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Comparative life cycle assessment of real pilot reactors for microalgae cultivation in different seasons

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HIGHLIGHTS

- Life cycle assessment was used to compare 3 real pilot systems for algae cultivation.
- The temperature control system was the main contributor to environmental impacts.
- Tubular reactors had lower impacts per unit of biomass produced than open pond.
- Meteorological conditions on the reactors played a critical role in LCA results.
- Environmental impact reductions of 17–90% were estimated for optimized full-scale reactors.

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ABSTRACT

Microalgae are promising natural resources for biofuels, chemical, food and feed products. Besides their economic potential, the environmental sustainability must be examined. Cultivation has a significant environmental impact that depends on reactor selection and operating conditions. To identify the main environmental bottlenecks for scale-up to industrial facilities this study provides a comparative life cycle assessment (LCA) of open raceway ponds and tubular photobioreactors at pilot scale. The results are based on experimental data from real pilot plants operated in summer, fall and winter at AlgaePARC (Wageningen, The Netherlands). The energy consumption for temperature regulation presented the highest environmental burden. The production of nutrients affected some categories. Despite limited differences compared to the vertical system, the horizontal PBR was found the most efficient in terms of productivity and environmental impact. The ORP was, given the Dutch climatic conditions, only feasible under summer operation. The results highlight the relevance of LCA as a tool for decision-making in process design. Weather conditions and availability of sources for temperature regulation were identified as essential factors for the selection of geographic locations and for microalgal cultivation systems based on environmental criteria. Simulation of large-scale reactors with optimized temperature regulation systems lead to environmental improvements and energy demand reductions ranging from 17% up to 90% for systems operated in favorable summer conditions.

1. Introduction

The scarcity of natural resources and particularly the exhaustion of fossil fuels are a global challenge to be addressed in forthcoming decades [1–3]. The current production framework based on non-renewable energies poses several problems to society, including economic instability and political conflicts (due to raw material scarcity and related increasing prices), as well as environmental concerns [4].

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Alternative sources including biomass feedstocks such as vegetable oils, waste oils or algal lipids are currently under development to reduce harmful effects on environment and ecological threats such as global warming [2,5,6].

Microalgae have shown a great potential for the production of numerous compounds with a wide variety of applications that include biofuels and other forms of energy as well as chemicals, food and feed, among others [1,7,8]. Some advantages of microalgae compared to other bioenergy feedstocks are their higher productivity per unit, the possibility to cultivate them on marginal land in fresh- or saltwater avoiding competition with food crops and the option of coupling their growth with the treatment of waste streams [2,5,9–12]. Despite the advantages of microalgae and their lower requirements in categories such as land competition or eutrophication [5,13], some aspects of environmental sustainability, such as the energy balance or greenhouse gas emissions, are still liable to improve, especially for the use of microalgae for energy applications [3,5]. Life Cycle Assessment (LCA) has the potential to be used as a guiding tool for decision-making in process design [8,14]. LCA may contribute to identify the main bottlenecks to be addressed during the scale up towards sustainable industrial facilities.

Algae cultivation has been identified as a major contributor to the operational and embodied energy of microalgal processes [3,7,15]. The total energy demand for cultivation stage usually ranges from 0.1 up to 5 MJ energy input per MJ energy produced [9,16]. This is mainly due to addition of nutrients and CO_2 [1,5] and the specific requirements of the selected reactor configuration, such as mixing and temperature control [9,15,17].

The embodied energy for nutrients is related to manufacturing of synthetic fertilizers and the reactor materials as well as CO_2 production, whereas the operational energy consumption is usually linked to pumping for the delivery of culture medium and CO_2 [1,5,9]. Since algae are temperature sensitive, heating and cooling is required to operate relatively close to the optimal temperature of the algal species. Temperature regulation allows high productivities and prevents growth inhibition, but may increase the energy demand of the process [18,19]. The integration of options such as waste heat from power generation or cold water resources allows reducing the energy requirements for heating or cooling the water from room temperature to the set point temperature, and thus, contributes to the optimization of the cultivation stage [19,20]. Furthermore, climatic data including irradiation and temperature depend on geographic location. Therefore, the heating and cooling needs of the system vary between locations [21]. The selection of an appropriate location according to available resources (energy, nutrients, waste heat, cooling water) and algal strains may serve to maintain the optimal temperature with low heating and cooling requirements so that the energy consumption is minimized.

The environmental performance of cultivation is also influenced by reactor selection. Open raceway ponds (ORPs) and closed tubular photobioreactors (PBRs) are currently considered as the two most feasible existing configurations for large-scale cultivation of microalgae [10,15]. Although simple reactors such as ORPs have fewer elements that consume energy than closed PBRs, the maximum biomass productivity is also lower and they are more sensitive to contamination risks [15,22]. However, closed PBRs have higher costs of infrastructure and operation [15]. These aspects should be considered when comparing the environmental performance of different configurations.

Numerous studies dealing with the environmental performance of different reactor designs for microalgae cultivation have been published [1,5,9,12,15,17,20,23,24]. However, most of this work considers hypothetical simulated scenarios or extrapolations from lab-scale data rather than existing pilot or commercial systems [1,5,9,12,15,17,24]. Few of them make a comparison between different reactor configurations, often restricted to a very limited set of indicators that only takes into account energy requirements and greenhouse gas emissions [1,9,15,17]. Moreover, they are based on average growth parameters and omit the influence of weather fluctuations, affecting reactor stability, on the environmental results.

This work provides a comparative life cycle assessment (LCA) of the two most common reactor configurations (ORPs and tubular PBRs) to evaluate the main environmental burdens of each option, to compare their performances and to identify bottlenecks for up-scaling. The evaluation considers the algal biomass production from the eustigmatophyte *Nannochloropsis* sp. due to its good biomass productivity and capability for high lipid content when stressed [13,25]. The evaluation is based on data from three real reactors operated in parallel at AlgaePARC pilot facility (Wageningen, The Netherlands) [26]. The use of real pilot data is expected to overcome current concerns of microalgal LCAs related to the lack of large-scale information [14]. The data are obtained for comparable weather conditions for each reactor, during three seasons (summer, fall and winter). These systems have been designed and operated as a first step to facilitate the transition from laboratory research to outdoor production for industrial applications [18].

2. Materials and methods

2.1. AlgaePARC cultivation systems

AlgaePARC is a research facility of Wageningen University and Research (The Netherlands) that was built with the aim of comparing different PBRs and optimizing process control strategies for microalgae cultivation and processing. The main objective of this facility is to develop systems with low production costs and energy requirements that can serve as a basis for the improvement of large-scale microalgae plants [18].

AlgaePARC outdoor facilities comprise several pilot-scale photobioreactors, including horizontal and vertical tubular PBRs and an ORP. Among the available systems, the operation of the ORP, a vertical and an horizontal tubular PBR was monitored throughout the year 2013. Part of these data on photosynthetic efficiency, areal and volumetric productivities have been published in De Vree et al. [26]. The layout of each system is depicted in Fig. 1. As described in Bosma et al. [18], the ORP consists of a 4.73 m^3 oval pond with a separation plate in the center and two additional plates that divide each of the rounded corners into three narrower channels to improve mixing. A paddle wheel drives the culture at a controlled speed of the motor. The CO_2 is dosed in a gas circulation loop, by injection at the bottom of the pond under a gas collection hood. The hood traps the CO_2 enriched air, minimizing CO_2 losses. Liquid culture medium is pumped from nutrient dosing stations close to the ORP and temperature is maintained above a set point with a submerged tubular heat exchanger. Active cooling was not needed.

The horizontal tubular PBR system (0.56 m^3) consists of three loops with transparent pipes that are placed in parallel at the same height, whereas the vertical system (1.06 m^3) is composed of seven loops with pipes "stacked" on top of each other. In both systems, the culture medium is divided over the loops by a distribution header. The accumulation of excess oxygen is avoided by using an oxygen stripper. This system receives air, blown by a compressor via a sparger at the bottom. Oxygen is transferred from the liquid to the gas phase and leaves the stripper at the top. The stripper contains three heat exchange spirals to keep the culture temperature between a minimum and a maximum value.

The operation of the three systems was performed under different Dutch weather conditions that can be classified as "summer", "fall" and "winter". However, the "winter" operation of the ORP was unfeasible as heavy rainfall in this period resulted in a too high dilution of the ORP in combination with the low solar radiation level and low temperatures. Geometric and average operating parameters in each reactor and season are specified in Table 1.