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Life Cycle Assessment Based on Primary Data of an Industrial Plant for Microalgae Cultivation

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Microalgae are a potential feedstock for a wide range of final products. However, the commercialization of simple process routes and multi-product biorefinery schemes is hindered by unsatisfactory or uncertain environmental and economic performances. Many life cycle assessment (LCA) studies have evaluated the environmental sustainability of microalgal systems, leading to controversial results. In most cases, they are affected by the use of lab-scale extrapolated or literature data, resulting in qualitative and unreliable projections.

This work presents a preliminary evaluation of the environmental profile of an industrial-scale plant by applying the LCA methodology with the use of primary data for the foreground inventory. The analyzed facility is installed in Caltagirone, Sicily (Italy). It has a capacity of 1200 kg_{DW} $year^{-1}$ (*DW = dry weight* biomass) cultivating *Chlorella vulgaris* in vertically stacked horizontal photobioreactors (VSt-PBRs) with a total volume of 40.4 m^3. Demineralized water, produced via reverse osmosis of tap water, is used for cultivation and maintenance (cleaning). Centrifugation is used for dewatering the algal suspension from 2 g_{DW} L^{-1} to ~200 g_{DW} L^{-1}. A cradle-to-gate assessment was performed using primary data on plant operation and poly(methyl methacrylate) (PMMA) usage (the main construction material for the PBRs). The LCA results highlight that (i) cultivation is by far the most impactful process step compared to cleaning and harvesting, and (ii) chemicals (nutrients for cultivation, and cleaning and sterilization agents) and electricity (pumping and agitation, thermoregulation, and LED lighting) are the flows that cause the main environmental hotspots. In contrast, PMMA usage and waste treatment provided lower relative contributions to generating potential impacts, while tap water consumption had negligible effects.

1. Introduction

In recent years, many research efforts have been devoted to promoting microalgae as a feedstock for a plethora of final products, which can be grouped into biofuels/bioenergy (Marangon et al., 2023), biomaterials (Nanda and Bharadvaja, 2022), and valuable biochemicals (Braun and Colla, 2022). However, the implementation of full-scale plants and the development of an industrial market are still limited by economic (Yadav et al., 2022) and environmental (Ubando et al., 2022) concerns. Simple process routes, but also more promising multi-product biorefinery schemes (Chew et al., 2017), have shown unsatisfactory or uncertain performances.

Regarding environmental sustainability, many life cycle assessment (LCA) studies have been conducted to evaluate microalgal systems. However, they led to controversial results. Uncertainties are associated with the process scale-up, as many assessments have been performed by using lab-scale extrapolated data or literature data, thus resulting in qualitative and unreliable projections. In contrast, a few large-scale cultivation systems, either closed photobioreactors (PBRs) or open raceway ponds (ORPs), have been assessed with the use of primary data, and even less large-scale downstream processing routes (Gurreri et al., 2023b). Moreover, previous LCA studies have used different methods and, in some cases, have been affected by a lack of

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transparency (not available information), making difficult or even ambiguous interpretations and comparisons of results (Gurreri et al., 2023b).

With specific regard to LCAs with the functional unit (FU) of 1 kg_{DW} (DW = dry weight) biomass, several studies have been conducted with data collected from pilot systems with culture volume in the order of 0.1 m^3, while only a few works have used primary data from large-scale plants with culture volume in the order of 1-10 m^3.

In the comparative analysis of pilot systems performed by Pérez-López et al. (2017), the highest environmental burdens were caused by electricity consumption, especially for thermoregulation. The global warming was in the range 214-4256 kg $CO_{2,eq}$ kg_{DW}^{-1}, and the total cumulative energy demand (CED) ranged ~3500-70,000 MJ kg_{DW}^{-1}, depending on the season and the cultivation system. The provision of nutrients contributed significantly to the categories of acidification (~20%) and non-renewable energy demand from biomass of primary forests (~60%). Overall, the environmental performance of tubular PBRs was less dependent on weather conditions and better compared to the ORP.

Yadav et al. (2020) assessed different growth conditions by testing a pilot ORP and found that the cultivation sub-process was by far the most impactful one, with contributions between 75 % and 85 % of most impact categories due to its electricity demand. It was followed either by dewatering or gas compression, depending on the assessed scenarios (without or with flue gas insufflation, respectively). Global warming and CED were 270 kg $CO_{2,eq}$ kg_{DW}^{-1} and ~30 GJ kg_{DW}^{-1}, respectively, under the best cultivation conditions (flue gas insufflation, semi-continuous regime), while they exceeded 1000 kg $CO_{2,eq}$ kg_{DW}^{-1} and 120 GJ kg_{DW}^{-1}, respectively, under the worst cultivation conditions (no flue gas, batch regime).

Onorato and Rösch (2020) compared thee full-scale plants for microalgae cultivation (primary data available for two of them) and a downstream section for astaxanthin (red carotenoid) extraction. The results of the comparative LCA showed that the use of artificial light (LEDs and electricity) can produce significant contributions to environmental impacts, which can be mitigated in most categories by the application of a grid mix with a higher renewable share. However, the most environmentally friendly system was that using sunlight (unilayer horizontal tubular PBR). For example, it produced a potential climate change of ~21 kg $CO_{2,eq}$ kg_{DW}^{-1}, while other scenarios exhibited values up to ~265 kg $CO_{2,eq}$ kg_{DW}^{-1}.

Herrera et al. (2021) assessed a full-scale ORP for the production of biostimulants and aquaculture feed. The system was characterized by a very low energy consumption (~1 kWh kg_{DW}^{-1}) and produced small impacts, from one to three orders of magnitude lower than those assessed by Onorato and Rösch (2020). For example, global warming was estimated at around 1 kg $CO_{2,eq}$ kg_{DW}^{-1}. Moreover, water recirculation (from microalgae harvesting) and nutrient supply with manure slurry were effective in impact reduction, but the most powerful scenario was based on the use of wastewater, leading to credits in some impact categories.

Pechsiri et al. (2023) compared different pilot bioreactors to produce biostimulants, finding that closed systems produced impacts roughly doubled compared to open systems, mainly due to the higher energy demand of the formers for culture medium circulation and agitation (vertically stacked horizontal PBR) or lighting (light exchange bubble-column PBR). The most impactful input flows were electricity consumption, synthetic nutrients, and CO_2. In contrast, reactor materials played a minor role. The results in terms of global warming potential were in the range ~4-27 kg $CO_{2,eq}$ kg_{DW}^{-1}, with the lowest value obtained in a scenario with solar energy (on-site photovoltaic production), wastewater as a nutrient source, and combustion flue gas as a CO_2 source, which led even to a net negative value (i.e., a credit) in the eutrophication impact category.

This brief literature review shows a great variability in the results obtained by different assessments. Therefore, further studies using primary data from large-scale plants and common methodologies are required to obtain reliable results and provide a consistent framework for comparisons. In this context, the present work aims to perform a preliminary LCA of an industrial process for microalgae production by using primary data from a full-scale facility. Its environmental profile is assessed and the environmental hotspots are identified by including a comparison of the present case study with literature data, thus suggesting the main areas of intervention for the development of sustainable systems.

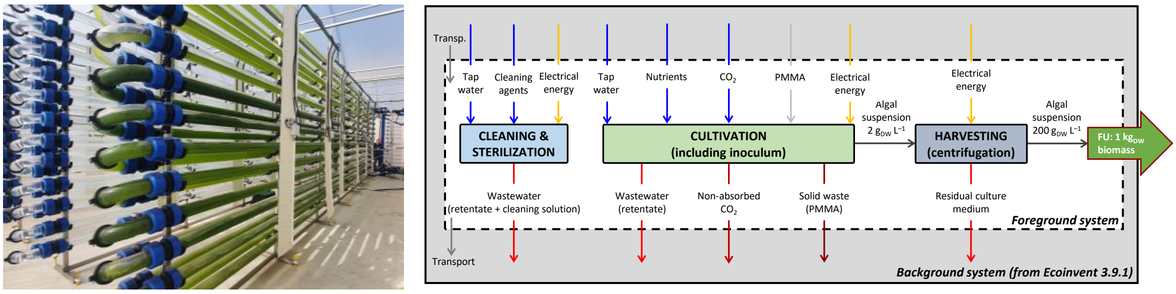
2. Methodology

The present LCA was carried out following the methodology of the international standards ISO 14040 (2006) and ISO 14044 (2006). A spreadsheet (Microsoft Excel) and the SimaPro (v. 9.5.0.0) software were used to model the product system. The former was elaborated to build the foreground inventory, while the latter led to the complete inventory (including background data) and the assessment of environmental impacts.

2.1 Goal and scope definition

The analysed industrial-scale plant is installed in Caltagirone, Sicily (Italy). It has a capacity of 1200 kg_{DW} $year^{-1}$ cultivating *Chlorella vulgaris* in vertically stacked horizontal photobioreactors (VSt-PBRs), which are placed in a greenhouse and have a total volume of 40.4 m^3 (Figure 1a). The corresponding average productivity is ~0.08

g_{DW} L^{-1} d^{-1}. Demineralized water, produced via reverse osmosis (RO) of tap water, is used for the operations of cultivation and maintenance cleaning. Centrifugation is used for dewatering the algal suspension from 2 g_{DW} L^{-1} to ~200 g_{DW} L^{-1}. For further details, see the previous work (Gurreri et al., 2023a), which was devoted to the elaboration and analysis of the foreground inventory and provides the basic information to conduct the present study.



(a) (b)

Figure 1: Industrial-scale plant for the cultivation of Chlorella vulgaris (Caltagirone, Italy): (a) picture of a detail of VSt-PBRs; (b) product system with the main input and output flows.

The goal of this study is to provide the main features of the environmental profile of the above-mentioned industrial-scale plant. A preliminary yet reliable LCA was performed with primary data. The environmental impacts were assessed, identifying the main environmental hotspots and suggesting perspectives for improvement.

A cradle-to-gate assessment for biomass production was performed with the functional unit (FU) of 1 kg_{DW} biomass. Primary data on plant operation were considered, including poly(methyl methacrylate) (PMMA) usage for the PBRs as the input material representative of the infrastructure. Transport of materials was included using background data for Italian, European or global markets (decreasing order of preference). The temporal boundary of the analysis was determined by a plant lifetime fixed at 30 y. The geographic boundary was defined by the real plant's location (Sicily, typical Mediterranean climate) and the use of the Italian grid mix for electricity. The plant operation was 300 d y^{-1}. The analysed product system, which is depicted in Figure 1b, was devised with three sub-processes to quantify the input and output flows, namely (i) cleaning and sterilization, (ii) cultivation (including inoculum), and (iii) harvesting (centrifugation).

2.2 Life cycle inventory

Raw primary data collected at the plant facility were used to compile a spreadsheet and elaborate the foreground inventory previously published (Gurreri et al., 2023a). In the present work, the inventory was updated (i) with data regarding energy consumption for thermoregulation (108 kWh kg_{DW}^{-1} instead of the value of 217 kWh kg_{DW}^{-1} previously inventoried) and (ii) by assuming a lifetime of PBRs of 20 y (instead of the value of 10 years previously considered, resulting in a PMMA consumption of 0.405 kg kg_{DW}^{-1} instead of 0.810 kg kg_{DW}^{-1}). Single input/output flows were aggregated into the three sub-processes depicted in Figure 1b. Moreover, they were also aggregated per flow type. These included PMMA (transparent material for the VSt-PBRs), tap water, chemicals (nutrients + cleaning and sterilization agents + CO_2), and electricity (Italian grid mix, medium voltage) for the inputs, while the flow named "waste and emissions" grouped the outputs (wastewater + waste PMMA + non-absorbed CO_2 lost in the air). Among them, waste fluid streams were the reverse osmosis retentate, the waste cleaning solution, and the residual culture medium from centrifugation (red arrows in Figure 1b). They were modelled as wastewater collected into the sewer system and sent to a conventional wastewater treatment plant. The waste PMMA was assumed as a flow of waste plastic mixture disposed of in a sanitary landfill.

Input/output flows were inserted into the product system modelled in SimaPro by using the Ecoinvent database (v. 3.9.1). To build the complete background inventory, chemicals missing in the database were modelled with proxies.

2.3 Impact assessment

The CML baseline (v. 3.09 / EU25) method was used for the assessment of the environmental impacts, providing a broad evaluation across eleven impact categories at the midpoint level (problem-oriented approach).

2.4 Interpretation

The presentation of the impact assessment results (characterization) was organized to identify the most impactful process stages and the most impactful input/output flows. A comparison with previous studies was also performed. All this enabled a proper interpretation of results in relation to the goal and scope of the study, reaching conclusions and recommendations.

3. Results and discussion

The environmental profile of the analysed full-scale plant can be described through the LCA results reported in Figure 2.

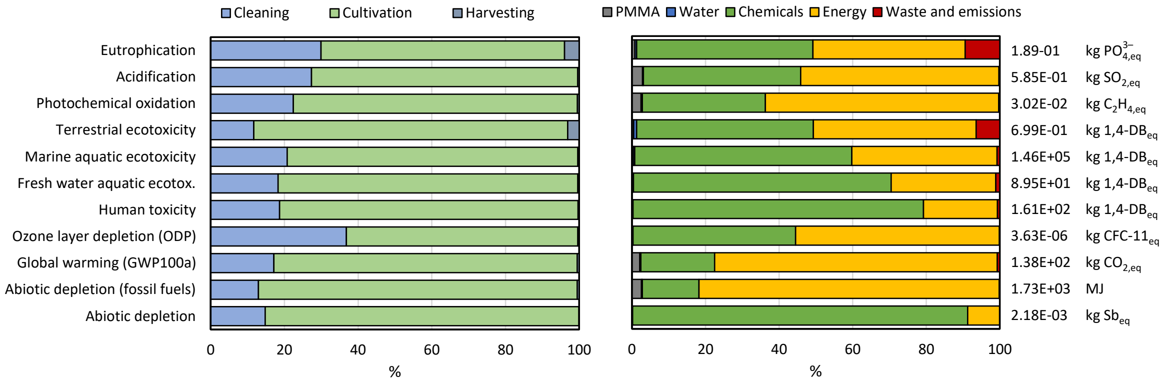


Figure 2: Environmental profile defined by impact characterization (CML method) of the industrial-scale plant for the production of 1 kg$_{DW}$ Chlorella vulgaris in VSt-PBRs – relative contributions of operative stages (left) and input/output flow types (right).

Figure 2 (left) shows that the cultivation phase is the most impactful one in all the assessed categories, with contributions across them from 63 % to 87 %. The cleaning and sterilization step contributes by 21 % on average, while harvesting has negligible impacts.

Figure 2 (right) provides a more detailed quantification of the relative contribution of the different input/output flow types. The consumption of chemicals is the most impactful flow in 6 over 11 categories, followed by the electricity from the grid, which is responsible for the largest contribution in the other 5. Across the various impact categories, chemicals and electricity cause contributions from 15 % to 91 % and from 9 % to 82 %, respectively. Other flows cause low or even negligible relative impacts, which are below ~3 % for PMMA, 1 % for tap water, and 9 % for waste and emissions.

These results can be qualitatively interpreted by considering the foreground inventory of the product system, which was analysed in a previous work (Gurreri et al., 2023a) and has been updated in the present one, as mentioned before (section 2.2). The cultivation step uses large amounts of electrical energy (~270 kWh kg$_{DW}^{-1}$) and chemical nutrients (~4 kg kg$_{DW}^{-1}$), while the cleaning and sterilization phase is characterized by a negligible demand for electricity but, at the same time, a high consumption of chemicals (~4 kg kg$_{DW}^{-1}$). Therefore, the impact share due to chemicals used in cleaning and sterilization is roughly equal to the percentage shown by the whole cleaning and sterilization phase (Figure 2 left). Finally, harvesting via centrifugation has only an almost negligible energy consumption.

The values of the assessed impacts are reported as labels in Figure 2, showing that the full-scale plant is potentially rather impactful. For example, the global warming potential (GWP) in a time horizon of 100 years amounts to 138 kg $CO_{2,eq}$ kg$_{DW}^{-1}$.

To perform a preliminary comparison with results from the literature, Table 1 reports the values of the greenhouse gas (GHG) emissions, due to the production of 1 kg$_{DW}$ microalgal biomass, assessed in various LCA studies conducted with primary data at the pilot- or industrial-scale (see also the Introduction). It can be highlighted that the various results are scattered over several orders of magnitude. In particular, the GHG emissions exhibit a minimum value of ~1 kg $CO_{2,eq}$ kg$_{DW}^{-1}$ assessed by Herrera et al. (2021) and a maximum value of more than 4000 kg $CO_{2,eq}$ kg$_{DW}^{-1}$ estimated by Pérez-López et al. (2017), both for ORP bioreactor systems. Regarding the industrial-scale plant assessed in the present study, Table 1 shows that it is characterized by an intermediate performance (138 kg $CO_{2,eq}$ kg$_{DW}^{-1}$). By focusing on the vertically stacked PBR systems, this result lies between the values reported by Pechsiri et al. (2023) (~27 kg $CO_{2,eq}$ kg$_{DW}^{-1}$) and

Pérez-López et al. (2017) (~570 kg $CO_{2,eq}$ $kg_{DW}{}^{-1}$). Figure 2 (right) shows that, in the present case study, the global warming potential is caused mostly (77 %) by electrical energy consumption. In turn, electricity is mainly required by pumping and aeration, thermoregulation, and LED lighting (115, 108, and 40 kWh $kg_{DW}{}^{-1}$, respectively). Therefore, optimizing the pumping system and choosing more favourable climatic regions could lead the assessed industrial plant to achieve an enhanced environmental performance.

On the other hand, many bioreactor technologies have been evaluated in the literature, but the LCA results from different studies show conflicting results. Therefore, further studies are needed to develop more sustainable production plants. In this regard, promising results have been shown by layouts conceived with the use of wastewater and solar energy (Pechsiri et al., 2023), thus deserving further studies. In a holistic approach, indeed, renewable energy and waste streams for nutrient provision can be advised as potential routes for sustainability enhancement. For example, Mancini et al. (2021) proposed a waste-wastewater-energy nexus scenario showing the environmental benefit of integrating different plants and industries within an industrial symbiosis district. This paradigm could be adapted to integrated schemes that involve microalgal systems, boosting their overall sustainability.

Table 1: GHG emissions of pilot- and industrial-scale microalgal plants estimated by LCA studies. A selection of basic case studies is considered.

Reference	Bioreactor system	GHG emissions [kg $CO_{2,eq}$ $kg_{DW}{}^{-1}$]
Pérez-López et al. (2017)	Horizontal PBR (fall)	433
	Vertically stacked horizontal PBR (fall)	574
	Open raceway pond (fall)	4256
Yadav et al. (2020)	Open raceway pond (best conditions)	270
Onorato and Rösch (2020)	Flat panel airlift PBR	265.21
	Green wall panel PBR	91.37
	Unilayer horizontal tubular PBR	20.93
Herrera et al. (2021)	Open raceway pond (freshwater and fertilizers, no recirculation)	1.5
Pechsiri et al. (2023)	Open raceway pond	9.8
	Thin layer cascade	8.8
	Vertically stacked horizontal PBR	26.6
	Light exchange bubble-column	24.7-44
This work	Vertically stacked horizontal PBR	138

4. Conclusions

This study presents a preliminary LCA of an industrial-scale production of microalgae. The analysed plant is located in Sicily (Italy) and produces *Chlorella vulgaris* in vertically stacked PBRs. Only primary data were used for the assessment, thus providing reliable results.The characterization results of the LCA (CML method) revealed that the environmental impacts were mainly caused by the cultivation phase (78 % as average contribution), with chemicals and electrical energy being the input flows producing the major environmental hotspots (50 % and 47 %, respectively, as average contributions). The potential impacts were rather high. For example, the GWP was 138 kg $CO_{2,eq}$ $kg_{DW}{}^{-1}$. However, this value represents an intermediate environmental performance of the plant when compared to the pilot- and industrial-scale facilities assessed in the literature.

On one hand, to provide a comprehensive assessment, the present study should be completed by including in the inventory all the materials and components that constitute the plant infrastructure. On the other hand, the preliminary results suggest that general approaches for environmental performance improvement should focus on process optimization from the technical standpoint (e.g., kinetics, mass transfer) to enhance productivity, which is a crucial performance metric indicating the relative consumption of resources. Moreover, strategies based on (i) the deployment of renewable energy and (ii) the integration of the microalgae production system within circular schemes for the valorization of waste streams, such as nutrient-rich wastewater, should be considered to alleviate the environmental impacts.

Abbreviations

CED – cumulative energy demand
CML – centrum voor milieukunde Leiden
DW – dry weight
FU – functional unit
GHG – greenhouse gas
GWP – global warming potential
LED – light emitting diode
ORP – open raceway pond
PBR – photobioreactor
PMMA – poly(methyl methacrylate)
RO – reverse osmosis

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