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LCA for technologies at low technological readiness level: A case study on microalgae cultivation system

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Abstract

Appropriate choices in the early technology development phase of a process can avoid large impacts on its future environmental performance. LCA can support efficient eco-conception, driving the development of immature technologies by identifying environmental hotspots and proposing alternatives with reduced impact. This work introduces an LCA-based methodology with an eco-design approach that aims to quantitatively demonstrate the importance in the selection of design parameters on the environmental impacts. The overall environmental impacts are evaluated for different functional units, extending the analysis to identification of process hotspots with iterative sensitivity analysis of the associated parameters. A case study based on an innovative Rotating Algal Biofilm (RAB) technology for microalgae (algae meal) production is presented to illustrate this methodology. The eco-design parameters were spotted from the process modelling through an iterative analysis. The resulting eco-designed technology was compared with classical approaches for producing protein sources (soymeal and fishmeal), and with other microalgae cultivation technologies (ORP and rotating carpet biofilms). Results show that the NH₃ emission factor, fabric support properties and electricity consumption turned out to be the crucial eco-design parameters. The impacts of the new eco-designed technology were reduced in a range from 25% to 88.3%. Algae meal from rotating algal biofilms outperformed the environmental footprint of the other conventional aquafeeds (fishmeal and soymeal). The proposed methodology can guide technology developers to understand the implications of design choices on the future environmental impacts. Since economic allocation was chosen, the evaluated impacts remain highly sensitive to the future price of these products.

Keywords: *Eco-design; Emerging technologies; Microalgae; Sustainable production; TRL (Technology readiness level).*

Palabras clave: *Eco-diseño, Tecnologías emergentes, Microalga, Producción sustentable, Nivel de madurez tecnológica.*

Palavras-chave: *Ecodesign; Tecnologias emergentes; Microalgas; Produção sustentável; Nível de prontidão tecnológica.*

Introduction

LCA is a useful tool to reduce the environmental impacts of a product at its design stage (Eksi and Karaosmanoglu, 2018), by quantifying the relation between the parameters and the environmental impacts. However, traditionally, LCA has been used to evaluate mature technologies (Moni et al., 2020). The limited data, uncertainties and scale up issues of low Technology readiness level (TRL 2–5) technologies, make it very challenging to carry out a standard LCA. Thus, methodological advances in the current LCA framework are required (Moni et al., 2020). Early decisions in the technology design phase can strongly reduce its future impacts, e.g., it has been estimated that around 80% of the total environmental impacts are related to the design phase (Tischner and Deutschland, 2000).

We propose an eco-design approach based on LCA to improve the design and further reduce the environmental impacts of a promising and emerging rotating cylinder biofilm technology used to produce two products (microalgae biomass and protein powder). Biofilm systems demonstrated multiple benefits in comparison to conventional cultivation systems, such as photosynthetic efficiency and areal productivity, while considerably reducing the cost for harvesting (Wang et al., 2015; Morales et al., 2020).

This study identifies the key parameters in the design of the rotating cylinder biofilm system and their influence on the resulting environmental burdens. Finally, we compare the eco-designed technology with other protein sources, such as soymeal and fishmeal, and with other microalgae cultivation technologies, such as open raceways and rotating carpet biofilms.

Material and methods

The research methodology was carried out including three main stages: i) Process modelling, ii) Environmental assessment, and iii) Selection of eco-design parameters.

In the first stage (Process modelling), a preliminary process design is proposed by using specific data from the Inalve S.A. company (France). These data are complemented by literature information for technologies not yet implemented. An excel-based tool was used for the estimation of mass and energy balances of the large-scale algal cultivation and downstream processing steps. The second stage (Environmental assessment) is based on the process modelling outputs (inventory data), which are evaluated in the LCA. A pond-to-gate LCA is performed. This system boundary is divided into four subsystems (1- Water treatment and fertilizer addition, 2 - Cultivation, 3 - Cell disruption and 4 - Protein recovery). Three functional units (FU) are considered: FU1 = 1kg biomass, FU2 = 1 kg algae meal and FU3 = 1000 WNDS (weight nutrient density score). Environmental footprint (EF) and Cumulative Energy demand (CED) methods are used to perform the impact assessment. The EF categories included in the study are Climate change (CC), Particulate matter (Respiratory inorganics, RI), Acidification (terrestrial and freshwater) (A), Land use (LU), Eutrophication terrestrial (ET) and Water scarcity (WS).

Finally, in the third stage (Selection of eco-design parameters), the relevant process steps were identified based on the environmental impacts, i.e., process steps with contributions higher than 10% of the total impact in each impact category. The relevant parameters for the hotspots process steps were then identified and evaluated in a sensitivity and iterative analysis. Finally, the eco-designed process was also compared with conventional protein meals (soybean meal and fishmeal) and with other microalgae cultivation technologies (open raceways (ORP) and rotational carpet system (RCAB)).

Results and Discussion

The main contributors on all assessed impact categories are subsystems 1 and 2, around 99%, while only 1% are attributed to subsystems 3 and 4. Processes with contributions above 10% are NH_4NO_3 production (in subsystem 1), contributing to fossil CED, CC and RI; P_2O_5 production (in subsystem 1) affecting LU; Cotton production (in subsystem 2) critical process for fossil CED, CC, LU and WS; Polyester production (in subsystem 2), which negatively affects fossil CED; Plastic production (in subsystem 2), representing an adverse effect on fossil CED; Electricity consumption of rotary engine (in subsystem 2) affecting the total CED category; Electricity consumption of blower engine (in subsystem 2) contributing to the total CED category; NH_3 emissions (in subsystem 2) affecting the ET, RI and A categories.

The parameters selected for the eco-designed system, after sensitivity analysis were: 'N-fertilizer source: NH_4NO_3 ', 'P-fertilizer source: P_2O_5 ', 'Fabric lifetime: 8 years', 'Fabric material: 100% Oleofin', 'Plastic lifetime and thickness: 8 years and 0.5 mm', 'Rotator power: 0.03 kW', 'Blower power: 0.025 kW', 'PVC lifetime: 25 years' and ' NH_3 emission factor: 90 g $\text{NH}_3/\text{kg N}$ '.

When comparing the environmental impacts to produce 1 kg of algae biomass (FU1), the lowest is the algae meal produced through rotational cylinder biofilm (where eco-designed technology reports the less impacting option), followed by rotating carpet biofilm, while open raceways have the highest environmental loads.

Considering the more refined FU3 (weight nutrient density score), the lowest impacts are reached with the eco-designed process in all the evaluated impact categories. The eco-designed technology achieves reduction higher than 25% in comparison to before eco-design and higher than 34% with respect to RCAB. When comparing to conventional protein meals (fish meal and soybean), improvements higher than 70.8% are reached for eco-designed algae meal in comparison to fishmeal and soymeal for CC, RI, A, E and CED. However, analyzing LU and WS, reductions higher than 99.7% are obtained by eco-designed algae meal in comparison to soymeal, in the same range of the ones obtained by the fishmeal.

Conclusions

This study proposes an LCA methodology for eco-designing new technologies, in their early design stages. The subprocesses with the highest environmental impact and the most influential parameters were identified. Nutrient production, cylinder production, electricity consumption, greenhouse production and gas emission are the processes with environmental loads higher than 10%. Then, by implementing a sensitivity analysis, the most influential parameters in the environmental design were identified, such as the lifetime and thickness of the plastic used in the cylinder, the power of the blower, the NH_3 emission factor, the lifetime of the fabric and its source.

Comparing the rotational cylinder cultivation technology (before and after eco-design) showed lower impacts in all impact categories than the other cultivation technologies (open raceway pond and rotational carpet systems). The same result is obtained when comparing algae meal with other protein sources (fish meal and soybean meal).

The eco-design approach reduces the environmental impact in all the categories. The eco-designed system compared to the system before eco-design is 65.7% less impacting for category LU, 88.3% for WS, between 25% and 27.6% for categories CC, RI, A and ET, and

50.3% for CED. The methodology used in this work can be adapted and implemented to analyze other technologies with low TRLs at early design stages, through the analysis, identification and selection of key parameters according to their environmental loads.

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