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Life cycle assessment of microalgal membrane photobioreactors

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Abstract The exploration of new biomass sources for energy purposes is increasing. Cultivation of algal biomass for biofuels production through photobioreactor represents an attractive and useful way to obtain clean energy, also thanks to the contribution that the system makes on the reduction of climate change through the recovery and reuse of CO_2. However, to prove the complete sustainability of a system the application of a holistic assessment, like Life Cycle Assessment (LCA) methodology, is necessary. To date LCA is applied through different methodologies, which make evaluations and systems difficult to compare and evaluate. Furthermore only few studies are present in the scientific literature that highlight the parameters used for the evaluation of membrane photobioreactors (mPBR). The research presents and discusses the state-of-the-art of the adopted LCA methodologies to assess mPBR, pointing out strengths and weaknesses. Knowledge gap, uncertainties and recommendations are highlighted. Furthermore, a case study LCA application onan advanced mPBR for the CO_2 capture and biomass production is presented. The study provides important information to the different scientists involved in the microalgae production sector in a holistic and proactive view in order to maximize its environmental sustainability.

Keywords: sustainability, biofuels, microalgae, climate change, life cycle assessment

1. Introduction

During the last two decades the exploration of new biomass sources for energy purposes is increasing due to the rise of global energy demand and the request of the European commission to implement renewable energy sources for the reduction of GHGs emissions and the mitigation of climate change (Oliva et al., 2021; V Senatore et al., 2020; Zarra et al., 2012). Cultivation of algal biomass for biofuels production through closed photobioreactor provides among other benefits, the capture of CO_2 from waste gases sources and the bioremediation of wastewater (Monari et al., 2016; Vermi et al., 2021). To prove the effectiveness of microalgae based biofuels in terms of environmental and economic sustainability LCA studies can be implemented (Branco-Vieira et al., 2020). LCA studies for the evaluation of the environmental sustainability of photobioreactors for the production of microalgae biomass, are applicable through the use of different methodologies (e.g. CML, ReCiPe 2016, CED) and characterizing the specific boundary conditions and inventories (Khoo et al., 2011; Sander & Murthy, 2010). Due to the differences betweenthe studies presents in the scientific literature in terms of boundary conditions and chosen inventories , standard guidelines would be suggested to allow comparison (Pérez-López et al., 2017; Porcelli et al., 2020; Resurreccion et al., 2012).

The present study aims to evaluate the environmental sustainability of an advanced membrane photobioreactors developed at SEED (Sanitary Environmental Engineer Division) Laboratory, University of Salerno, Italy. A complete description of the technology implemented is reported in other studies (Senatore et al., 2021a; Senatore et al., 2021b). The environmental impact of the system has been assessed implementing ReCiPe 2016 methodology. Three scenarios have been tested with reference to the cultivation stage: the first scenario uses purchased nutrients, the second wastewater as natural nutrient source with a low productivity and the third uses wastewater but with high productivity. A membrane module was adopted to harvest microalgae biomass. While for the dewatering phasea drum dryerwas applied.

2. Methodologies

2.1. Experimental set up

Chlorella vulgaris was implemented as photosynthetic organism. The reactor was maintained at a temperature of 25-28 ºC and at a pH between 7 and 9. The initial concentration of biomass at the starting point was 0.1 $g\,L^{-1}$. During the cultivation phase a light/dark cycle 12:12 h with a light intensity of 110 $\mu mol\,m^{-2}\,s^{-1}$ was used. A maximum CO_2 - air ratio of 15% was sparged into the mPBR. For the measurement of CO_2 concentrations, a gas analyzer GA 2000 (Geotechnical Instrument) was used. The CO_2 fixation rate was calculated with the following equation:

CO_2 fixation rate (P_{CO2}) = 1.88×biomass productivity (P)

where: P is the biomass productivity ($g\,L^{-1}\,d^{-1}$).

The equation for the calculation of CO_2 fixation rate (P_{CO2}) derives from the molecular formula of microalgal biomass, $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$. This approach considers the simplified method that 1 kg of biomass produced is equivalent to 1.88 kg of recycled CO_2 (Wang et al., 2008). Results obtained from experimental activity showed that 5 days are necessary for the production of 1 kg of biomass with a productivity of 0.166 g $L^{-1}d^{-1}$. For this purpose, 10 reactors of 100 L with the characteristic reported in Table 1, were considered for each scenarios.

Table 1. Operational characteristics for each reactor.

Operational Parameters	Amount	Unit of measure
Biomass concentration at harvest	1	g L^{-1}
Biomass productivity	0.166	g $L^{-1}d^{-1}$
CO_2 fixation rate	0.376	g $L^{-1}d^{-1}$
Harvesting rate (R)	50	g $m^{-2}h^{-1}$
Permeate flow (J)	60	L $m^{-2}h^{-1}$
Recirculation flow (L)	1.5	L min^{-1}
L/G	15	-
Air flow (G)	100	mL min^{-1}
CO_2	52.65	mg $m^{-3}h^{-1}$

2.2. Life cycle assessment

Life Cycle Assessment (LCA) has been applied according to ISO 14040:2006 and ISO14044:2018. The application was carried out following 4 steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results (Sarat Chandra et al., 2018).

The method takes into account all stages of the life of the system, from the raw materials production to the final waste disposal, e.g. from the cradle-to-grave approach (Morales et al., 2019). This type of approach guarantees an assessment from resource extraction (cradle) to the factory gate (not taking into account the final transportation). The end use and the processes for the treatment of final waste generated are not taken into account. For the specific research, the functional unit used was 1 kg of biomass harvested and the system boundaries were “cradle to gate”. Four phases were taken into account: cleaning, cultivation, harvesting and drying; these phases are based on experimental data and peer-reviewed literature.

The ReCiPe2016 method was selected for environmental impact assessment. The method was used to estimate indicators such as global warming potential (GWP), ozone depletion potential (ODP), particulate matter formation potential (PMFP), photochemical oxidant formation potential: ecosystems and humans (EOFP and HOFP), terrestrial acidification potential (TAP), freshwater eutrophication potential (FEP), marine eutrophication potential (MEP), human toxicity potential (cancer) (HTPc), human toxicity potential (non-cancer) (HTPnc), terrestrial ecotoxicity potential (TETP), freshwater ecotoxicity potential (FETP), marine ecotoxicity potential (METP), agricultural land occupation potential (LOP), water consumption potential (WCP), surplus ore potential (SOP) and fossil fuel potential (FFP).

3. Results and discussions

Figure 1 shows the comparative profile for the three investigated scenarios in terms of normalized enviromental impact for each category of the RePiPe 2016 methods. Experimental results highligts how the use of wastewater (scenario 2 and 3) allows to achieve a reduction of impacts for some categories. Nevertheless, the use of wastewater as a substitute of nutrients is not sufficient to provide optimal conditions necessary for the fast growth of microalgae biomass. This leads to an increase in impacts, particularly in the climate change category (GWP). Nevertheless, he reduction in biomass productivity from 0.166 to 0.1 g $L^{-1}d^{-1}$ leads to an increase in algal biomass cultivation days thus major energy and resource consumption.

While the use of wastewater for the cultivation phase and the increase in biomass productivity (scenario 3). proves to be the most advantageous case in terms of environmental impacts. Moreover, even if for the specific study the economic aspects were not analyzed, it it is possibile to affirm that the reuse of wastewater leads to other significant benefits in terms of economic sustainability and therefore to the global sustainability of the technology.

4. Conclusions

LCA is useful methodology to investigate and promote environmental sustainability. From the results obtained it is possible to observe that cultivation and drying are the phases that lead to a greater consumption of energy as well as greater environmental impacts according to the evaluation method Recipe2016. The second scenario shows no obvious advantages in terms of energy saving; however it is more advantageous in some environmental impact categories, due to the choice of replacing the chemical agents of the medium with domestic wastewater. While the third scenario highlights the highest performaces in terms of sustainability.

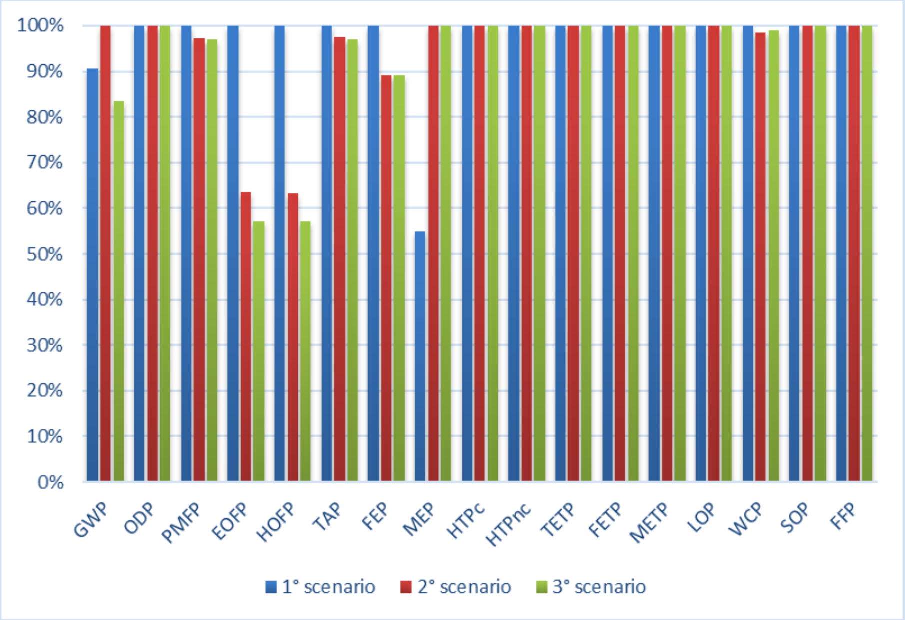

Figure 1. Comparative profile of the impacts for the three scenarios, in blue the first scenario that use artificial nutrients, in red the second scenario that use wastewater as nutrients source with low microalgae productivity and in green the third scenario that use wastewater as nutrients source with high microalgae productivity.

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