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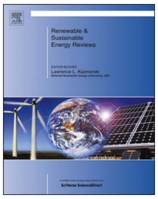

Integration of microalgae production with industrial biofuel facilities: A critical review

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ABSTRACT

Microalgae are a promising aquatic culture for supplying biofuels and other bioproducts in the near- to medium-term. For this potential to develop into reality, an interesting alternative is to couple microalgae production with large-scale facilities in order to benefit from process integration. This review aims at analyzing the main inputs of microalgae cultivation and how they could be supplied by integrated biorefineries, namely carbon source, nutrients, water use, plant location and geographic conditions. A special focus is given to Brazilian sugarcane mills acting as hosting complexes for microalgal biomass production. Such industrial plants are able to supply cheap carbon for microalgae growth in the form of CO_2 from boiler emissions, ethanol fermentation off-gas, or biogas from vinasse anaerobic digestion; water, organic molecules, and nutrients from *in natura* or processed vinasse; and renewable electrical energy obtained from sugarcane bagasse and straw burning. The effects of the location of possible sugarcane-microalgae biorefineries are also discussed, particularly points related to land suitability and availability in Brazil.

1. Introduction

In the medium term, the reduction in the global dependence on fossil-based fuels passes by the production of large amounts of biomass for the synthesis of biofuels. Biodiesel and ethanol are currently the biofuels with the largest production volumes [1] and positive environmental impacts on the displacement of fossil fuels [2–4]. This substitution, in fact, needs to occur in order to attend the increasing requirements to reduce greenhouse gases (GHG) emissions and other environmental impacts. The potential of employing conventional energy crops, like sugarcane, corn, soybean, palm, and rapeseed, for the production of ethanol and biodiesel are somehow limited due to the difficulty in increasing the already low carbohydrate and lipid productivities of such species and to the large projected increase in global consumption of liquid fuels, usually obtained from fossil sources, in future years [5]. Another fact drawing attention towards alternative sources of carbohydrates and lipids is the concern with land use change combined with food production issues [6]. The possibility of using microalgal biomass for the production of biofuels and other bioproducts is currently being considered an interesting option for the near future [7] due to positive sustainability impacts resulting from the technology [8–10].

Microalgae are eukaryotic microorganisms which perform photosynthesis as the primary route for assimilating carbon. They may develop as individual cells or in small colonies, being found in freshwater and marine environments [11]. There are, potentially, several reasons for microalgae to become largely employed by the industry with the aim of producing biofuels: (1) microalgae present high theoretical lipid and carbohydrate productivities, by far exceeding those of conventional energy crops like soybean and sugarcane, respectively; (2) these microorganisms can thrive in different aqueous media, with saline, brackish, and other non-potable water sources, thus reducing the pressure on water catchment for crop irrigation, process use and human consumption; (3) associated production of high-value compounds, such as proteins and pigments, which are recovered from the extraction debris after lipid and/or carbohydrate separation; (4) composition profile of the strain can be regulated according to the compound of interest through the modulation of process variables and nutritional conditions [12,13].

Historically, industrial microalgae production focused on small consumer markets, namely pigments and dried whole microalgae for human consumption or animal feed [14]. Typical designs of industrial microalgae facilities are often based on stand-alone or minimally-integrated configurations, in which raw materials, energy supply, and

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product distribution are managed independently. Studies aiming to assess the potential of microalgae processes in large scale [15–19] usually consider isolated units acquiring all or most part of the main inputs (water, nutrients, carbon sources) at prices found in the open market, which greatly increase operational expenses. In the incipiency of microalgae utilization as raw material for biofuels production, cost reduction in several possible sections of microalgae production should be carried out to make the process economically feasible, hence, competitive. Since biofuels production from microalgal biomass will require the expansion of microalgae units in both number and scale, their integration to other established facilities emerges as a real opportunity to leverage the worldwide deployment of microalgae projects and to outperform stand-alone microalgae units.

Only recently the production of microalgae has been thought of as an integrated concept, either by recovering various compounds from the microalgal biomass or by employing raw materials supplied by adjacent industrial units. The utilization of industrial effluents from different sources is an interesting option to tackle economic and environmental issues in a single step [20].

The generation of liquid and gaseous effluents by chemical plants is an integral part of the processing of raw materials into finished products. In such typical sites, waste streams undergo several treatment techniques before being disposed in the environment. One alternative to conventional end-of-pipe effluent treatments, the employment of heat and mass integration strategies with other processes represents a real opportunity for a suitable, low-cost effluent management. Some types of effluents – CO_2 in gaseous streams and liquid effluents with organic and inorganic content, are appropriate for use in microalgae cultivation as sources of carbon and other nutrients, as further discussed in this paper. Different aspects can be pointed out as direct advantages of process integration with industrial facilities: minimization of water, process steam, and energy requirements, reduction of effluent sent to treatment, and reduction of contaminating charges disposed in the environment.

Microalgae processes may also benefit from thermal and electrical energy supplied by established plants when an integrated design approach is considered. In this way, the integration opportunity offered by sugarcane mills is unique due to the available material and energy vectors: carbon, inorganic nutrients, water, process steam, and electrical energy. The sugar-energy sector in Brazil, in constant development since the 70′s, combines these features with the availability of low land prices and high solar insolation, besides water availability, to generate an ideal panorama for the deployment of microalgae plants in the country. Also, the establishment of a biorefinery concept between ethanol distilleries and microalgae production adds solidity and environmental benefits to the economic viability of the joint project, as ethanol production is highly affected by raw material prices [21].

Although the technology of microalgae production in industrial scale is widely sought-after for meeting the rising biofuel demand, it is still at an early stage [22,23] and more research in the field is needed. In the case of sole biofuel production (namely ethanol, biodiesel, and oil-derived fuels), the use of conventional microalgae production technologies involves high investments and results in high biofuel production costs, as shown in Table 1. Ultimately, production costs and minimum selling prices are highly dependent on the scale of reactor deployment, since the biomass production step is cost-intensive. Besides, Table 1 shows that the techno-economic analysis of theoretical microalgae cultivation and processing plants are often based on the sole utilization of concentrated and compressed CO_2 from nearby flue gas sources and, still, the results are widely variable according to the processing technology. This review expects to show the numerous approaches of integrating microalgae facilities into other more consolidated plants, from which the former may benefit in terms of technical practicality, environmental, and economic performance. In view of such fact, the present paper examines the potential of process integration to assist the development of microalgae production and processing technologies in the early stages of their industrial deployment. The main inputs for industrial production of microalgal biomass - carbon and nutrient sources, water, energy, and land availability, are initially discussed. Special focus is given to Brazilian sugarcane mills acting as backbone to larger and more complex biorefineries by exploring the current status of existing examples of integration between mills and non-microalgae related industrial plants. Additional arguments are put forward to assert that Brazilian sugarcane mills stand out as one of the best options for hosting microalgae biorefineries and supporting their development. The main goal is to lay solid foundations for the deployment of zero-carbon emission, integrated biorefineries for the production of microalgal biofuels by showing different configuration possibilities.

2. Large-scale microalgal biomass production

In the current scenario, large-scale microalgal biomass production for biofuel obtention generally involves higher costs and higher technical challenges than land crops [24], since strict cultivation conditions must be provided to obtain favorable microalgae growth rates and biomass processing is performed using sophisticated techniques. In addition, industrial microalgae cultivation is known for the consumption of copious amounts of carbon, water and nutrients, notably nitrogen (N) and phosphorous (P), which are supplied by conventional plant fertilizers or specially-developed formulae designed to suit the requirements of each microalgae species. Fig. 1 shows an overview of a typical unit for the obtention of microalgal biomass-derived products. Main operations include microalgae cultivation, followed by biomass harvest, drying, extraction of compounds, and final processing into consumer goods. This broad outline, however, corresponds to microalgae production as thought of nowadays, employing conventional systems. Many studies aim at the simplification of microalgae processing through combining multiple unit operations into single steps or using novel, recently-developed techniques in order to improve the economic feasibility of the process: direct transesterification (*in situ*) [25] or hydrothermal liquefaction [26] of undried biomass, thus avoiding the need for an energy-intensive drying step; biomass harvest using nonconventional techniques alternative to chemical flocculation, such as electrical-based systems [27] and micro/ultrafiltration [28]; microalgal cell disruption in water suspensions with Pulsed Electric Field and Supersonic Flow Fluid Processing techniques [29]; cultivation and biomass pre-harvest in a single membrane bioreactor [30,31]; microalgae growth in biofilms to avoid dewatering [32]; among others. The detailing of such alternatives is not in the scope of this review.

2.1. Cultivation

Microalgae are able to grow by using different metabolic regimes, namely the autotrophic, heterotrophic, and mixotrophic metabolisms. The autotrophic metabolism occurs through photosynthesis, a process that allows carbon assimilation from CO_2 using light energy. Eq. (1) displays the overall reaction for photosynthetic growth of microorganisms.

$$nCO_2 + nH_2O \xrightarrow{light} (CH_2O)_n + nO_2 \tag{1}$$

Heterotrophic growth of microalgae occurs through the uptake of low molar mass organic compounds dissolved in the culture medium, mainly carbohydrates (pentoses and hexoses), acetic acid, acetate, glycerol and other organic acids. The third type, mixotrophic growth, incorporates characteristics of the previous metabolic regimes: the microalgae absorb CO_2 when in the presence of light, shifting to the uptake of organic compounds in the medium under dark conditions and *vice versa*. Microalgae may also be cultivated in consortia with bacteria, which is beneficial for enhancing biomass productivities of