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Environmental impact assessment in microalgal lipid production: carbon footprint and net emissions

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Abstract: This study focuses on analyzing the role of microalgae in mitigating climate change through CO_2 capture and lipid production, which can be used in the development of energy products and commercially relevant products. The aim of this research was to assess the net CO_2 emissions associated with three lipid production scenarios from microalgae, in addition to analyzing the impact of various biomass pretreatment technologies before lipid extraction. For this purpose, only the emissions directly generated by energy consumption in the process and the amount of CO_2 that can be captured by microalgae cultivation were considered. In all three scenarios, CO_2 capture during biomass cultivation and emissions associated with maintaining the process in operation were evaluated. The results show that the emissions generated by energy consumption were 3.56 kg CO_2/kg oil, 2.19 kg CO_2/kg oil, and 2.36 kg CO_2/kg oil in scenarios 1, 2, and 3, respectively, whereas the CO_2 emissions captured in microalgae cultivation were three to four times higher, ultimately resulting in negative emissions in all scenarios. The efficiency of CO_2 capture per kilogram of oil produced varies between scenarios, suggesting that the choice of technology and process conditions significantly influence the overall environmental impact. This analysis identifies areas of opportunity to improve microalgal biomass utilization processes, highlighting the stages of the process with the greatest impact on the carbon footprint and enabling the comparison of different technologies on the same basis.

Keywords: microalgae; lipids; carbon footprint; CO_2 emissions.

Introduction

Climate change is one of the major global threats with significant long-term consequences, as it is linked to rising sea levels, increased greenhouse gas (GHGs) concentrations, and increasingly severe and widespread heatwaves (Alishah Aratboni *et al*., 2019). Reducing carbon dioxide (CO_2) emissions and capturing them are essential to counteract this phenomenon. In this context, microalgae have emerged as a promising alternative for CO_2 capture systems due to their ability to transform carbon dioxide into biomass (Baral *et al*., 2015).

Microalgae have the capacity to capture up to 1.8 kg of CO_2 per kilogram of biomass produced (Cheah *et al*., 2015). Microalgae cultivated in open and closed systems could, in theoretical terms, convert 513 tons of CO_2 into 280 tons dry biomass per hectare per year, utilizing approximately 9% of light energy to sequester this gas (Zhou *et al*., 2022). *Chlorella* is characterized by its ability to grow in a gas atmosphere containing up to 40% (v/v) CO_2, with a fixation rate ranging from 0.73 to 2.22 g/L/day (Brennan *et al*., 2010). Although it is not the only species capable of capturing CO_2, it is one of the most widely used and studied for this purpose (Brennan *et al*., 2010).

Conversely, humanity faces two critical challenges: environmental pollution and energy crisis (Valdovinos-García *et al*., 2020). This is mainly due to the use of fossil fuels, since their combustion contributes to environmental problems by emitting GHGs such as CO_2, nitrogen oxides (NOx), sulfur oxides (SOx), unburned hydrocarbons, and ash (Clemente *et al*., 2009). To address this issue, a potential solution involves the production and use of biodiesel from microalgae, thereby reducing the consumption of energy derived from fossil sources. It has been reported that microalgal biomass provides high yields for bio-oil production (e.g., 59 m^3/ha/year, (Lee *et al*., 2012)). Most known microalgal species store fatty acids, triglycerides, and glycolipids intracellularly. This intracellular storage requires lipid extraction processes that increase biodiesel production costs (Lee *et al*., 2012).

Previously, the design of a chemical or industrial process primarily considered technical and economic criteria, often neglecting the environmental impact associated with the process (Julio *et al*., 2017; Loayza *et al*., 2013). Currently, there is substantial interest in sustainability driven by factors such as population growth, industrialization, depletion of natural resources, increasing consumption of non-renewable resources, and climate change. Responsible processes could prevent environmental problems related to their industrial activities by implementing clean and safe processes that minimize environmental issues, without compromising complexity (Loayza *et al*., 2013); this approach is a fundamental component of sustainable development. Assessing the sustainability of a process or product is founded on the measurement and analysis of indicators across multiple dimensions: environmental, economic, and social (El-Halwagi, 2012).

The carbon footprint is an environmental indicator that allows us to assess the GHGs emissions produced by an activity throughout its life cycle for a specific product, process, or service, and is usually expressed in tons of CO_2 equivalents (tCO_2e) (Guallasamin *et al*., 2018). This indicator reflects the environmental impact, indicating how much it affects living beings and potentially causes health damage and disrupts natural processes; a higher value of this indicator implies a more harmful effect. Although the calculation of the carbon footprint is increasingly common, the measures taken to reduce it have not been sufficient; on the contrary, it continues to rise (Garza-Galicia *et al*., 2021). This analysis supports the development of new processes as it allows for the identification and evaluation of opportunities to implement environmental improvements in the process (Julio *et al*., 2017).

Carbon capture through microalgae, along with the potential for bio-oil production from their biomass, represents highly promising strategies for mitigating atmospheric CO_2 concentrations. Nevertheless, it is crucial to recognize that the proposed process requires energy for its operation. Therefore, it is necessary to assess whether the CO_2 emissions produced from this energy consumption exceed or are less than the emissions that can be captured during biomass cultivation. In this context, the objective of this study was to evaluate the net CO_2 emissions in three lipid production scenarios proposed by (Valdovinos-García *et al*., 2022) and to analyze the impact of various biomass pretreatment technologies before lipid extraction. For the carbon footprint assessment of the scenarios, only emissions directly generated by energy consumption in the process were considered. Additionally, in all three processes, net CO_2 emissions are evaluated by considering CO_2 capture during the biomass cultivation stage and the emissions generated during the process to maintain its operation.

Materials and Methods

The processes analyzed in this study were taken from the work published by Valdovinos-García *et al*. (2022). These processes consider various technologies at different stages of lipid production from microalgal biomass and evaluate the impact on energy consumption and the operational cost. Three scenarios were selected, where only the biomass pretreatment technology before oil extraction varies. These three scenarios were chosen because they are reported to have the lowest unit production costs and the lowest energy consumption for dry biomass production (Valdovinos-García *et al*., 2020).

Description of the Scenarios to be Evaluated

The three process scenarios considered for this study include: the cultivation stage in an open system, specifically in a raceway pond (Technology A); the biomass collection (first harvest) is carried out through flocculation by increasing the pH with NaOH and sedimentation (Technology B); and subsequently, the secondary harvest is performed using filtration with filter presses (Technology C). At this stage, the biomass is collected but still contains 80% (w/w) moisture. All scenarios employ the same technologies for these stages of the process. After this stage, oil extraction is performed, where the technology changes to define the three scenarios considered.

To facilitate oil extraction, some researchers recommend performing a cell disruption of the microalgal biomass followed by the use of various extraction methods, a stage referred to as pretreatment (Valdovinos-García *et al*., 2022). Scenarios 1 and 2 consider the use of wet biomass for the cell disruption stage (pretreatment). Scenario 1 employs bead milling technology (Technology E1), while Scenario 2 uses high-pressure homogenization (HPH, Technology E2). These two technologies require the biomass to have a high moisture content, and following this pretreatment stage, solvent extraction is performed (Valdovinos-García *et al*,. 2022). Scenario 3 does not include a pretreatment stage; instead, oil extraction is conducted directly using pressing technology (Technology E3). However, for this stage to be carried out efficiently, the biomass must be completely dry. Therefore, when this technology is used, Scenario 3 requires an additional drying stage (Technology D) after the secondary harvest, followed by pressing of the biomass (Technology E3). Figure 1 illustrates the block diagram of the different stages involved in the process and how each scenario is formed. The flowsheets for the simulation of the three analyzed scenarios can be found in (Valdovinos-García *et al*., 2022).

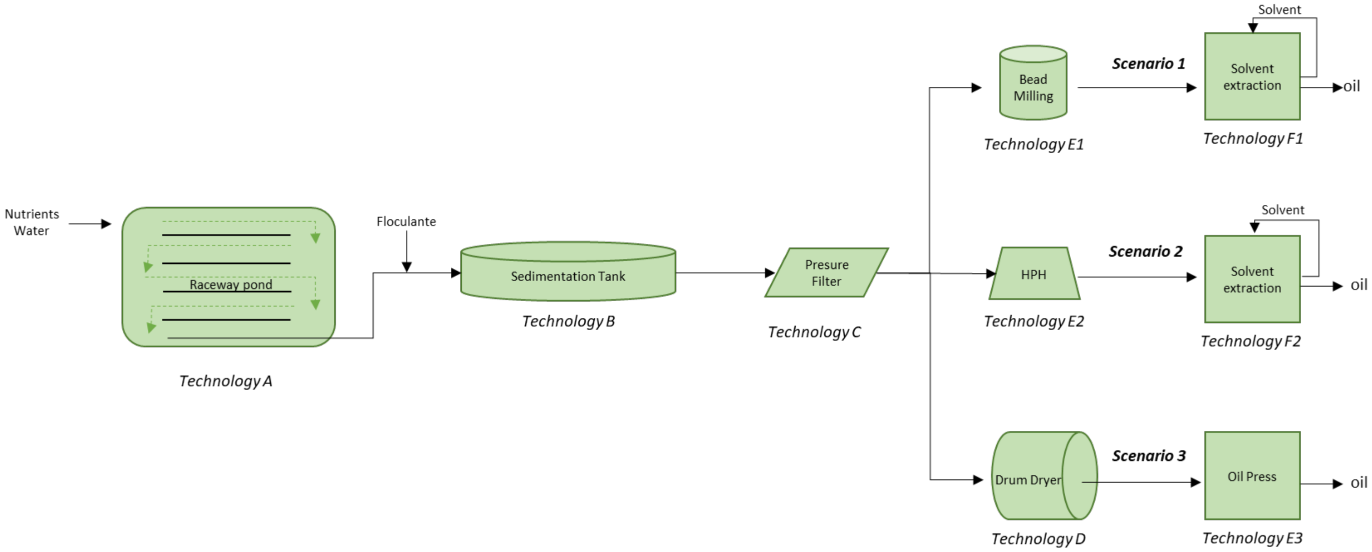

Figure 1. Stages of the lipid production process and the scenarios analyzed.

Carbon Footprint Assessment

The carbon footprint assessment employed the GHGs Protocol developed by the World Business Council for Sustainable Development (WBCSD), the World Resources Institute (WRI), and the Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT) (WRI & WBCSD, 2019). The protocol is based on establishing boundaries for calculating and quantifying emissions across three different scopes: 1) direct GHGs emissions, 2) indirect GHGs emissions associated with electricity consumption, and 3) other indirect emissions (Sandoval Gavira *et al*., 2021; WRI & WBCSD, 2019). For this study, only the energy consumption of the processes was considered, meaning that only Scope 2 indirect emissions were evaluated. This is because the processes considered differ only in the biomass pretreatment technology, and no additional chemicals are added during these stages; rather, only the technology is modified, affecting energy consumption and oil extraction efficiency. The study's boundaries encompass only the scenarios from the biomass cultivation stage to the final microalgal oil production.

The calculation of the carbon footprint was performed using documented emission factors. It is important to note that these factors are calculated ratios that relate GHGs emissions to a measure of activity from a source of emissions. The following equation allows for the calculation of emissions in CO_2 equivalents:

$$GHG\ emissions = \mathrm{A} * \ \mathrm{FE} * \left(1 - \frac{ER}{100}\right) \tag{1}$$

Where A is the activity rate, expressed in kWh/year for this study; FE is the emission factor, and ER is the emission reduction efficiency of a control device. For this study, ER is 0 since no emission controls are present. The emission factor is a representative value that relates the amount of a pollutant to an activity associated with the release of that pollutant. Since only energy consumption is considered for the carbon footprint calculation, the emission factor for energy generated from the burning of thermal coal at the Presidente Plutarco Elías Calles Thermoelectric Plant, located in La Unión, Guerrero, México, was used, as it is one of the highest CO_2 emitting power plants in the country, Fe = 111,408.76 kg CO_2/TJ; the FE value was obtained from (INECC, 2014). The energy consumption for each stage of the process is shown in Table 1 and was taken from the report by Valdovinos-García *et al*. (2022).

According to the reports by Valdovinos-García *et al*. (2020, 2022) all the scenarios considered in this study established 1 ha as the cultivation area. Mass and energy balances were modeled considering a biomass productivity of 12.71 g/m^2/day. The algal concentration obtained at the pond exit was 0.9 g/L (considering a retention time of 12 days). For biomass cultivation, an aeration system was used at 0.03 vvm, mixed with the combustion gases from a thermoelectric plant, with a typical composition of 11% v/v CO_2. The selected microalgal species, Chlorella vulgaris, is capable of capturing 46% w/w of the supplied CO_2, allowing for the fixation of 1.83 kg of CO_2 per kg of biomass produced. All scenarios were analyzed under continuous operation mode, for 330 days per year.

Table 1. Energy consumption by technology (Activity Rate) (Valdovinos-García *et al*,. 2022).

Technologies	**Energy consumption (kWh/year)**
A	38,575
B	5,837
C	963
D	1,497
E1	34,650
E2	8,331
E3	6,633
F1	6,644
F2	6,647
Scenario 1	86,669
Scenario 2	60,371
Scenario 3	53,495

Quantifying net emissions by microalgae cultivation and oil production systems

Another objective of this study is to evaluate the net amount of emissions captured or emitted in microalgae cultivation systems and their utilization. Specifically, it aims to assess the emissions captured during the cultivation phase by the microalgae and the emissions released throughout the cultivation and utilization of microalgal biomass. Valdovinos-García *et al*., 2022, reported that in the open cultivation system considered in all the scenarios analyzed in this study, with a productivity of 12.71 g/m²/day, a CO_2 capture of 102.13 tCO_2/year can be achieved per hectare of cultivation area. According to the reports by Valdovinos-García *et al*. (2022) the scenarios 1, 2 and 3 produce 9,749.70 kg of lipids/year, 11,049.82 kg of lipids/year and 9,089.95 respectively. Based on this data, the amount of CO_2 captured per kg of oil produced in all scenarios was determined, as well as the net emissions. To calculate the net emissions for each scenario, the following equation was used:

$$Net\ emissions = CO_2\ emissions - \ CO_2\ capture \quad \textbf{(2)}$$

Where CO_2 emissions refer to the emissions generated in each scenario from energy consumption required to maintain the operation of the process, and carbon capture refers to the amount of CO_2 that can be captured by the microalgae during the cultivation stage of each scenario.

Results and Discussion

The results of the carbon footprint assessment are shown in Table 2, for both individual technologies and the analyzed process scenarios. Figures 2 and 3 show the analysis of the results. Figure 2 illustrates that not all scenarios emit the same amount of CO_2, with Scenario 1 showing the highest emissions and Scenario 3 the lowest.

The highest amount of CO_2 emissions is attributed to the cultivation stage (Technology A) across all scenarios. This stage is identical in all scenarios and emits 15.468 tCO_2/year; this amount represents 44.5%, 63.89%, and 72.10% of the total emissions for Scenarios 1, 2, and 3, respectively (Figure 3). The primary harvest stage (Technology B) and the secondary harvest stage (Technology C) emit 2.34 and 0.38 tCO_2/year, respectively. These emissions account for 6.7% to 9.6% of the primary harvest in all scenarios, while the secondary harvest ranges from 1% to 2%. Scenario 3 is the only one that includes the biomass drying stage (Technology D), which emits 0.60 tCO_2/year and represents 2.8% of the total emissions for this scenario.

Table 2. Carbon Footprint Assessment Results.

Technology	**Activity rate (kWh/year)**	**Emission factor (tCO_2/kWh)**	**Emission (tCO_2/year)**	**Emission (kg CO_2/kg oil)**
A	38,575	$4.01*10^{-4}$	15.468	
B	5,837	$4.01*10^{-4}$	2.340	
C	963	$4.01*10^{-4}$	0.386	
D	1,497	$4.01*10^{-4}$	0.600	
E1	34,650	$4.01*10^{-4}$	13.894	
E2	8,331	$4.01*10^{-4}$	3.340	
E3	6,633	$4.01*10^{-4}$	2.659	
F1	6,644	$4.01*10^{-4}$	2.664	
F2	6,647	$4.01*10^{-4}$	2.665	
Scenario 1	86,669	$4.01*10^{-4}$	34.754	3.56
Scenario 2	60,371	$4.01*10^{-4}$	24.208	2.19
Scenario 3	53,495	$4.01*10^{-4}$	21.451	2.36

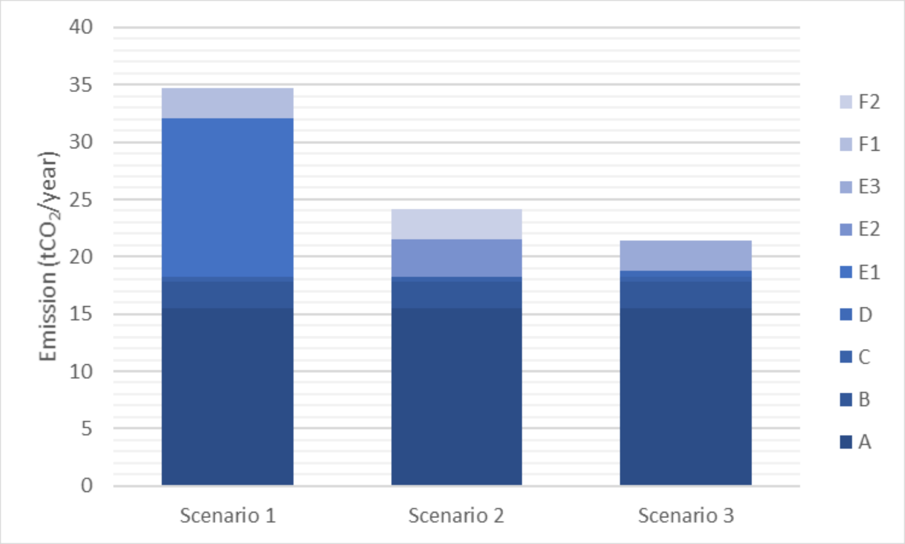

Figure 2. Emissions by process stage.

Two methods were proposed for oil extraction, using either wet or dry biomass. Scenarios 1 and 2 require wet biomass for cell disruption (pretreatment stage), with bead milling (Technology E1) and high-pressure homogenization (HPH, Technology E2) being considered. Technologies E1 and E2 emit 13.90 tCO_2/year and 3.34 tCO_2/year, respectively. Table 2 illustrates that the result obtained from E2 technology is roughly four times greater than the results from E1. For Scenario 1, the pretreatment technology (E1) accounts for 40% of the total emissions for this scenario, while in Scenario 2, pretreatment contributes only 13.8% of the total emissions (Figure 3). This substantial difference is primarily due to the high energy consumption of bead milling technology; this technique requires constant agitation to achieve cell disruption, which generates excessive heat, necessitating a robust cooling system and consequently increasing energy consumption significantly. Despite this, bead milling technology is widely used industrially (Valdovinos-García *et al*., 2022). On the other hand, HPH technology is also highly energy-intensive, ranging from 0.25 to 147 kWh/kg of treated biomass. However, its energy consumption is related to the pressure required for cell disruption and the number of passes the sample makes through the equipment. For this case, a single pass and a pressure of 100 MPa were considered (Valdovinos-García *et al*., 2022).

In Scenario 3, the pressing technology directly from biomass for lipid extraction emits only 2.70 tCO_2/year, representing 12.40% of the total process emissions (Figure 3). Unlike the other two scenarios, Scenario 3 does not require an additional stage to complete the oil extraction. However, the extraction yield is lower with this technology. In Scenarios

1 and 2, an additional stage is necessary for separating the oil from the aqueous phase, which requires solvent extraction (Valdovinos-García *et al*., 2022). It can be observed that CO_2 emissions during solvent extraction for Scenarios 1 and 2 are the same, as the energy consumption is similar in both cases. This stage of the process emits 2.66 tCO_2/year, representing 7.66% and 11% of the total emissions for Scenarios 1 and 2, respectively (Figure 3).

Regarding the total emissions per scenario, Scenario 1 results in 34.80 tCO_2/year, Scenario 2 results in 24.20 tCO_2/year, and Scenario 3 results in 21.45 tCO_2/year. Although it might seem that adding a drying stage to the oil extraction process would increase total energy consumption and, consequently, CO_2 emissions, this is not the case. Scenario 1 emits 62% more CO_2 compared to Scenario 3, primarily due to the high energy consumption associated with the bead milling pretreatment technology (Technology E1). Meanwhile, Scenario 2 emits only 12.8% more CO_2 than Scenario 3.

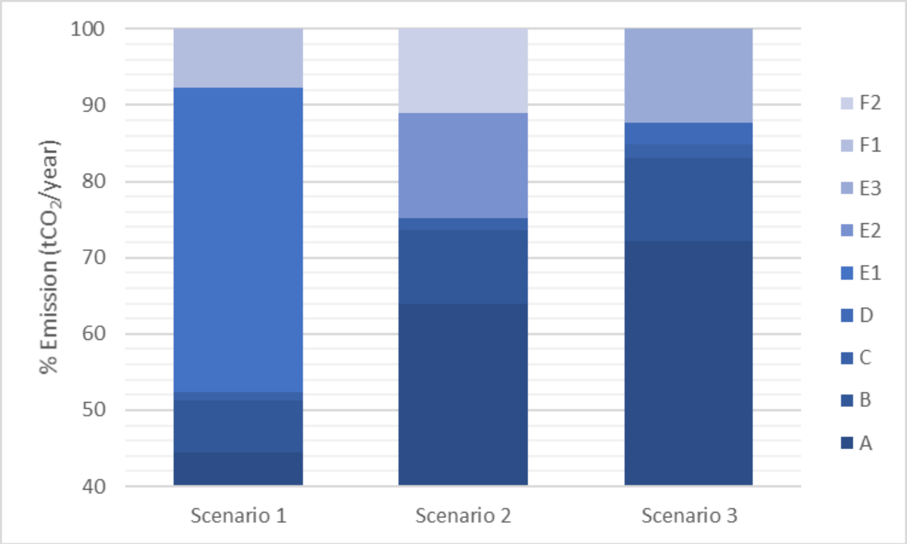

Figure 3. Percentage distribution of emissions by process stage.

For a better comparison between scenarios, CO_2 emissions per kilogram of oil produced were determined. For Scenario 1, emissions are 3.56 kg CO_2/kg oil; for Scenario 2, 2.19 kg CO_2/kg oil; and for Scenario 3, 2.36 kg CO_2/kg oil. As observed, Scenario 3 is not the lowest emitter of CO_2 per functional unit (1 kg oil), despite having significantly lower total emissions compared to the other oil production scenarios. This is because the extraction of dry biomass via pressing is less energy-intensive, but the oil extraction efficiency is lower for this scenario (Valdovinos-García *et al*., 2022). The efficiency of CO_2 capture per kilogram of oil produced varies across scenarios, suggesting that the choice of technology and process conditions significantly influence the overall environmental impact.

Alcock *et al*., (2022) conducted a study to assess the variation in global GHGs emissions resulting from the production of palm, soybean, rapeseed, and sunflower oils. Their results indicate that the average total emissions were 3.81 kg CO_2e/kg oil for all crops, with emissions of 3.73 kg CO_2e/kg oil for palm oil, 4.25 kg CO_2e/kg oil for soybean oil, 2.49 kg CO_2e/kg oil for rapeseed oil, and 2.94 kg CO_2e/kg oil for sunflower oil. As observed, the emissions for all oil production processes presented by Alcock *et al*. (2022) are comparable to those calculated in this study for microalgal oil production. Alcock *et al*., (2022) note that land use for cultivation accounts for more than 50% of emissions for soybean, rapeseed, and sunflower oil production, while land use represents 39.5% of total emissions for palm oil production. Land use is the dominant source of GHGs emissions in all cases where the crop requires fertile land for growth. This source of emissions is not reflected in the emissions for microalgal cultivation for oil production. Microalgal biomass has an advantage as it does not belong to edible crops and does not compete for arable or forest land, as it does not require fertile land for cultivation, thereby ensuring food security and land use (Ahmad *et al*., 2011; Brennan *et al*., 2010; Huang *et al*., 2010; Raheem *et al*., 2018).

Bioenergy can play a significant role as an option for reducing GHGs emissions from this sector; however, several considerations must be addressed, such as food security, land use, minimal water resources, air quality improvement (e.g., CO_2 sequestration), and biodiversity conservation (Brennan *et al*., 2010). For several years, the scientific community has highlighted that the best options for bioenergy production are those that generate low GHGs emissions over their lifecycle, such as rapidly growing biomass and the sustainable use of biomass residues. The outcomes vary and largely depend on the efficient integration of biomass conversion systems and the sustainable management and governance of land use (Core *et al*., 2014; IPCC, 2014). Additionally, it is unlikely that agricultural biomass production can meet the demand, creating an urgent need for new sources of biomass that do not compete with agriculture (Vandamme *et al*., 2013). Furthermore, it is important to note that microalgal biomass is not only an energy source but also provides a wide range of organic chemicals.

Net emissions captured by microalgae cultivation and oil production systems

As observed (Table 3), all scenarios capture more CO_2 than is emitted during the cultivation and utilization of microalgal biomass. Based on these results, Scenario 3 is identified as the one with the highest net CO_2 absorption by the system. Conversely, when considering only the emissions generated from energy consumption, Scenario 2 has the lowest atmospheric emissions. However, in Scenario 2, the amount of CO_2 captured per kilogram of oil produced is lower compared to the other two scenarios.

Table 3. Carbon footprint and net emissions results.

Scenario	Capture through biomass cultivation (kg CO_2/kg oil)	Emission from energy consumption (kg CO_2/kg oil)	Net emissions (kg CO_2/kg oil)
Scenario 1	10.475	3.56	- 6.91
Scenario 2	9.242	2.19	- 7.05
Scenario 3	11.235	2.36	- 8.88

These results indicate that, although the process involves technologies with high energy consumption, CO_2 capture remains greater due to the cultivation of microalgae. This demonstrates that microalgae have significant potential to be used as CO_2 capture systems while simultaneously utilizing their biomass to produce commercially valuable compounds on an industrial scale.

Energy production or valuable products from microalgae biomass is an example of circular bioeconomy, as CO_2 emissions can be utilized as carbon sources for biomass production, contributing to the mitigation of greenhouse gas (GHG) emissions. Power plants, one of the industries with the highest impact in terms of CO_2 emissions, could consider installing a microalgae cultivation facility on-site or nearby to utilize their gaseous effluents. On the other hand, the resulting biomass, rich in carbohydrates, lipids, and proteins, could serve as feedstock for the production of biofuels, biolubricant oils, and other valuable by-products, which can be either consumed on-site or commercialized. These factors increase the interest in cultivating microalgae as a raw material for obtaining valuable products, providing alternative methods for the utilization of CO_2 emitted by power plants. Additionally, the use of process simulation tools allowed us to save time, gain a deeper understanding of the functionality of each piece of equipment involved in the different stages of the process, and identify the key variables for design and the potential industrial application of these processes.

Conclusions

It was determined that all analyzed scenarios capture more CO_2 than is emitted from energy consumption required to operate the process. The emissions for each scenario are 3.56 kg CO_2/kg oil for Scenario 1, 2.19 kg CO_2/kg oil for Scenario 2, and 2.36 kg CO_2/kg oil for Scenario 3. This analysis identified areas of opportunity in the development of processes for utilizing microalgal biomass. Specifically, it highlighted the stages of the process with the greatest impact on the carbon footprint and enabled a comparison of different production scenarios involving various technologies on a uniform basis.

Author contributions: S.P.-de la C. and B.A.A.-P.: data collection, writing, editing analysis and interpretation; M.A.P.-P. and E.M.V.-G.: Conceptualization, data analysis, interpretation, editing, administration and project supervision.

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