Environmental performance for microalgae cultivation commercial systems: sustainability metrics and indicators

Desempenho ambiental para sistemas comerciais de cultivo de microalgas: métricas e indicadores de sustentabilidade

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ABSTRACT
In this study, we evaluated metrics and sustainability indicators for cultivation commercial systems based on microalgae. Cultivation systems as a raceway pond, tubular photobioreactor, flat plate photobioreactor, and fermenter were evaluated under a standard functional unit of 1 m^3. These cultivation systems were estimated by midpoint indicators through the nine impact categories and later submitted to the normalization phase. Among the results found, three impact categories were shown to be more expressive to contribute to environmental impacts for the four cultivation systems, which are ecotoxicity potential, energy resource, and global warming potential. The best environmental performance was identified for raceway pond, although the worst-case scenario for the water footprint category was identified. Besides, in a comparative analysis between closed systems, fermenters showed better environmental indicators, followed by tubular and flat plate photobioreactors. In this way, the life cycle assessment allowed to highlight the hot points of the process, identifying the energy requirements as the critical points of the whole performance of the cultivation systems. Finally, regardless of the impacts associated with different cultivation configurations, it is important to note that the choice of the system will be directly associated with the target product to be produced. Therefore, the results found about the environmental performance of cultivation systems can serve as basic information to reduce the global environmental impacts of microalgae-based processes and bioproducts.

Keywords: biomass, raceway pond, tubular photobioreactor, flat plate photobioreactor, fermenter, life-cycle assessment.

RESUMO
Neste estudo, avaliamos métricas e indicadores de sustentabilidade para sistemas comerciais de cultivo baseados em microalgas. Sistemas de cultivo como lagoa aberta, fotobiorreator tubular e placa plana, e fermentador foram avaliados sob uma unidade funcional padrão de 1 m^3. Esses sistemas de cultivo foram estimados por indicadores de ponto médio através das nove categorias de impacto e posteriormente submetidos à fase de normalização. Dentre os resultados encontrados, três categorias de impacto mostraram-se mais expressivas para contribuir com os impactos ambientais para os quatro sistemas de cultivo, que são potenciais de ecotoxicidade, recurso energético e potencial de aquecimento global. O melhor desempenho ambiental foi identificado para a lagoa do canal adutor, embora o pior cenário para a categoria de pegada hídrica tenha sido identificado. Além disso, em uma análise comparativa entre sistemas fechados, os fermentadores apresentaram melhores indicadores ambientais, seguidos pelos fotobiorreatores tubulares e de placa plana. Desta forma, a avaliação do ciclo de vida permitiu destacar os pontos quentes do processo, identificando as necessidades energéticas como os pontos críticos de todo o desempenho dos sistemas de cultivo. Finalmente, independentemente dos impactos associados às diferentes configurações de cultivo, é importante notar que a escolha do sistema estará diretamente associada ao produto alvo a ser produzido. Portanto, os resultados encontrados sobre o desempenho ambiental dos sistemas de cultivo podem servir como informações básicas para reduzir os impactos ambientais globais de processos e bioprodutos baseados em microalgas.

Palavras-chave: biomassa, lagoa aberta, fotobiorreator tubular, fotobiorreator de placa plana, fermentador, avaliação do ciclo de vida.

1 INTRODUCTION

Environmental and energy challenges currently arise from industrialization associated with the growing demand for services, where it has negatively impacted the environment, leading to the need to discover promising alternatives (Bhattacharya and Goswami, 2020; Hussain et al., 2021). Based on this understanding, emerge microalgae as a potential source of biotechnological transformation molecules and can lead to a portfolio of alternative resources for today's world. In addition, it presents great market possibilities such as the production of food, fuel, and pharmaceutical products (Rahman, 2020; Erbland et al., 2020). According to market look, seaweed products in various segments is expected to expand at a compound annual growth rate of approximately 4.2% from 2018 to 2025 and will have a total market value of over 3,4 billion dollars (Markets and Markets, 2021). Associated with this, statistics show that the seaweed industry is becoming increasingly popular and can be used in different branches of the industrial sector (Tang et al., 2020).

As consequence, algae cultivation has become a growing area of research in recent years. However, the success in large-scale commercial production of microalgae depends on several factors, mainly the microalgae cultivation system used, which becomes the core for this purpose. In this sense, continuous efforts are deliberated in the construction of models with low energy consumption to ensure the economic viability of microalgae bioprocesses (Qin and Wu, 2019).

Many configurations of cultivation systems have been developed over the years to increase the productivity of microalgae biomass (Deprá et al., 2019). However, regardless of the target product, algae-based products at an industrial scale are produced exclusively in open systems (Ramírez-Mérida et al., 2017). These, in turn, consist of simple external lagoons, where the commercial operation of microalgae because they are more economical and relatively easy to expand. However, these systems are widely known for having low cell productivity, high contamination rates, cell selectivity, beyond demanding intensive for energy and nutrients. On other hand, closed systems provide controlled conditions and weathering, maximum cell productivity, automated maintenance of environmental parameters (Kirnev et al., 2020).

Notwithstanding, beyond cultivation systems meeting the intrinsic demands of microorganisms, these processes need to adapt to the demands for sustainability indicators imposed by society and regulatory bodies (Deprá et al., 2021). To do this, environmental performance must be examined to predict and model what the future impacts will be and, consequently, how industry stakeholders can align with this. It is worth mentioning that, as microalgae production systems are on the rise, it is highly recommended to subject them to sustainability assessments to support their implementation. In short, these tools become a powerful way to quantify and examine the potential environmental impacts of the process based on the principles of life cycle assessment (LCA), the application of sustainability metrics (Corona et al., 2019).

Recently, some studies have focused on environmental assessments associated with microalgae processes and their potential in the treatment of waste, such as the research by Tua et al. (2021) and Santos et al. (2020). On the other hand, other research lines have suggested the assessment of the environmental scenario of energy potential (Cruce et al., 2021) and microalgae bioproducts (Deprá et al., 2020). However, although these studies have shown and it is now widely disseminated that downstream processes are the hotspot of the environmental impacts of microalgae-based processes, to date, no article has attempted to review the environmental impact of processes core – the cultivation systems. Therefore, the present work aims to explore the potential impact through indicators and metrics of sustainability generated by the use of the main systems of marketable cultivation based on microalgae. In this study, once the values of the potential environmental impacts characterized were identified, the LCA methodology allowed the results to be normalized to a global reference value, in order to assess the magnitude of the impacts aiming to optimize their environmental performance in the scenario industrial application.

2 MATERIAL AND METHODS

The general framework for LCA was determined according to the International Organization for Standardization (ISO) 14000 series (ISO, 2006). The implementation methodology of LCA was determined according to four phases: (I) goal and scope definition, (II) inventory analysis, (III) impact assessment, and (IV) interpretation. Further, the procedures considered in each step are detailed below.

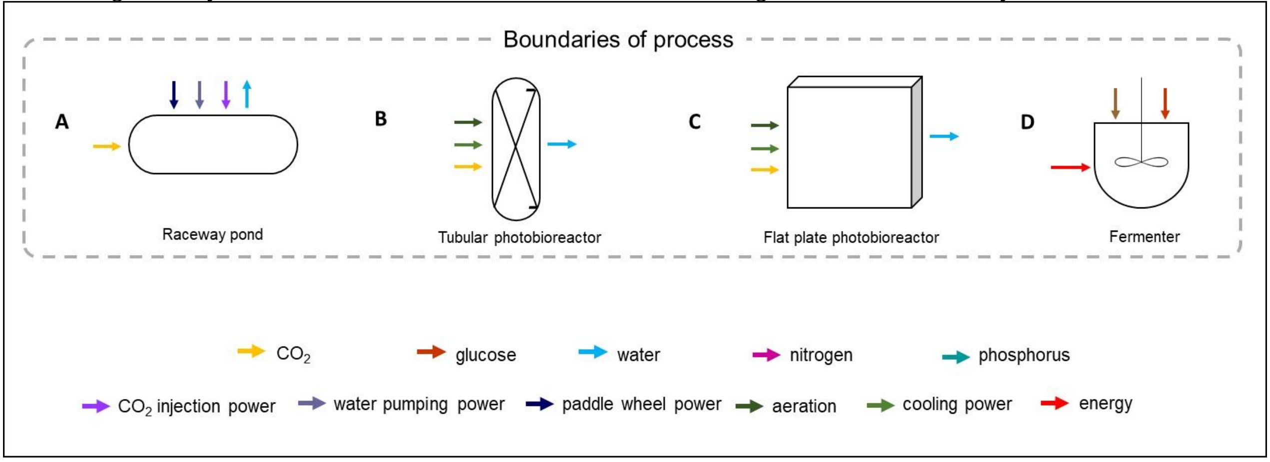
2.1 GOALS AND SCOPE DEFINITION

The study aim was to evaluate the main cultivation systems based on microalgae, which consist of (i) raceway ponds, (ii) tubular photobioreactor, (iii) flat plate photobioreactor, and (iv) fermenter. The cultivation systems evaluated involve biotechnological equipment commercially consolidated. Besides, data collection for theoretical-experimental analysis was based on process data consolidated by classic references in the literature.

2.2 FUNCTIONAL UNIT AND SYSTEM BOUNDARIES

The present study considered the functional unit indicated the comparison of microalgae cultivation systems under the 1 m³ operating mode. In addition, system boundaries have been set from the gate-to-gate life cycle, according to Deprá et al. (2020). The general layout of all the technical features of the case studies analyzed is presented in Figure 1.

Figure 1: Systems boundaries for the evaluation of the microalgae-based cultivation systems.



2.3 LIFE CYCLE INVENTORY (LCI)

Life cycle inventory data were obtained from the literature. For microalgal culture systems, the energy and nutrient specifications required for operation are based on the main industrial-scale configurations (Table 1).

Table 1: Energy requirements for the operation volume of 1 m³ the different operating cultivation systems.

Process	**Unit**	**Raceway pond**	**Tubular photobioreactor**	**Flat-panel**	**Fermenter**
Cultivation					
Power consumption for cooling	kWh	-	15	3.5	-
Aeration power	kWh	-	0.1	0.9	1.0
Agitation	kWh	-	-	-	0.0073
Sterilization	kWh	-	-	-	7.22
Water evaporation	m^3	1.3×10^1	1×10^{-4}	5×10^{-5}	1×10^{-4}
Electric power for paddle wheel	kW	0.54	-	-	-
Electric power for water pumping	kW	0.5	-	-	-
Electric power for CO_2 injection	kW	0.33	-	-	-
CO_2 consumption	kg	2.0	1.5	2.5	-
Glucose	kg	-	-	-	5.0

Adapted from Lee and Low (1992); Marsullo et al. (2015); Albarelli et al. (2018); Kumar et al. (2019

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2.4 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Potential environmental impacts were calculated according to a hierarchical approach (Goedkoop et al., 2009). The assessment was based on a wide spectrum of environmental indicators, divided between midpoint indicators, the energy indicator, the water demand indicator, and an indicator associated with land occupation and transformation.

In the midpoints, the global warming potential (GWP) was determined according to Laratte et al. (2014). Besides, photochemical ozone creation potential (POCP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), and ecotoxicity (ECO) were quantified according to Hauschild and Wenzel, H. (1998). While, the energy resource (ER), water footprint (WF), and land use (LU) were evaluated according to Maroneze et al. (2019), Hoekstra (2016), and Lathuillière et al. (2017), respectively. More details about the characterization factors are shown in Table 2

Table 2: Factors of characterization of environmental impacts of materials and energy in processes.

		Ozone Depletion	Global Warming	Smog	Acidification	Eutrophication	Ecotoxicity	Fossil Fuel Depletion
	Units	(kg CFC-11 eq)	(kg CO_2 eq)	(kg O_3 eq)	(kg SO_2 eq)	(kg N eq)	(CTUe)	(MJ Surplus)
Sodium hypochlorite	1 kg	1.2×10^{-6}	9.3×10^{-1}	1.0×10^{-2}	3.16×10^{-3}	2.29×10^{-2}	-	16.7
Glucose	1 kg	-	1.60×10^{-1}	-	1.21×10^{-3}	1.23×10^{-3}	-	14.23
Food grade CO_2	1 kg	3.28×10^{-8}	9.54×10^{-1}	1.12×10^{-1}	2.75×10^{-3}	1.65×10^{-3}	4.13	1.02
Electricity	1 kWh	9.39×10^{-8}	3.08×10^{-1}	6.84×10^{-3}	1.64×10^{-3}	5.86×10^{-4}	2.18	0.665

2.5 NORMALIZATION

The normalization step was established according to ILDC (2010), and the reference value corresponding to the world environmental impact normalization factor was provided by the European Commission (Table 3).

Table 3: Global normalization factors for emissions and resource extraction.

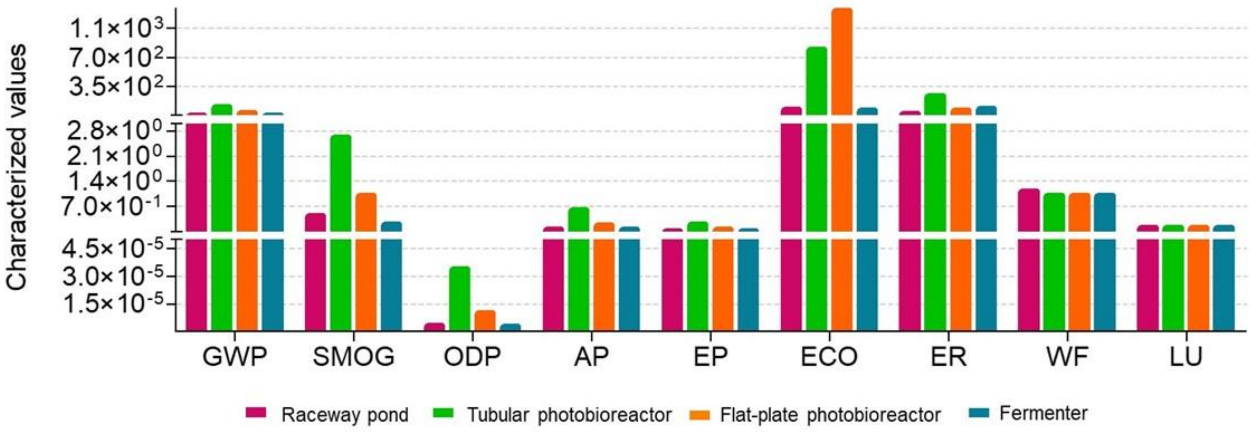
Impact categories	Unit	Reference value
Energy resource	MJ	$4.50\times10^{+14}$
Global warming potential	kg CO_2 eq	$5.79\times10^{+13}$
Water footprint	m^3	$7.91\times10^{+13}$
Acidification potential	kg SO_2 eq	$3.83\times10^{+11}$
Eutrophication potential	kg N eq	$1.95\times10^{+11}$
Ozone depletion potential	kg CFC-11 eq	$1.61\times10^{+08}$
Ecotoxicity	CTUe	$8.15\times10^{+13}$
Land use	ha	$9.64\times10^{+15}$
Photochemical ozone formation	kg O_3 eq	$2.80\times10^{+11}$

3 RESULTS AND DISCUSSION

3.1 CULTURE SYSTEMS

The main hardware of any microalgae-based process is the bioreactor, whose operation is part of the upstream processing stage. Today, raceway ponds, tubular and flat-panel photobioreactors, and fermenters are the most widely accepted existing designs for large-scale work. Although open systems require fewer consumables than closed systems, it is known that productivity is also lower. In contrast, photobioreactors overcome these yield issues, but with higher capital and operational expenses (Deprá et al., 2019). In view of this, the environmental performance of microalgae cultivation systems should be compared, since the selection of the reactor strongly influences it. Thus, the Figure 2 shows the environmental impact categories evaluated (GWP, SMOG, ODP, AP, EP, ECO, ER, WF, and LU), associated with the elements demanded the operation of the different microalgae cultivation systems.

Figure 2: Characterized values of environmental impact categories associated with cultivation systems.



Based on Figure 2, the raceway pond had a potential impact in the order of 79.93 CTUe, 23.90 MJ, 12.02 $kgCO_2eq$, and 1.13 m^3/d for the ECO, ER, GWP and WF categories, respectively. In this system, the electricity consumption considered was of the order of 0.54, 0.50, and 0.33 kW/m^3 for the culture mixture, water pumping, and CO_2 injection, respectively. These three demands depend on each other to improve the performance of the track. In addition, technically, these devices are part of crucial procedures for gas-liquid mixing. In this way, the identification of this hottest point reveals that the engineering element contributes to the scenario of environmental emissions, beyond the high energy in the operations of the primary unit of processes based on microalgae as a fundamental economic prerequisite for commercialization (Quin et al., 2012).

However, whether, on the one hand, the paddlewheel impacts the categories supported by fossil energy, on the other, it influences the WF category. For hydrodynamic reasons, the raceway pond has a considerable demand for freshwater, whose value obtained here was 1.13 $m^3/m^3/d$. This is precisely due to the movement of the paddle wheels, blade configuration, and geometry, which leads to an increase in total water losses through evaporation. According to the study by Kumar et al., (2015), propeller, centrifugal pump, and micro-channel paddlewheels could replace conventional paddle wheels, which have been tested to increase efficiency. This approach allows the operation of raceway ponds with shallow levels of WF and higher efficiency of water circulation, with a parallel reduction in energy consumption. These issues depend, of course, on factors that affect productivity in the raceway pond, such as depth and length (Chiaramonti et al., 2013).

In terms of a tubular photobioreactor, the most expressive potentials of the impact categories were 796.22 CTUe (ECO), 242.52 MJ (ER), 113.04 $kgCO_2eq$ (GWP), and 2.63 kgO_3eq (SMOG). The hotspot identified in the environmental load is due to the energy consumption for refrigeration, which in this study is 15 kWh/m³. Due to the arrangement of the tubes, the light penetration is high enough to cause the system to overheat and, consequently, photo-oxidative damage to the culture. Therefore, in addition to the mixture for efficient energy and mass transfer (CO_2/O_2 exchange), it is essential to balance the temperature throughout the system. Heat exchange devices generally assist cooling at regular intervals. However, this consumable severely increases the demand for energy (Molina et al., 2001). The use of heat exchangers requires the analysis of the global heat transfer coefficients between the tubes of the photobioreactor with the microalgae broth and the surrounding air and between the culture and the liquid medium that circulates within the internal heat exchanger (Sierra et al., 2008). To get around these problems, the most obvious solution would be to cool the system with freshwater or seawater for thermoregulation. However, this demand has an unsustainable effect because it would impact the WF category (Nowoba et al., 2019).

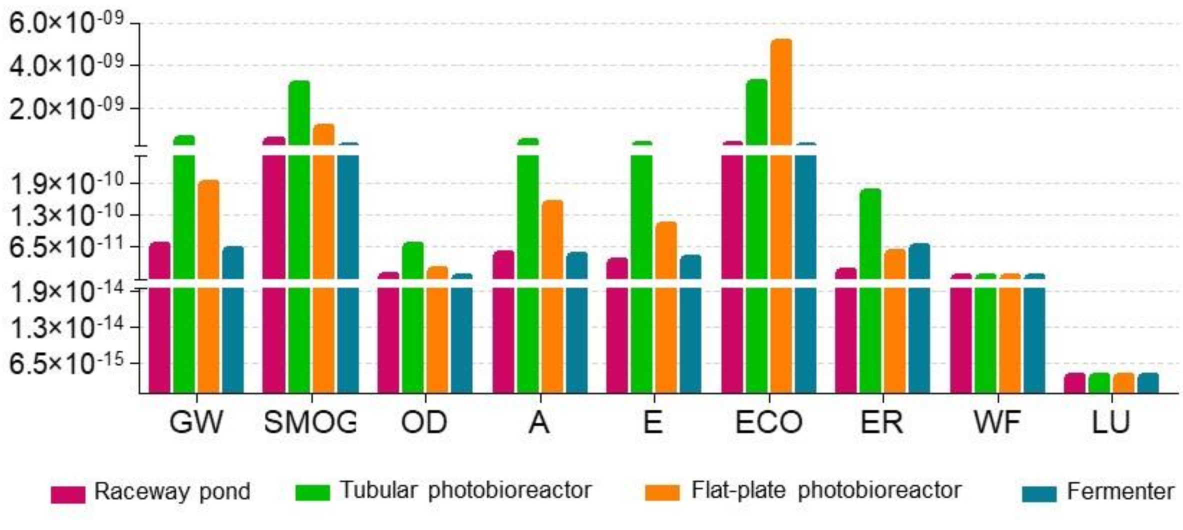
In addition, the analysis of the impact categories attributed to the flat plate photobioreactor indicated potential values of 1262.20 CTUe (ECO), 72.77 MJ (ER), 34.9 kgCO_2eq (GWP), and 1.0 kgO_3eq (SMOG). The hotspot recognized in these bioreactors is due to the aeration power of the culture mixture. This is due to the design of the system, which consists of a rectangular and narrow vertical reaction vessel. Its structure is individually designed, but for commercial operation, it is necessary to expand the number of plate units instead of increasing the volume of the reactor. Therefore, according to hydrodynamic principles, as the plates have a larger lateral area for a unit compared to a tubular photobioreactor, for example, aeration occurs mainly on the vertical axis, disadvantaging mixing on the horizontal axis. In this zone, the fluid flow pattern is lower, and the aeration is insufficient (Sierra et al., 2008). This results in increased shear force (can cause cell damage) and intense energy demand from the aerator source to maintain flow and a more homogeneous mixture. Generally, mixing is induced by high electrical capacity consumables, such as blowers, mechanical agitation using an impeller, static mixer or bubble aeration, or pumping of CO_2-enriched gas (Huang et al., 2017). Thus, adequate aeration strategies on the hardware are needed to minimize the effects of this engineering demand on the environmental impact.

The use of the fermenter for the cultivation of microalgae contributes to the following impacts: 68.43 CTUe (ECO), 92.02 MJ (ER), 10.48 kgCO_2eq (GWP), and 0.21 kgO_3eq (SMOG). Although this type of agitated tank bioreactor requires fewer elements throughout the process compared to a photobioreactor, the hottest point identified is that of sterilization, with an energy consumption of 7.22 kWh/m³. Second, aeration also contributes to the environmental load (1.0 kWh/m³). Under non-sterile conditions, the cultivation of heterotrophic microalgae is susceptible to contamination and competition with other microorganisms. Therefore, sterilization becomes essential at this stage of the process. This implies the implementation of a heat exchanger in the facility to obtain sufficient sterility and ensure productivity. However, in addition to being a lengthy operation, this additional equipment consumes a lot of energy due to the high heat demand. On a small scale, sterilization is possible because the volume of the bioreactor rarely exceeds 200 L. Still, it would be difficult for large quantities, as the equipment available for this purpose does not reflect a level of technological readiness for large-scale operations (Walls et al., 2019). At the same time, the energy associated with the aeration system, including the expense of the compressor with the additional expense of the airflow supply agitator, may even improve mass transfer, but contribute to the carbon footprint. The energy reduction of these demands can be achieved; however, careful selection of the impeller type, geometry, and size of the fermenter should be taken into account (Fitzpatrick et al., 2017).

3.2 NORMALIZATION

To facilitate the comparison and interpretation of results, and to understand the magnitude of environmental impacts, from uncertainties assessment perspectives, the normalization step was applied to our results, as shown in Figure 3.

Figure 3: Impact categories normalized data for the microalgae-based cultivation systems.



As can be seen in Figure 3, considering the integrity of the reference data sources used, among the nine categories evaluated for the cultivation system, four are considered to be the majority: ECO, SMOG, GWP, and ER. In contrast, the categories of AP, EP, and ODP have an impact that varies from intermediate to low, followed by the categories WF and LU. In this way, it can be inferred that these five minority categories are unlikely to contribute to the significant environmental impact.

The data normalization procedure indicates that the majority categories have a marked impact on the damage of the midpoint, linked to the deterioration of the resource base, that is, the high indirect demand for non-renewable primary energy resources. Second, the normalization of the other categories also indicates an impact associated with the extraction and consumption of energy resources, such as water and land, human health, and quality of the ecosystem. Under this assessment, among the evaluated cultivation systems, environmental charges were included in groups, with the major determining aspects being considered: (i) electricity consumption, (ii) nutrient production, (iii) water consumption, and (iv) demand land use and transformation.

From this, it is suggested that assessing the pros and cons of the cultivation system choice is crucial to introducing the technology and comparing it with a baseline option to verify whether there is a gap for future improvement. This is because the cultivation phase associated with the harvesting process is always the most impactful in microalgae cultivation processes (Sills et al., 2020). Therefore, to develop environmentally sustainable products, the algae industry needs to be aware of the environmental performance in order to obtain a holistic view of the critical points of the process, so that it can then apply optimization in the face of technical and economic challenges, and these, at last, will are overcome.

4 CONCLUSIONS

The strategy proposed in this study allowed the evaluation of metrics and sustainability indicators for microalgae-based cultivation systems. The results found indicated that the system with the greatest environmental impact prevails in the tubular photobioreactor, whereas the raceway pond presented the best environmental performance among the evaluated configurations. While we believe that these results provide an indication of the magnitude of the impacts caused by emissions from cultivation systems, we are aware that they are estimates based on experimental theoretical values, and consequently, it not perfect and cannot replace reliable statistics compiled in industrial practice. In this way, both the characterized results and the normalized data found in this study suggest visualizing the environmental impacts under the global context of sustainability indicators, in order to bring numerically values that can fill gaps for the implementation of processes based on microalgae.

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REFERENCES

Albarelli, J. Q., Santos, D. T., Ensinas, A. V., Marechal, F., Cocero, M. J., & Meireles, M. A. A. (2018). Product diversification in the sugarcane biorefinery through algae growth and supercritical CO2 extraction: Thermal and economic analysis. Renewable energy, 129, 776-785. DOI: 10.1016/j.renene.2017.05.022

Bhattacharya, M., & Goswami, S. (2020). Microalgae–A green multi-product biorefinery for future industrial prospects. Biocatalysis and Agricultural Biotechnology, 101580. DOI: 10.1016/j.bcab.2020.101580

Chiaramonti, D., Prussi, M., Casini, D., Tredici, M. R., Rodolfi, L., Bassi, N., ... & Bondioli, P. (2013). Review of energy balance in raceway ponds for microalgae cultivation: re-thinking a traditional system is possible. Applied Energy, 102, 101-111. DOI: 10.1016/j.apenergy.2012.07.040

Corona, B., Shen, L., Reike, D., Carreón, J. R., & Worrell, E. (2019). Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resources, Conservation and Recycling, 151, 104498.DOI: 10.1016/j.resconrec.2019.104498.

Cruce, J. R., Beattie, A., Chen, P., Quiroz, D., Somers, M., Compton, S., ... & Quinn, J. C. (2021). Driving toward sustainable algal fuels: A harmonization of techno-economic and life cycle assessments. Algal Research, 54, 102169. DOI: 10.1016/j.algal.2020.102169

Deprá, M. C., Mérida, L. G., de Menezes, C. R., Zepka, L. Q., & Jacob-Lopes, E. (2019). A new hybrid photobioreactor design for microalgae culture. Chemical Engineering Research and Design, 144, 1-10. DOI:10.1016/j.cherd.2019.01.023

Deprá, M. C., Severo, I. A., Dias, R. R., Zepka, L. Q., & Jacob-Lopes, E. (2021). Photobioreactor design for microalgae culture. In *Microalgae* (pp. 35-61). Academic Press. DOI: 10.1016/B978-0-12-821218-9.00002-5

Deprá, M. C., Severo, I. A., dos Santos, A. M., Zepka, L. Q., & Jacob-Lopes, E. (2020). Environmental impacts on commercial microalgae-based products: Sustainability metrics and indicators. Algal Research, 51, 102056. DOI: 10.1016/j.algal.2020.102056

Erbland, P., Caron, S., Peterson, M., & Alyokhin, A. (2020). Design and performance of a low-cost, automated, large-scale photobioreactor for microalgae production. Aquacultural Engineering, 90, 102103. DOI:10.1016/j.aquaeng.2020.102103

Fitzpatrick, J. J., de Lima, K. G., & Keller, E. (2017). Application of mathematical modelling for investigating oxygen transfer energy requirement and process design of an aerobic continuous stirred tank fermenter. Food and bioproducts processing, 103, 39-48. DOI: 10.1016/j.fbp.2017.02.009

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, 1, 1-126.

Hauschild, M. Z., Wenzel, H. (1998). Environmental Assessment of Products. Volume 2: Scientific Background. 1st edition, Springer US, 566p.

Heinrich, A. B. (2010). International reference life cycle data system handbook. The International Journal of Life Cycle Assessment, 15(5), 524-525.

Hoekstra, A. Y. (2016). A critique on the water-scarcity weighted water footprint in LCA. Ecological indicators, 66, 564-573. DOI: 10.1016/j.ecolind.2016.02.026

Huang, Q., Jiang, F., Wang, L., & Yang, C. (2017). Design of photobioreactors for mass cultivation of photosynthetic organisms. Engineering, 3(3), 318-329.DOI: 10.1016/J.ENG.2017.03.020

Hussain, F., Shah, S. Z., Ahmad, H., Abubshait, S. A., Abubshait, H. A., Laref, A., & Iqbal, M. (2021). Microalgae an ecofriendly and sustainable wastewater treatment option: Biomass application in biofuel and bio-fertilizer production. A review. *Renewable and Sustainable Energy Reviews*, *137*, 110603. DOI: 10.1016/j.rser.2020.110603

ISO (International Organization for Standardization), 2006. ISO 14040:2006(E) Environmental Management – Life Cycle Assessment – Principles and Framework.

Kirnev, P. C. S., Carvalho, J. C., Vandenberghe, L. P. S., Karp, S. G., & Soccol, C. R. (2020). Technological mapping and trends in photobioreactors for the production of microalgae. World Journal of Microbiology and Biotechnology, 36(3), 1-9.DOI: 10.1007/s11274-020-02819-0

Kumar, K., Mishra, S. K., Shrivastav, A., Park, M. S., & Yang, J. W. (2015). Recent trends in the mass cultivation of algae in raceway ponds. Renewable and Sustainable Energy Reviews, 51, 875-885. DOI: 10.1016/j.rser.2015.06.033

Kumar, L. R., Yellapu, S. K., Zhang, X., Tyagi, R. D. (2019). Energy balance for biodiesel production processes using microbial oil and scum. Bioresource technology, 272, 379-388. DOI: 10.1016/j.biortech.2018.10.071

Laratte, B., Guillaume, B., Kim, J., Birregah, B. (2014). Modeling cumulative effects in life cycle assessment: The case of fertilizer in wheat production contributing to the global warming potential. Science of The Total Environment, 481, 588-595. DOI: 10.1016/j.scitotenv.2014.02.020

Lathuillière, M. J., Miranda, E. J., Bulle, C., Couto, E. G., & Johnson, M. S. (2017). Land occupation and transformation impacts of soybean production in Southern Amazonia, Brazil. Journal of cleaner production, 149, 680-689. DOI: 10.1016/j.jclepro.2017.02.120

Lee, Y. K., Low, C. S. (1992). Productivity of outdoor algal cultures in enclosed tubular photobioreactor. Biotechnology and bioengineering, 40(9), 1119-1122. DOI: 10.1002/bit.260400917

Market Research Reports (2021). Algae Products Market by Type (Spirulina, Chlorella, Astaxanthin, Beta Carotene, and Hydrocolloids), Source (Brown Algae, Blue-Green Algae, Red Algae, and Green Algae), Form (Solid and Liquid), and Application (Food &

Beverages, Nutraceuticals & Dietary Supplements, Personal Care, Feed, Pharmaceuticals, Chemicals, and Fuel): Global Opportunity Analysis and Industry Forecast, 2018 – 2025. Accessed in January, 10th, 2021 <https://www.alliedmarketresearch.com/algae-products-market>

Maroneze, M. M., Deprá, M. C., Zepka, L. Q., & Jacob-Lopes, E. (2019). Artificial lighting strategies in photobioreactors for bioenergy production by Scenedesmus obliquus CPCC05. SN Applied Sciences, 1(12), 1-12. DOI: 10.1007/s42452-019-1761-0

Marsullo, M., Mian, A., Ensinas, A. V., Manente, G., Lazzaretto, A., & Marechal, F. (2015). Dynamic modeling of the microalgae cultivation phase for energy production in open raceway ponds and flat panel photobioreactors. Frontiers in Energy Research, 3, 41. DOI: 10.3389/fenrg.2015.00041

Molina, E., Fernández, J., Acién, F. G., & Chisti, Y. (2001). Tubular photobioreactor design for algal cultures. Journal of biotechnology, 92(2), 113-131.DOI: 10.1016/S0168-1656(01)00353-4

Nwoba, E. G., Parlevliet, D. A., Laird, D. W., Alameh, K., & Moheimani, N. R. (2019). Light management technologies for increasing algal photobioreactor efficiency. Algal research, 39, 101433. DOI: 10.1016/j.algal.2019.101433

Qin, C., & Wu, J. (2019). Influence of successive and independent arrangement of Kenics mixer units on light/dark cycle and energy consumption in a tubular microalgae photobioreactor. *Algal Research*, *37*, 17-29. DOI: 10.1016/j.algal.2018.09.020

Quinn, J. C., Yates, T., Douglas, N., Weyer, K., Butler, J., Bradley, T. H., & Lammers, P. J. (2012). Nannochloropsis production metrics in a scalable outdoor photobioreactor for commercial applications. Bioresource Technology, 117, 164-171. DOI: 10.1016/j.biortech.2012.04.073

Rahman, K. M. (2020). Food and High Value Products from Microalgae: Market Opportunities and Challenges. In Microalgae Biotechnology for Food, Health and High Value Products (pp. 3-27). Springer, Singapore. DOI: 10.1007/978-981-15-0169-2_1

Ramírez-Mérida, L. G. R., Zepka, L. Q., & Jacob-Lopes, E. (2017). Current production of microalgae at industrial scale. Recent advances in renewable energy, 242-260.

Santos, A. M., Deprá, M. C., Cichoski, A. J., Zepka, L. Q., & Jacob-Lopes, E. (2020). Sustainability metrics on microalgae-based wastewater treatment system. Desalin. Water Treat., 185, 51-61. DOI: 10.5004/dwt.2020.25397

Sierra, E., Acién, F. G., Fernández, J. M., García, J. L., González, C., & Molina, E. (2008). Characterization of a flat plate photobioreactor for the production of microalgae. Chemical Engineering Journal, 138(1-3), 136-147. DOI: 10.1016/j.cej.2007.06.004

Sills, D. L., Van Doren, L. G., Beal, C., & Raynor, E. (2020). The effect of functional unit and co-product handling methods on life cycle assessment of an algal biorefinery. Algal Research, 46, 101770. DOI: 10.1016/j.algal.2019.101770

Tang, D. Y. Y., Khoo, K. S., Chew, K. W., Tao, Y., Ho, S. H., & Show, P. L. (2020). Potential utilization of bioproducts from microalgae for the quality enhancement of natural products. Bioresource Technology, 304, 122997. DOI: 1016/j.biortech.2020.122997

Tua, C., Ficara, E., Mezzanotte, V., & Rigamonti, L. (2021). Integration of a side-stream microalgae process into a municipal wastewater treatment plant: A life cycle analysis. Journal of Environmental Management, 279, 111605. DOI: 10.1016/j.jenvman.2020.111605

Walls, L. E., Velasquez-Orta, S. B., Romero-Frasca, E., Leary, P., Noguez, I. Y., & Ledesma, M. T. O. (2019). Non-sterile heterotrophic cultivation of native wastewater yeast and microalgae for integrated municipal wastewater treatment and bioethanol production. Biochemical Engineering Journal, 151, 107319. DOI: 10.1016/j.bej.2019.107319