Life cycle inventory of microalgae production in a real industrial plant

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Microalgae are a valuable feedstock with great potential in a plethora of production routes, including valuable biochemicals (Braun and Colla, 2022), biofuels/bioenergy (Marangon et al., 2023), and biomaterials (Nanda and Bharadvaja, 2022). Microalgae-derived biochemical products could be applied in the nutraceutical, cosmetic, pharmaceutical, and feed/food sectors. However, the environmental sustainability of microalgal systems is uncertain. Indeed, life cycle assessments (LCAs) have been characterized by the adoption of heterogeneous methodologies. They are also affected by the use of hypothetical or lab-scale extrapolated data in most cases. Therefore, they have led to controversial results. This issue also regards the basic step of the analysis, i.e., the life cycle inventory (LCI).

A few LCA studies have been performed so far with primary data from pilot- or industrial-scale plants. For example, Pérez-López *et al*. (2017) compared two photobioreactor (PBR) configurations (vertically stacked, *Vst*, and horizontal, *Hor*) and an open raceway pond (ORP) at pilot scale. Onorato and Rösch (2020) compared three commercial-scale PBR plants, i.e, Flat Panel Airlift (*FPA*), Green Wall Panel (*GWP*), and Unilayer Horizontal Tubular (*UHT*), with a cultivation volume of 93 m^3, using primary data at that scale for the *FPA* and *GWP* PBRs.

This work aims at compiling the LCI of an industrial-scale plant, thus taking a further step in the realistic evaluation of the environmental sustainability of microalgae production systems. Moreover, the results are compared with LCI data from the two abovementioned studies.

The inventoried plant is installed in Caltagirone (Italy) within the facility of Plastica Alfa. *Chlorella vulgaris* is cultivated in a 42 m^3 vertically stacked horizontal PBR system located in a greenhouse. The plant has a capacity of 1600 kg_{DW} $year^{-1}$ (*DW* = dry weight), corresponding to a productivity of ~0.1 g_{DW} L^{-1} day^{-1}. Microalgae are harvested via centrifugation at a concentration of 200 g_{DW} L^{-1}. Demineralized water, produced via reverse osmosis (RO) of tap water, is used for both cleaning and cultivation.

The functional unit (FU) selected for all elementary input/output flows was 1 kg_{DW} biomass. Energy, nutrients, water, chemicals, and infrastructure (PBR) materials were inventoried to characterize the plant operation and construction. The LCI was compiled by assuming 300 operating days per year, 10 years of lifetime for construction materials, and 5 complete operating cycles per year. The inventory was elaborated in a spreadsheet (Excel). Three subsystems were identified in the product system, i.e., reactor cleaning, cultivation (including inoculum), and harvesting.

Results showed that the tap water consumption is 1.14 m^3 kg_{DW}^{-1}, with a contribution of ~50% in both cleaning and cultivation. The main chemicals are citric acid (~4 kg kg_{DW}^{-1}) for cleaning and sodium bicarbonate (~1.7 kg kg_{DW}^{-1}) in the cultivation. The total energy consumption is 440 kWh kg_{DW}^{-1}, and its main contributions are pumping (210 kWh kg_{DW}^{-1}) and thermoregulation (163 kWh kg_{DW}^{-1}) in the cultivation phase, followed by lighting by LEDs (64 kWh kg_{DW}^{-1}). In contrast, cleaning and harvesting centrifugation play a marginal role in energy consumption. Plastic materials (mainly PMMA) amount to ~1.8 kg kg_{DW}^{-1}.

Figure 1a shows that, compared to the other systems evaluated in the literature, the plant investigated in the present study is characterized by an intermediate value of water consumption, which is 72% of that of a plant with the same PBR configuration (*Vst*). The present plant exhibits the minimum and maximum value of chemical consumption in the cleaning and cultivation phase, respectively (Figure 1b). Note that the cultivation of *Haematococcus pluvialis* assessed by Onorato and Rösch (2020) does not require nutrients in the red phase to promote astaxanthin accumulation. Regarding the total energy consumption, the present plant exhibits an intermediate value (Figure 1c), corresponding to 59% of the energy consumption of the *Vst* system inventoried by Pérez-López *et al*. (2017). The energy required for temperature control is the lowest one compared to that of the *Hor* and *Vst* systems. Similarly. the energy consumption of the LEDs was the lowest compared to the *FPA* and *GWP* systems. This behavior is likely due to the more favorable geographic location in terms of climatic conditions and irradiance (Sicily for the present study *vs*. the Netherlands for *Hor* and *Vst*, Germany for *FPA*, and France for *GWP*). However, pumping (mixing and aeration) energy plays a major role. Finally, the present plant exhibits the largest value of the relative mass of plastic materials for PBR construction compared to the *Hor* and *Vst* systems (Figure 1d). This is partially related to the lower productivity of the present plant (0.1 g_{DW} L^{-1} day^{-1} *vs.* ~0.25 and 0.24 g_{DW} L^{-1} day^{-1} for *Hor* and *Vst*, respectively).

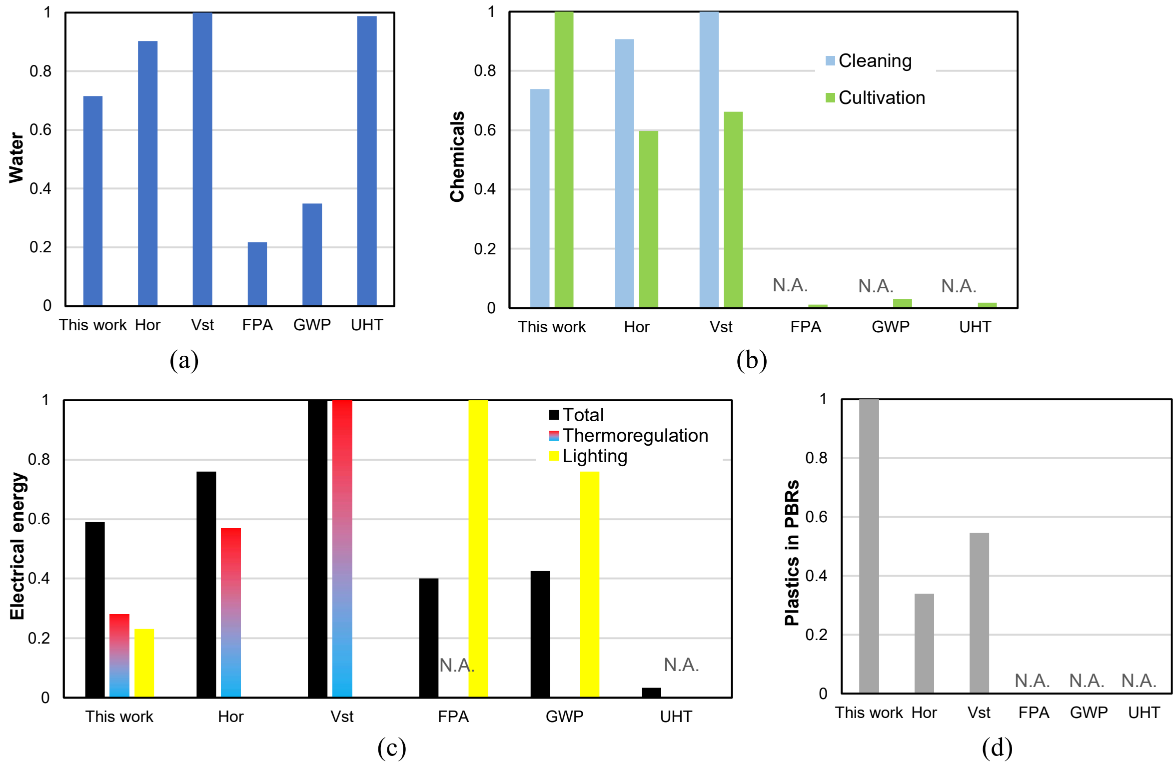

Figure 1: Relative main inputs of pilot/industrial-scale plants for microalgae cultivation in PBRs: (a) water, (b) chemicals, (c) electrical energy, and (d) plastic materials for PBRs. *N.A.* means not available. Data for *Hor* and *Vst* systems are from Pérez-López *et al*. (2017), and data for *FPA*, *GWP*, and *UHT* are from Onorato and Rösch (2020).

Future studies (i) will integrate the present results with further data on construction materials and transport of materials, and (ii) will perform LCAs providing the environmental profile of the plant under study and its potential improvement through alternative scenarios.

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