of debate, in terms of feedstock availability and potential negative effects on carbon balances and biodiversity [9,10]. On the other hand, biofuels produced from microalgal biomass (third generation biofuels) can potentially overcome the drawbacks of first and second generation biofuels, being more productive and sustainable [11–13].

Microalgae have faster growth rates than other crops and thus higher yields per unit area. The selection of productive strains can lead to the harvesting of cells with high lipid and carbohydrate contents, and different strains can be grown in fresh, brackish and sea water. Microalgae cropping does not compete with food crops since they can be produced in non-arable land, and additionally can be grown in wastewater as their culture medium, reducing the use of freshwater and nutrients [11–15]. Microalgae as a source of biofuels have been widely studied for the production of bioethanol [16–19], biodiesel [20–26], biogas through anaerobic digestion [27–32] and biohydrogren [33–36]. However, more research is needed in order to increase the efficiency for microalgal biofuel production and thus enhance its commercial viability, and at the same time increase the sustainability of the production process.

Maximizing production and reduction of inputs could be achieved through the development of an integrated system for biodiesel and biogas production, using anaerobic digestion (Fig. 1). That is because, besides biogas production, anaerobic digestion leads to the production

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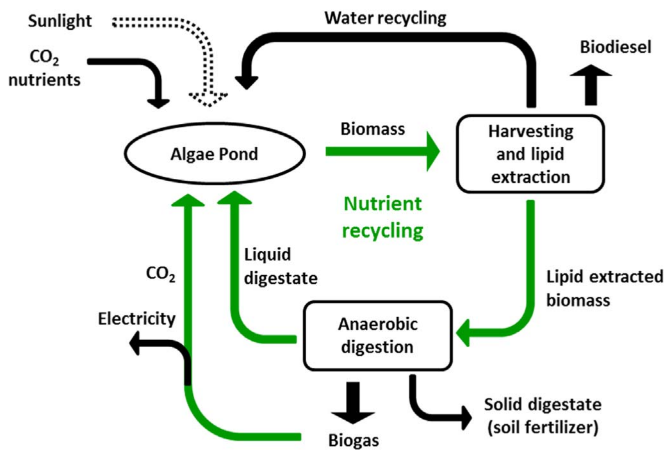

Fig. 1. Schematic model of an integrated closed loop of biodiesel and biogas production using microalgae. The diagram shows minimal inputs in an integrated system for solar biodiesel and biogas production. In this system, lipids are extracted from the concentrated biomass while water is reused to repeat algae cultivation. The defatted biomass is used as substrate for anaerobic digestion to produce biogas. Biomethane is burned to produce the electricity needed to maintain the system, while nutrients and CO_2 are recycled. The liquid phase of the digestate is used as algal culture broth and the solid phase can be used as soil fertilizer. Nutrient recycling is highlighted in green color.

of an effluent that can be used as fertilizer for algae culture, reducing the need of costly nutrients [37]. Thus, the integration of biodiesel and biogas production through anaerobic digestion of algae debris after lipid extraction is a promising way to significantly enhance methane production [38–40], while the recycling of nutrients from anaerobic digestion is a key step to make microalgal biodiesel production sustainable and reduce overall production costs [19,41–45]. In fact, Sialve et al. conclude that coupling anaerobic digestion with biodiesel production is essential for microalgal fuels to be viable [43]. Additionally, if biogas is used for the production of heat or electricity, CO_2 will be available for algae cultivation while reducing production costs [12]. The integrated system has the potential to reduce energy consumption and reduce up to 71% greenhouse gas emissions compared to petroleum fuel [46].

Here, we wish to provide a perspective on a closed loop system focused on nutrient recycling, including an analysis on available pretreatments for cell disruption that may enhance biofuel production. Through this review we aim to bring together relevant studies on biodiesel and biomethane production from microalgae, focusing on nutrient recycling through anaerobic digestion for the development of a sustainable and profitable closed loop for energy production with minimal inputs. First, we describe the current methods and requirements for the production of biodiesel and biomethane, comparing different microalgal strains in terms of biodiesel and biogas production potential. Then, we provide an overview of the different pre-treatments that can be suitable both for biodiesel and biogas production, which will potentially improve an integrated biorefinery. Finally we discuss the advances towards the development of an integrated nutrient closed loop for biofuel production through anaerobic digestion, including economic and sustainability aspects.

2. Algal biomass production: culture conditions and harvesting

Light and nutrients are the main factors that determine cell production while herbivory and sedimentation lead to population loss [47], becoming the main factors that should be controlled in order to guarantee algal productivity and consequently high biomass yields. Besides, other variables such as temperature, pH, turbulence and salinity are crucial for culture growth [12–14,48].

Different microalgae species have specific nutrient requirements and are limited by different resources [49,50]. Within inorganic nutrients, macronutrients (mainly nitrogen and phosphorus) are needed at high concentrations—on average, the production of 1 kg dry algal biomass requires around 55 g N and 11 g P. On the other hand, micronutrients are needed at low concentrations and have a specific metabolic role on microalgae physiology [48,51,52]. The specific optimal proportion of nutrients for each species may change depending on factors that include growth rate, temperature, light or CO_2 availability. Likewise, species differ in their nutrient requirements and nutrient uptake kinetics which results in different optimal proportions [52]. A general list of the main nutrients required by algal cells is detailed in Table 1.

Table 1
Elementary composition of microalgae.
Source: Adapted from Healey [53] and Grobbelaar [54].

Element	Compounds	Cell composition (μg/mg dry weight)	
		Average	Range
H	H_2O, organic molecules, H_2S	65	29–100
C	CO_2, HCO_3^{2}, CO^{3-}, organic molecules	430	175–650
O	O_2,H_2O, organic molecules	275	205–330
N	N_2, NH_4^+, NO_3^-, NO_2^-, amino acids, purines, pyrimidines, urea, etc	55	10–140
Si	$Na_3SiO_3{\cdot}9H_2O$	54	0–230
K	Several inorganic salts, i.e. KCl, K_2SO_4, K_3PO_4	17.3	1–75
P	Several inorganic salts, Na or K phosphates, Na_2 glycerophosphate·$5H_2O$	11	0.5–33
Na	Several inorganic salts, i.e. NaCl, Na_2SO_4, Na_3, PO_4	6.1	0.4–47
Mg	Several inorganic salts, i.e. Co_2^{3}, SO_4^{2-} or Cl^- salts	5.6	0.5–75
Ca	Several inorganic salts, i.e. $CaCO_3$, Ca^{2-} (as chloride)	8.7	0.0–80
S	Several inorganic salts, $MgSO_4{\cdot}7H_2O$, amino acids	5.9	1.5–16
Fe	$FeCl_3$, $Fe(NH_4)_2SO_4$, ferric citrate	5.9	0.2–34
Zn	SO_4^{2-} or Cl^- salts	0.28	0.005–1.0
B	H_3BO_3	0.03	0.001–0.25
Cu	SO_4^{2-} or Cl^- salts	0.1	0.006–0.3
Mn	SO_4^{2-} or Cl^- salts	0.06	0.02–0.24
Co	Vitamin B_{12}, SO_4^{2-} or Cl^- salts	0.06	0.0001–0.2
Mo	Na^+ or NH_4^+ molybdate salts	0.0008	0.0002–0.001

Because moisture content can reach more than 99% of total microalgae cultures [55], harvesting is one of the biggest bottle necks for biodiesel production. Harvesting is difficult due to the small size of microalgae, their low specific gravity and similar density of the growth medium. Microalgae typically form stable suspensions in the water column and their high growth rates require regular harvesting [55,56]. Many techniques for primary dewatering of microalgae have been developed (sedimentation, flocculation, flotation, filtration and centrifugation) but many of them are strain specific or have complicated operation methods that represent high economic and energy costs [15,56,57]. For achieving a sustainable and profitable integrated biofuel production system, the most efficient and economic harvesting method is sedimentation by gravity. In this way, the economic impact is minimal and ideally, wet biomass can be used for direct lipid extraction.

3. Biodiesel from microalgae

Microalgae have the capability to accumulate large amounts (20–50% dry weight) of triacylglycerides (TAGs)—which are the main compounds for biodiesel production—especially under nutrient deprivation, photo-oxidative stress or other disadvantageous environmental conditions [58,59]. Several studies have reported increases in lipid