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Life cycle assessment of microalgae production in a raceway pond with alternative culture media

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ABSTRACT

Microalgae production is responsible for phycoremediation and the development of green products synthesis and for cleaning processes. Studies on the environmental impacts of this process are fundamental to make these systems feasible. In these studies, a life cycle assessment of the production of microalgae biomass is important. We performed this study considering the production in wastewater or NPK medium and different methods of biomass separation. The LCA model was developed for the production of 9 and 12 kg of *Desmodesmus subspicatus* microalgae biomass in 10 days, which represents the production in 8000 L of wastewater and NPK solution, respectively. The total volume corresponded to 4 tanks of 2000 L each. The growth system used was an open raceway pond with culture movement caused by an air-lift system or by paddle wheels. Flocculation with NaOH and electroflotation with Al and Fe were chosen as the methods of biomass separation. These methods were chosen because they facilitate the separation using filtration or centrifugation. The final step was drying, which can be conducted with the biomass after filtration (80% water) or centrifugation (40% water). Several scenarios were examined to identify a more environmentally friendly method for microalgae biomass production. There were no differences using air lift or paddle wheels, however it was identified impacts in all stages. Also, there were fewer impacts using wastewater than using NPK. Regarding the separation of the biomass, electroflotation caused fewer impacts when compared to flocculation with NaOH. Overall, the scenario with fewest impacts was the one configured using wastewater for microalgae cultivation, followed by centrifugation and drying.

1. Introduction

There is a wide range of potential technologies for capturing CO_2 from the atmosphere, and their cost and performance should be assessed. With the capture of this gas by microalgae, other benefits are also achieved, and this has the potential to be an economically interesting system.

Thus, microalgae have been suggested as excellent candidates for carbon sequestration and biofuel production. Among its advantages are high photosynthetic efficiency, high biomass production and rapid growth compared to other crops used for energy purposes. The growth of microalgae requires sunlight, water, CO_2, and nutrients for photosynthesis [1].

In addition, the use of microalgae for carbon mitigation includes the ability to capture nutrients from wastewater and other gaseous emissions [2].

According to Kumar et al. [3], Ahmad et al. [4], Khan et al. [5], 1 kg dry biomass requires approximately 1.8 kg of CO_2, and this fixation efficiency is 10–50 times greater than that of terrestrial plants.

The possibility of using wastewater to reach the nutrient amounts necessary for biomass growth should also be highlighted. This would mean lowering costs and the volume of treated water, providing a method of water reuse as well as nutrients for the algae [6].

Microalgae species can grow efficiently in wastewater due to their ability to utilize the inorganic and organic carbon, nitrogen and phosphorus present in these waters [7]. A wide variety of urban wastewaters have been tested as culture media for microalgae, from raw sewage to previously treated effluent at different levels (primary, secondary, activated sludge, clarified effluents), and even effluents from activated sludge thickening processes have produced satisfactory biomass productivity results [8]. Municipal wastewater typically contains approximately 350 mg L^{-1} of COD (chemical oxygen demand), 50 mg L^{-1}

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of NH_4^+ (N) and 10 mg L^{-1} of PO_4^{-3} (P) [9]. In treated effluents, high concentrations of nutrients such as nitrogen, phosphorus, and trace elements (K, Ca, Mg, Fe, Cu and Mn) are present, and these are essential for the metabolism and growth of microalgae [10].

Wastewater is always a waste product with high environmental impact, and it has been popular as a microalgae cultivation medium in many recent studies, for example: with municipal wastewater [11–15], manure [15,16], pulp and paper industry wastewater [17], textile wastewater [18,19], pharmaceutical wastewater [20], agro-industrial wastewater (liquid fraction of pig manure) [21], and brewery wastewater [22].

The method used to grow microalgae is important. The most utilized basic cropping systems are divided into two types [23,24]: open systems, which include ponds, raceway ponds and turf scrubbers [25], and closed systems, such as photobioreactors [3,26–28].

Closed systems minimize contamination and allow for the cultivation of monocultures that can be controlled for pH, temperature, light, CO_2 concentration, etc. In these systems, overheating and O_2 accumulation occur, requiring efficient refrigeration and gas exchange systems, increasing the operational costs of biomass production [29].

Open ponds are the most basic and economical cultivation system to produce microalgae. On a commercial scale, approximately 95% of algae production worldwide is carried out in raceway ponds. Although open systems have poor control over operating conditions that diminish final productivity, that is usually compensated by the low cost of construction, easy scale up, and low level of energy use. Operational systems for the production of microalgae should consider a series of variables that determine and lower environmental impacts, such as the use of energy, the choice of fertilizers, the use of water and the composition of algae, aiming to develop sustainable processes [24,30,31].

To evaluate the environmental impacts of processes or products, one of the tools used is the life cycle assessment (LCA). In this method, all important steps in the life cycle of the study subject are included in the analysis, such as the extraction of the raw material from the environment, the production of the materials or products, their use, and the destination of the waste or recycling [32–34].

The concept of “cradle-to-grave” is sometimes used for microalgae biofuel LCA, considering the cycle from crops to biofuel use. The environmental burdens associated with each step are obtained by recognized methodologies, often including the ecoinvent database [35]. The cradle-to-grave LCA for the GHG emissions of algae fuels shows a 50% reduction compared to fossil fuels [36]. According to Scherer et al. [16], the wastes from microalgae production result in less environmental impact once fertilizer and water are reduced.

Recently, LCAs were carried out by several authors aiming to evaluate the impact of microalgae production, with focus on the products developed from the biomass of microalgae, such as biodiesel [1,35,37,38], biomethane [39], limonene [40], ethanol [41], biocrude oil [42], phycocyanin [43], protein [44], aviation fuel [45], PUFAs, α-tocopherol, chlorophyll, β-carotenoid and polyphenols [46].

According to the LCA results presented by Carneiro et al. [41], microalgae biodiesel is the most efficient alternative in terms of land use compared to other biofuels, avoiding competition with food crops; however, in terms of energy efficiency, microalgae cannot compete with other biofuels or fossil fuels.

To improve various aspects of production responsible for economic or environmental impacts, the microalgae can be manipulated to increase biomass productivity and lipid or carbohydrate content as well as to produce other interesting compounds. These manipulations include environmental stressors and cleaner technologies that introduce combustion gas as an inorganic carbon source and wastewater as a culture medium, reducing the environmental impacts. Through LCA, we have tools that help to identify the best technological paths to successfully scale up microalgae production [37,47].

In this context, microalgae are responsible for phycoremediation and the development of products as a clean alternative to fossil fuels. Therefore, it is still necessary to study the production system to ensure a lower environmental impact in addition to productivity. Thus, in this work, the objective was to perform a life cycle assessment of the production of microalgae biomass, considering the production in wastewater or NPK medium and different configurations of biomass separation.

2. Methodology

LCA is a compilation and evaluation of the inputs, outputs and potential environmental impacts of a process or product system throughout its life cycle. A product or process causes impacts on its ecosystem during production, distribution, consumption, disposal and recycling [48]. LCA includes the following steps: Goal and scope definition, inventory analysis, impact assessment and interpretation, all of which were followed in this work.

The life cycle assessment method was used to evaluate the environmental impacts of all stages of microalgae *Desmodesmus subspicatus* production in raceway ponds. The configuration of pilot equipment for the production of microalgae was similar to equipment that is commonly used to produce microalgae biomass. The characteristics, size, power consumption and other necessary attributes were inventoried for assessment. The procedure proposed for microalgae production was cultivation in a raceway pond followed by biomass separation and drying.

The life cycle impact assessment (LCIA) was carried out before installation of the equipment was complete. Separation and drying were studied on a minor scale. This tool was used to support decisions about the recommended stages and care of microalgae during production. The procedures to assess the environmental impacts of microalgae production have been further detailed.

2.1. Goal and scope

The goals were to evaluate the potential environmental impacts of microalgae biomass production and to interpret the results to determine the best strategy for reducing impacts in the future. This evaluation is associated with the use of wastewater or NPK in the cultivation of microalgae followed by several separation methods and drying. The research seeks to find a more environmentally friendly method of microalgae biomass production.

The growth of microalgae in wastewater contributes to the treatment of the water. Already, using NPK reduces the cost of production compared to traditional media. It is important to emphasize that both are alternative culture media, are not selective for a specific group of microalgae and can be used in different scenarios.

Microalgae were grown with CO_2 from the air dissolved in the cultivation medium (the source of inorganic carbon) and with organic carbon from that medium. The growth system used was an open raceway pond with movement of culture produced by an air-lift system or by paddle wheels. Considering the nutritional needs of microalgae based on N and P consumption, wastewater or NPK may be promising media for producing biomass.

In addition, if we recognize that the use of wastewater to produce microalgae biomass reduces the environmental impacts, we may make the biomass production chain more sustainable, such that it would produce more economic gains and cause less damage to the natural resources, ecosystem and human health.

The system boundary for the life cycle assessment of this biomass production with different methods of production is illustrated in Fig. 1. The LCA model is related to the production of 9 to 12 kg of *Desmodesmus subspicatus* microalgae biomass in 10 days, which represents the production in 8000 L of wastewater or NPK solution. The total volume corresponds to 4 tanks of 2000 L each. This is consistent with the available primary data. The evaluation assumes that the focus of the research is on the biomass production process. It is emphasized that this