



Environmental Impact of Microalgae Production in an Industrial-Scale Plant: a Comparative Scenario Analysis

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This study conducts a comparative life cycle assessment to explore the potential for improvement in the environmental profile of an industrial-scale microalgal production system. The base case regards a pilot plant with vertically stacked photobioreactors for cultivating *Chlorella vulgaris*, where electricity (from the Italian grid) and chemical fertilizers emerge as the key impact drivers. To address these hotspots, renewable energy and circular bioeconomy approaches were assessed in a scenario analysis. Specifically, these included the use of on-site photovoltaic panels (PV) for energy supply and reclaimed wastewater (WW) for nutrient provision. The results showed that the PV scenario can reduce the global warming potential by 55%, demonstrating its decarbonisation potential, though it increased other impacts (some toxicity-related categories and abiotic depletion). Instead, the WW scenario yielded reductions across all impact categories, albeit to varying degrees. The PV+WW combination outperformed the base case in all impact categories and emerged as the best option in the impact categories not adversely affected by the deployment of photovoltaic panels. Finally, an uncertainty/sensitivity analysis on biomass productivity under wastewater-based cultivation highlighted potential risks of poor environmental performance, but also opportunities for improvement through the use of native microalgal strains.

1. Introduction

Microalgae have a wide potential as a renewable, versatile raw material for the production of a large variety of bioproducts. These include 3rd and 4th generation biofuels and bioelectricity (Wang et al., 2024); feeds, food, nutraceuticals, pharmaceuticals, healthcare products and cosmetics (Ibrahim et al., 2023); biofertilisers and biostimulants (Cao et al., 2023); biopolymers and bioplastics (Adetunji and Erasmus, 2024). Numerous biorefinery approaches have been proposed for the production of multiple co-products, following zero-waste principles aimed at maximizing the overall value derived from microalgal biomass (Cheirsilp and Maneechote, 2022). However, the environmental sustainability of microalgal systems remains uncertain. Life cycle assessments (LCA) studies have reported highly variable outcomes, including those based on primary data from large-scale pilot installations (Gurreri et al., 2023b). This variability stems not only from the diversity in cultivation and processing technologies but also from inconsistencies in methodological assumptions. Comparative LCAs, including those incorporating scenario analyses, can pinpoint major environmental hotspots and reveal more sustainable alternatives. For example, Pérez-López et al. (2017) found that the electricity supply was the most significant impact driver in different pilot-scale microalgae systems. In a virtual scenario that omitted the energy demand for temperature control, the environmental impacts were reduced by 17–77%. When the measured electricity use was replaced with literature-based estimates for an upscaled system, the impacts declined by 23–93%.

Evaluating an open raceway pond (ORP) system, Yadav et al. (2020) confirmed the central role of energy consumption in microalgae cultivation. A sensitivity analysis performed by increasing the biomass productivity by 50–200% showed a corresponding reduction in environmental impacts, approximately following an inverse proportionality.

Similarly, Onorato and Rösch (2020) identified electricity demand as the primary environmental hotspot in three large-scale pilot photobioreactor (PBR) configurations, with a sunlight-illuminated system outperforming others. Two alternative scenarios were based on different national grid mixes, i.e., German and French. Due to the high share of nuclear power, the French mix reduced climate change by 2/3 but increased ionising radiation by three times.

Herrera et al. (2021) found electricity, chemical fertilizer use, and materials transportation as the main impact drivers in a large ORP system. Of nine nutrient and water scenarios evaluated, waste streams (manure slurry and wastewater from sewage) most effectively reduced the environmental impacts. However, a sensitivity analysis showed that either a 40 km transport distance or a 20% reduction in productivity would cancel the potential benefits of the slurry scenario over chemical fertilizers. In the wastewater scenario, system substitution to credit water treatment delivered a zero impact in several categories and even some negative values in others. In a comparative analysis of several bioreactor configurations, Pechsiri et al. (2023) identified energy and nutrient provision as the key environmental hotspots and conducted a scenario analysis. The base case relied on the Spanish electricity mix, chemical fertilizers, and injected CO₂. Alternative scenarios explored the French electricity mix, the European network, and on-site photovoltaics, as well as an urban-industrial symbiosis approach involving microalgae cultivation in treated wastewater (source of N and P) and with flue gas (C source). Two environmental impacts were analysed, i.e., global warming potential and eutrophication, and credits were computed for the CO₂ sequestration from flue gas and the removal of N and P from wastewater, respectively. The results showed that photovoltaic energy could reduce the impacts, especially the global warming potential, and that photovoltaic energy or the French grid mix combined with the symbiosis strategy could lead to a global warming reduction by ~85% and even to negative net values for eutrophication.

More recently, Zarra et al. (2024) evaluated three scenarios to assess the effect of the nutrient source and biomass productivity. The base case was built with primary data from pilot tests with chemical fertilizers (Bold's basal medium). The second scenario was derived from literature data on domestic wastewater used as a nutrient source, which was accompanied by a 50% reduction in biomass productivity. The third scenario was a hypothetical case assuming wastewater use without productivity loss. Due to the counteracting effects of no chemical fertilizers and lower productivity (higher resource demand), scenario 2 yielded mixed results (a significant reduction in a couple of impact categories, a mild reduction in eight categories, a negligible effect in three categories, and even an increase in a couple of categories). Thanks to the same energy consumption as scenario 1 and the avoided chemicals, scenario 3 was the most environmentally friendly, though with a different performance across the various categories (~45% reduction in the best case, negligible effects in the worst case). Moreover, a sensitivity analysis showed that quadrupling productivity could reduce impacts by 2–20% and even cut global warming potential by 37%.

In a previous study, we formulated and analysed the foreground life cycle inventory (LCI) of an industrial-scale pilot plant with vertically stacked horizontal PBRs for the cultivation of *C. vulgaris* (Gurreri et al., 2023a). Primary data on operational flows and PMMA material (representative of infrastructure) were considered, highlighting the high values of chemical consumption and energy demand (from the grid) compared to other studies. Then, a preliminary LCA showed that these flows were the most important impact drivers (Gurreri et al., 2024b). Upon completing the LCI with all infrastructure items, a comprehensive LCA qualitatively upheld these results, apart from an exceptionally high contribution of the construction materials subprocess (specifically, reverse osmosis modules) in one impact category (ozone layer depletion) (Gurreri et al., 2024a).

Building on our previous works, the present study investigates targeted mitigation strategies through a scenario analysis. The impacts of on-site photovoltaics (renewable energy provision) and wastewater reuse (circular nutrient sourcing) are evaluated—both singularly and in combination—to assess their potential in reducing the environmental burdens of the PBR system, along with associated limitations and uncertainties.

2. Methodology

This study was carried out in compliance with the principles and guidelines on LCA set out in the ISO 14040 (2006) and ISO 14044 (2006) norms, using the SimaPro (v. 9.5.0.0) software platform as primary modelling tool with supplementary data processing performed in Microsoft Excel.

2.1 Goal and scope definition

The goal of this LCA study is to quantify the environmental impacts of an industrial-scale pilot system for microalgae cultivation through a comparative analysis of alternative scenarios with potential for improvement.

The microalgal plant under assessment is a demonstration facility located in Caltagirone, Italy, featuring vertically stacked PBRs with a total volume of $\sim 40 \text{ m}^3$, used for cultivating *Chlorella vulgaris*. Further details on the microalgal pilot plant are available in a previous study (Gurreri et al., 2024a). A cradle-to-gate assessment was performed with the functional unit of 1 kg of dry-weight biomass. The analysis considered a 30-year operational lifetime.

The product system was assessed under four scenarios (Table 1). Scenario 1 represents the base case, previously assessed in detail using primary data (Gurreri et al., 2024a). It was characterized by the environmental hotspots associated with electricity from the grid and chemical inputs for cultivation and maintenance. To explore potential mitigation strategies, three virtual alternatives were formulated. Scenario 2 introduces renewable energy via on-site photovoltaic panels (PV), while scenario 3 considers the reuse of treated wastewater (WW). Finally, scenario 4 simulates the combination of both strategies (PV+WW) to evaluate their cumulative effects.

Table 1: Scenarios of the comparative analysis, distinguished by energy and nutrient sources.

Scenario	Energy source	Nutrient source
1 (base case)	Italian grid mix	Chemical fertilizers
2 (PV)	On-site photovoltaics	Chemical fertilizers
3 (WW)	Italian grid mix	Wastewater
4 (PV+WW)	On-site photovoltaics	Wastewater

The CML-IA baseline (v. 3.09/EU25) method was selected for the life cycle impact assessment (LCIA).

2.2 Life cycle inventory

The foreground LCI was elaborated in an Excel spreadsheet that included operational and infrastructural data from the microalgal plant. The input/output flows of the product system were selected from Ecoinvent (v. 3.9.1), Agri-footprint (v. 6.3), USLCI 2015, and Industry data 2.0 databases within the SimaPro platform.

The base case LCI, previously published (Gurreri et al., 2024a), reported key input flows that included an energy consumption of 267 kWh/kg_{DW} and chemicals comprising 1.25 kg/kg_{DW} of NaNO₃, 1.67 kg/kg_{DW} of NaHCO₃, 3.80 kg/kg_{DW} of citric acid, and several minor components. Scenario 2 (PV) was created by replacing the Italian grid mix with a process for electricity production via photovoltaic panels (on-site 3kWp slanted-roof installation). Scenario 3 (WW) was built by removing all flows of chemical fertilisers (including micronutrients) and tap water for cultivation (including inoculum). Moreover, the flow of wastewater generated by the cultivation process and the negligible energy consumption for producing the growth medium through tap water reverse osmosis were removed. Assuming the presence of a wastewater treatment plant in the proximity of the microalgal facility, no energy input was considered for wastewater pumping. Nitrogen and phosphorus assimilations by the microalgal biomass were estimated as averages from literature data (Cordoba-Perez and de Lasa, 2021; Mandalam and Palsson, 1998; Raheem et al., 2015) allowing for the assignment of credits associated with pollutant removal from treated wastewater in the eutrophication impact category (Pechsiri et al., 2023). Finally, scenario 4 (PV+WW) was set as the combination of scenarios 2 and 3.

2.3 Life cycle impact assessment

The environmental impacts assessed via the CML baseline method (midpoint level) are: (i) abiotic depletion (ADP), (ii) abiotic depletion (fossil fuels) (ADPF), (iii) global warming potential over a time horizon of 100 years (GWP100a), (iv) ozone layer depletion (ODP), (v) human toxicity (HTP), (vi) freshwater aquatic ecotoxicity (FAETP), (vii) marine aquatic ecotoxicity (MAETP), (viii) terrestrial ecotoxicity (TETP), (ix) photochemical oxidation (POP), (x) acidification (AP), and (xi) eutrophication (EP). Credits in the EP category, resulting from N and P removal from wastewater, were calculated by multiplying the secondary inventory data on N and P content in the microalgal biomass by the PO₄ equivalence factors for total N and total P (emission in water), respectively. The LCIA phase was conducted by importing the characterization factors for all input and output flows of the product system from SimaPro into Excel. Therefore, the complete model comprising the foreground LCI and the LCIA was built within a spreadsheet, covering all simulated scenarios.

2.4 Interpretation

The LCIA results were examined through a contribution analysis of the following subprocesses: chemical and water inputs, electrical energy inputs, construction materials inputs, waste and emissions outputs, and N and P credits (negative impact) specifically addressing the effect of pollutant removal on the EP impact category (WW and PV+WW scenarios). All impacts were expressed relative to the base case to facilitate the comparative interpretation across scenarios.

An uncertainty/sensitivity analysis was performed to account for the variability in biomass productivity under wastewater-based cultivation. For example, Zarra et al. (2024) reported a 50% decrease in productivity when switching from a synthetic medium to domestic wastewater, which provided non-optimal growth conditions. Conversely, productivity may even increase when cultivating native microalgal strains in wastewater (Chen et al., 2015). For example, the highest biomass production with wastewater was 1.72 times that achieved with BG 11 medium in Cho et al. (2013). Drawing on these findings, a simple analysis of LCIA results was conducted in scenarios 3 (WW) and 4 (PV+WW) by recalculating all impact indicators under two additional sub-scenarios. Assuming an inverse proportionality of the impacts with biomass productivity, a reduced-productivity case (factor of 0.5) and an enhanced-productivity case (factor of 1.72) were simulated.

3. Results and discussion

Figure 1 compares the LCIA results for all simulated scenarios, illustrating the subprocess contributions and the influence of biomass productivity variations in wastewater-based cultivation (scenarios 3 and 4) across the assessed impact categories.

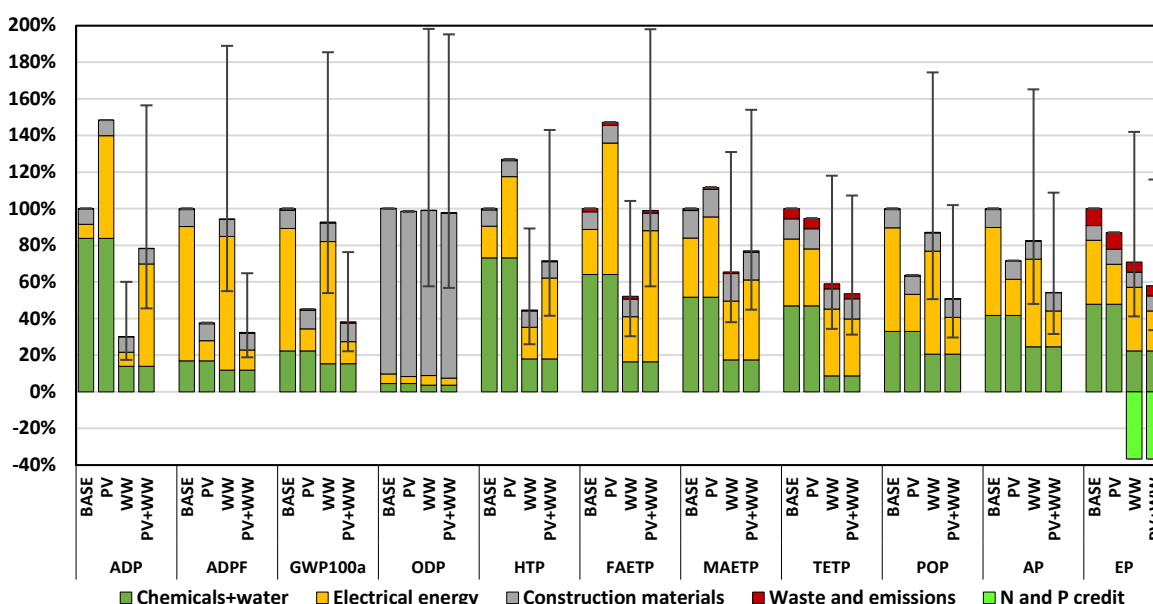


Figure 1: Comparative LCIA of all simulated scenarios, with impacts expressed relative to the base case and the breakdown of the subprocess contributions. “Error” bars represent the effect of biomass productivity variations on the total impacts in wastewater-based cultivation scenarios (WW and PV+WW).

In the base scenario, inputs of chemicals and grid-supplied electricity produce the dominant contributions, whereas construction materials and waste/emissions play only minor roles. The sole exception is the ODP impact category, where the reverse osmosis equipment is the primary impact driver (Gurreri et al., 2024a).

In scenario 2 (PV), substituting grid electricity with on-site photovoltaic generation substantially alters the contributions of the electrical energy subprocess. Notably, using photovoltaic panels increases impacts by 12%–48% in several categories (ADP, HTP, FAETP and MAETP). Conversely, it delivers improvements in most impact categories (ADPF, GWP100a, ODP, TETP, POP, AP and EP), achieving the greatest reductions in ADPF (relative impact = 38%) and GWP100a (relative impact = 45%).

In scenario 3 (WW), which employs treated wastewater for microalgal cultivation, impacts from chemical fertilizer inputs are fully eliminated, and those from waste and emissions are reduced (owing to less effluent sent to treatment). Additionally, environmental credits accrue in the EP category (through N and P removal). Under the assumption of unchanged biomass productivity, the WW scenario would represent an effective strategy in lowering all the environmental impacts. The reductions are moderate in some impact categories (ADPF, GWP100a, ODP, POP and AP) and more pronounced in others (ADP, HTP, FAETP, MAETP, TETP, EP), with the largest improvements in ADP and EP (relative impact = 30% and 34%, respectively).

In the PV+WW scenario, which combines the renewable energy (PV) and circular bioeconomy (WW) approaches, the less favorable performance of photovoltaic panels leads to increased impacts in the ADP, HTP, FAETP, and MAETP categories compared to the WW-only scenario. However, combining the advantages of

the PV and WW separate cases, the PV+WW scenario achieves (i) the lowest impacts across all other categories (ADPF, GWP100a, ODP, TETP, POP, AP, and EP) compared to all the simulated scenarios and (ii) lower impacts in all categories compared to the base case. The second outcome results from the fact that wastewater-based cultivation more than compensates for the PV-related drawbacks precisely in the four abovementioned impact categories.

Figure 1 illustrates the effects of biomass productivity in the WW and PV+WW scenarios through error bars. Within the tested range, environmental impacts may double under the most pessimistic conditions (see Section 2). This substantial uncertainty highlights the risk of poor environmental performance, with the worst case for both the WW and PV+WW scenarios characterised by environmental impacts exceeding those of the base case in most categories. Conversely, under enhanced productivity, which may derive from cultivating native microalgae in wastewater, all impacts may decrease by ~42% under the most optimistic conditions (Section 2). In this case, the relative impacts for both the WW and PV+WW scenarios fall between 20% and 60% of the base case values, except for EP, which reaches the exceptionally low values of 4% in the WW scenario and even -3% (net environmental credit) in the PV+WW scenario.

In a previous study, we observed that the environmental impacts of tap water use were negligible (Gurreri et al., 2024a). Consequently, the “chemicals + water” subprocess impacts reported in Figure 1 can be attributed entirely to chemical inputs. This is particularly relevant for scenarios 3 (WW) and 4 (PV+WW), where treated wastewater replaces all chemical fertilizers. In these cases, the “chemicals + water” subprocess encompasses only cleaning and sterilisation agents (aside from the CO₂ provision). Their inputs contribute by ~15% to each impact category (Figure 1), a magnitude comparable to that of construction materials.

4. Conclusions

To mitigate the environmental impacts of an industrial-scale microalgae cultivation facility, primarily driven by grid electricity and chemical fertilizers, alternative (virtual yet realistic) scenarios were modelled. Compared to the baseline, the PV scenario reduced most environmental impacts, particularly ADPF and GWP100a (relative impact of ~40%), but increased MAETP < HTP < FAETP < ADP (relative impact of ~110%–150%). Under the hypothesis of unchanged biomass productivity, the WW scenario delivered reductions across all categories (relative impact from 30% to 99%), driven by avoided chemical fertilizer use and, in the specific case of the EP impact category, N and P removal credits. The PV+WW combination was less effective than the WW-only case in the impact categories adversely affected by the PV option, but outperformed the baseline in every category (relative impact of ~21%–99%).

Uncertainty concerning the productivity of biomass cultivated in wastewater was reflected in the LCA results of scenarios 3 (WW) and 4 (PV+WW). A 50% productivity decline would worsen impacts beyond the baseline in most categories (relative impacts between ~60% and 200%), whereas a 72% productivity increase—achievable via native strain selection—could lower environmental impacts across the various categories (relative values between 20% and 60%) and eliminate EP (or even produce credits). Therefore, biomass productivity represents a crucial parameter for the environmental profile of microalgal cultivation systems, and its potential variability must be properly accounted for in scenario-based LCAs to ensure robust and reliable outcomes.

Abbreviations

ADP – abiotic depletion	LCI – life cycle inventory
ADPF – abiotic depletion (fossil fuels)	LCIA – life cycle impact assessment
AP – acidification	MAETP – marine aquatic ecotoxicity
DW – dry weight (biomass)	ODP – ozone layer depletion
EP – eutrophication	ORP – open raceway pond
FAETP – freshwater aquatic ecotoxicity	PBR – photobioreactor
GWP100a – global warming potential for a time horizon of 100 years	POP – photochemical oxidation
HTP – human toxicity	PV – photovoltaic energy, on-site panels
LCA – life cycle assessment	TETP – terrestrial ecotoxicity
	WW – treated wastewater

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