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Improving the energy balance of microalgae biodiesel: Synergy with an autonomous sugarcane ethanol distillery

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A B S T R A C T

This study analyzed the algal biodiesel production system via dry-route, based on Chlorella vulgaris cultivated in raceways, by comparing the Net Energy Balance (NEB) and the Fossil Energy Ratio (FER) of five scenarios: C0 (single system of biomass production); C1 (C0 + pyrolysis of the microalgae press cake); C2 (C0 + anaerobic co-digestion of the microalgae press cake); C3 and C4 (same conditions of C1 and C2, but integrating both scenarios into an autonomous ethanol distillery). Each scenario was analyzed under de perspective of energy allocation (a) and system expansion with avoided product (b). The results showed that with the energy allocation, only C3a and C4a improved the values of baseline scenario (C0a) for NEB, in 120% and 72% respectively. When the system expansion is considered, none of the scenarios was better than the respective baseline scenario (C0b), in relation to the NEB. Considering the FER, C3a increased in 3.4% the values of C0a, while C3b and C4b increased the values of C0b in 54.1% and 28.8%, respectively. In general, system expansion showed the best scenarios: for the NEB C0b showed the highest average values while C3b showed the highest average values for the FER.

1. Introduction

Although projections indicate that, until about 2030, crude oil will remain the dominant source of transportation energy, over the last ten years, biofuels such as ethanol and biodiesel have been emerging in the global energy scenario as complete or partial substitutes for petroleum products [1].

According to the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP),, Brazil has turned into a major player in the energy sector over the last years, due to a share of 43.5% renewable energy in its primary energy production, three times more than the world average [2]. Brazil is the world's second largest ethanol producer. Based on the use of sugarcane as feedstock, the Brazilian Government projected the production of 30.68 billion liters of ethanol for 2016, a substantial increase over the previous production peak of 24 billion liters [3]. Regarding biodiesel based on feedstocks such as soybean (77.4%), beef tallow (18.5%), and cotton oil (2.0%), Brazil became an important world player with a production around 3.94 billion liters per year [4]. The biodiesel industry is regulated by the government, with a current compulsory biodiesel content of 7% in the diesel fuel being in effect, while the industry advocates an increase of 10% in the blend by 2020. However, the projections of an increasing demand of biofuels are now causing concern. Although important for reducing the atmospheric CO_2 impact resulting from the use of fossil fuels, these first generation biofuels, which are based primarily on edible commodities as feedstock, may result in competition for food and the expansion of agricultural lands, causing the release of carbon (as CO_2 or CH_4) stored in soil and biomass, besides the indirect emissions caused by the increasing use of natural resources and fossil fuels, which tend to intensify the greenhouse gas (GHG) emissions [1,5].

Under these circumstances, compared to land crops, microalgae appear as potential biofuel feedstock, due to their positive characteristics. Microalgae can be cultivated in a variety of water sources, do not compete with food crops for arable land and have a higher

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growth rate, generally doubling their biomass in 6–12 h, reaching 25–50 g m^{-2} d^{-1}. If located in appropriate regions, harvesting can be done all-year around. Their higher oil yields per area (rich in triacylglycerols) can exceed 10 times the productivity of terrestrial crops, such as palm oil. This high productivity results in a high capacity of CO_2-recycling (about 1 ton. ha^{-1} d^{-1} can be fixed as biomass, through photosynthesis), thus reducing the GHG generation [6–8].

Although the production of liquid transportation fuels from algae has proven to be technically feasible, the energy-intensive processes involved in the microalgae production systems represent a drawback to the positive impacts of biofuels derived from these organisms [9–12]. These limitations impact the environmental and economic viability of biodiesel from microalgae, and therefore have motivated the search for alternative cultivation methods to fill the demand in a large scale [6,12–14].

In view of the need to increase the pressure of CO_2 in the algal cultivation system far above the actual atmospheric concentration to provide its effective recycling into biomass, the costs of commercial CO_2 used during cultivation (including capture, liquefaction, storage in cylinders and transport), may represent up to 50% of the total biomass and oil production costs, thus raising the price of these biofuels to levels above those of petroleum-based diesel [15].

The integration of industries, such as the Brazilian sugar-cane/ethanol plants, which process in average 2 million ton cane. y^{-1} (500 ton of cane. h^{-1} during the harvest period), generating 33.6 m^3; ethanol and 16 ton of CO_2. h^{-1}, or with any other low-cost supply point of concentrated CO_2, may contribute to lower algal-biodiesel costs [16].

Nevertheless, other essential resources, such as recycled nutrients (mostly phosphorous and nitrogen), are also necessary to make any substantial production of algal biofuels viable [9]. Additionally, the selection of productive algal strains and their metabolic improvement, the development of more efficient oil extraction processes, and the recovery of energy contained in the cake are necessary to make the production and commercialization of algal biodiesel economically viable.

In order to assess alternative technologies for its production, several environmental studies based on Life Cycle Assessment (LCA) have been conducted on biodiesel from oil seeds [17–21], waste oils [22–24] and fats [20,25–27], since the late 1990s of diesel [1,28]. These studies confirm a direct relationship between environmental impacts and energy consumption (total and non-renewable), inferring that products with lower primary energy consumption, especially of fossil energy, have comparatively lower environmental impacts. Under current conditions, the energy balance of biodiesel from microalgae tends to be unfavorable, especially due to the energy consumption during the cultivation and recovering processes: for each 1 MJ of biodiesel produced from microalgae (output), the cumulative energy demand (input) can be as high as 1.66 MJ [29].

Motivated by the above-mentioned limitations, the objective of this research was to point out alternatives for biodiesel production from microalgae on a commercial scale, based on the "Integrated Biorefinery" concept [12,30–32].

The Integrated Biorefinery concept aims at the development of an industry capable of converting a wide range of biomass feedstocks into biofuels, biomaterials and biochemicals. This concept can optimize the use of the inputs and reduce the negative environmental impacts as well as the production costs [12,33–35].

Some studies [7,12,13,15,34,36] indicate the ethanol industry (autonomous ethanol distilleries and sugar mills with annexed ethanol distilleries) as potential partners for a synergistic integration of a large scale production of microalgae biodiesel. The positive effects of this integration would be reflected in the economic and environmental performances of the entire life cycle of sugarcane ethanol and microalgae biodiesel, mainly by the use of co-products from the sugarcane industry. Nevertheless, the scope and specific conditions of those studies require new integration scenarios and analysis perspectives.

Aiming at complementing the study by Maranduba et al. (2015) [12], and in order to demonstrate the effects of alternative scenarios on the energy balance, the present work analyzes the energy balance of a biodiesel produced by the dry route process (oil extraction after biomass drying: 85 wt%), based on the microalgae *Chlorella vulgaris* cultivated in raceways, as well as two technological alternatives for the reuse of energy from residual biomass (cake): pyrolysis, and anaerobic co-digestion with cattle manure and its integrated production with a sugarcane ethanol distillery.

2. Materials and methods

This study applied the methodological principles of ISO 14,040/44 [37,38] to define the goal and scope, inventory data, and to calculate the cumulative energy demand of the proposed scenarios for microalgae biodiesel production.

According to Almeida Neto et al. (2004) [28], the ratio between "energy invested in producing a fuel" (input) and "energy obtained after fuel combustion" (output), was taken as an important indicator of the technical, economic and environmental feasibility of microalgae biodiesel. The parameters Net Energy Balance (NEB) and Fossil Energy Ratio (FER) were used to assess two technological alternatives for the reuse of the energy contained in the residual biomass (pyrolysis and anaerobic co-digestion), as well as the synergies between the production of microalgae biodiesel and the sugarcane ethanol distillery.

The "cradle to gate" approach was chosen, starting with the microalgae cultivation and ending with the biodiesel production. The usage phase of the biodiesel was ignored, because it is not relevant for the proposed comparative energetic assessment.

2.1. Process description

An energetic assessment according to the resource accounting method "Cumulative Energy Demand" (CED), was performed to analyze the direct and indirect energy consumption of the proposed integration of microalgae biodiesel production with an autonomous sugarcane ethanol distillery [39]. Both production systems (ethanol and biodiesel) were assumed to be on a large scale. Data for ethanol production were derived from Ecoinvent 2.2 (Cultivation Area: 20,223 ha y^{-1}. Ethanol production: 90,000 t y^{-1}). Data for biodiesel production were derived from the system described by Xu et al. (2011) [41] (Cultivation Area: 100 ha y^{-1}. Biodiesel production: 2081 t y^{-1}).

The inventory data were the same as used by Maranduba et al. (2015) [12], with the data for ethanol derived from the database ecoinvent 2.3, and the data for biodiesel production derived from the system described by Xu et al. (2011) [41], which considers a large-scale microalgae cultivation in a farm with 100 ha.

The product system consists of a single integrated structure that produces ethanol and co-generated energy, biodiesel and other byproducts with energetic value (in this study ethanol was left outside the border). The relations between the distillery byproducts and the inputs for microalgae cultivation were established based on the amount of mass and energy necessary to produce 1 ton of microalgae biodiesel.

All scenarios of microalgae biodiesel production assessed by Maranduba et al. (2015) [12] were considered, highlighting the stages: cultivation (in raceways) of one of the most studied microalgae species with potential as biodiesel feedstock in large