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Evaluation of Technical and Economic Indicators for the Production Process of Microalgae Lipids Considering CO_2 Capture of a Thermoelectric Plant and Use of Piggery Wastewater

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Abstract: Microalgae are highly studied microorganisms for the production of high-value products due to their high content of proteins, lipids, carbohydrates, and chlorophyll. These compounds are refined to obtain profitable industrial products. This article analyzes the lipid production of *Chlorella* sp. biomass, considering 18 scenarios for its production, with 9 of these being partially supplemented with swine wastewater. A 1 ha area was considered for biomass cultivation, primary and secondary biomass harvesting, and lipid extraction. Using simulation in the software SuperPro Designer v10, parameters such as CO_2 capture (from a thermoelectric power plant), freshwater consumption, wastewater consumption, energy consumption, and unit production cost were evaluated. The results show that the production cost is high, ranging from 836.9 US $/kg to 1131.5 US $/kg of produced lipids, with a maximum CO_2 capture of 454 kg of CO_2/kg of lipids. The use of wastewater reduces the production cost by approximately 10%. The evaluation of technical and economic parameters allows us to identify bottlenecks and implement strategies to reduce production costs.

Keywords: techno-economic; *Chlorella* sp.; lipid; simulation; biorefinery

Citation: Valdovinos-García, E.M.; Cabrera-Capetillo, C.A.; Bravo-Sánchez, M.G.; Barajas-Fernández, J.; Olán-Acosta, M.d.l.Á.; Petriz-Prieto, M.A. Evaluation of Technical and Economic Indicators for the Production Process of Microalgae Lipids Considering CO_2 Capture of a Thermoelectric Plant and Use of Piggery Wastewater. *Energies* **2024**, *17*, 92. https://doi.org/10.3390/en17010092

Academic Editors: Leonidas Matsakas and Dimitrios Sidiras

Received: 17 November 2023
Revised: 17 December 2023
Accepted: 19 December 2023
Published: 22 December 2023

1. Introduction

Microalgae are used in various areas of commercial and research interest [1] due to their high biotechnological potential and the generation of products with high added value. Every part of their composition, such as proteins, carbohydrates, lipids, pigments, and biomass, has been studied and utilized [2,3]. The diverse industrial applications of microalgae are found in the chemical, pharmaceutical, cosmetics, bioremediation, dietary supplements, conventional food, biofuel, feed, and fertilizer fields [1,4].

All the valuable components of microalgae have been manipulated to develop refined products for various applications. However, lipids have been the most extensively studied for the production of biodiesel [5]. When lipids are refined using transesterification processes, they have the potential to be transformed into alternative fuels like biodiesel, bioethanol, glycerol, and biobutanol, among others [6,7]. Microalgae can be subjected to specific cultivation conditions that promote lipid production, such as heterotrophic cultivation [8]. In microalgal biomass, these lipids range from 2% to as high as 84% (wt)

of the composition, with the species *Chlorella ellipsoidea* having the highest reported concentration, as documented by Menetrez M. in 2012 [9] and reaffirmed by Babi et al. in 2022 [10]. Microalgal lipids are considered low-value products since their common use is for conversion into biodiesel, and biodiesel production still does not economically compete with petroleum-derived diesel. This represents one of the significant limitations for the development of cost-effective processes and technologies for algae-derived biodiesel production [11,12]. However, there are other uses for this product, such as its use as a base for biolubricants, biopolymers, dietary supplements, etc. [13]. From microalgae, we obtain two types of lipids: polar and nonpolar. Nonpolar lipids are the primary ones used for biofuel production, as they represent stored forms of fats, also known as neutral fats [10].

Another intracellular product of microalgae of significant value is proteins. These proteins have many applications in the medical field (vaccines, antibodies, recombinant proteins) and in the field of nutrition (supplements, human nutrition). From them, we can obtain amino acids, polypeptides, and enzymes [14]. The amount of proteins varies in each species of evaluated microalgae, with a range from 4% to as high as 58% of composition (%wt), with *Chlorella vulgaris* having the highest protein concentration [10]. Pigments, as the main product, are used in the cosmetic, food, and human nutrition industries, as chlorophyll, carotenoids, and phycobilins can be extracted from them [15]. The production of chlorophyll depends on various factors such as the growth type, reactor type, environmental conditions, and photosynthetic activity [3]. As for carbohydrates, which include monosaccharides and polysaccharides [12,15], their composition ranges from 4% to 53% depending on the type of microalga, with *Chlorella vulgaris* once again having the highest carbohydrate concentration [10].

For the study of microalgae-based biorefineries, three main stages must be considered, starting with the growth conditions of microalgae and biomass production, then progressing to the extraction of lipids and other compounds of interest, and finally, the processing methods of the extracted products into commercially viable products [16,17]. One of the current approaches to the use of microalgal lipids is for biodiesel production, which offers several advantages over petrodiesel, including a sulfur content of 0%, lower levels of CO_2, CO, unburned hydrocarbons (HC), reduced particulate emissions, and a higher oxygen concentration, allowing for complete combustion [18]. However, it has been reported that it currently does not match the economic competitiveness of petrodiesel [19]. Currently, research on biofuel and other products derived from microalgae must take into account economic analysis, technical analysis, energy effects, and environmental effects [20].

The contribution of microalgae to the green bioeconomy requires the sustainable production of microalgal biomass, environmental protection, the reduction in resource waste, and the use of green technologies during processing steps [21]. This includes the use of culture media supplemented with wastewater in the early stages of cultivation for microalgal biomass production, which significantly reduces the production costs of lipids [22] and other derivatives.

When obtaining high-value-added products for the industry, it's crucial to consider all process variables, and this depends on the research focus [23]. The most challenging issues for the microalgae industry include high installation and operational costs, difficulty in controlling cultivation conditions, synergy with bacteria, energy supply, and weather conditions [24], as well as determining the appropriate technologies to achieve the desired outcome in the process.

Numerous investigations have been carried out related to the proposal and evaluation of processes aimed at lipid production from microalgae biomass. Some of these investigations are laboratory-scale proposals and do not include a techno-economic evaluation, while others aim to assess both the technical and economic aspects of a specific procedure, although they incorporate particular technologies for the purpose investigated [25,26]. This has given rise to various process scenarios under different conditions, which makes their comparison difficult and restricts their applicability to other contexts. There are few investigations that address the comparison of multiple technologies in the same study and that

generate various process scenarios or that include all stages of the process in the evaluation (that is, from the cultivation stage, biomass harvest, and lipid extraction). By comparing and evaluating various technologies involved in the different stages of the process, a wide range of scenarios is obtained that highlight the techno-economic potential of lipid production from microalgal biomass. Each scenario could have different objectives since, in most cases, the choice of technology is conditioned by the intended end use of the biomass and lipids. A study with these characteristics would give us the opportunity to analyze and compare various technological options for the extraction of lipids from microalgae, with possible diverse applications depending on the technological route selected.

On the other hand, the concept of circular economy involves the exchange of waste and/or products between different industries with the purpose of using resources efficiently and minimizing the generation of waste. Furthermore, one of the most significant challenges for the global industry is to rely on renewable sources, adopt a long-term perspective, and meet sustainability requirements. Hence, arises the motivation of this research, which seeks to evaluate the production of microalgal lipids, including the cultivation stage, biomass harvest, and extraction, as well as including the capture of CO_2 from the combustion gases of a thermoelectric plant and the use of wastewater as a source of nutrients in the biomass cultivation stage.

Therefore, in this paper, a techno-economic analysis of lipid production from the microalga *Chlorella* sp. is conducted, considering cultivation in a closed system (tubular photobioreactor) and the use of wastewater as a partial nutrient source. Additionally, the capture of CO_2 in biomass cultivation and the technical and economic impact of various technologies for the final lipid extraction were evaluated. The assessment was carried out by simulating production scenarios using the SuperPro Designer v10® software for the entire process, encompassing all stages from cultivation to lipid extraction. The software performs material and energy balances, as well as an evaluation of operating and production costs. This provides valuable insights into the economic and environmental impacts of the process and offers essential information for the development of an efficient microalgae-based biorefinery process.

2. Materials and Methods

Various lipid production scenarios from *Chlorella* sp. microalgal biomass were established and evaluated in continuous operation mode. These scenarios were created by combining microalgal precultivation, horizontal tubular photobioreactor biomass production, biomass harvesting, biomass pretreatment, and lipid extraction, as depicted in Figure 1. The aim of these scenarios was to assess the energy and economic impact of various biomass pretreatment technologies from closed system cultivation, as well as to evaluate the impact of using wastewater in biomass cultivation and capturing CO_2 from a thermal power plant. This study was based on data reported in the literature and only considered technologies with the potential for pilot or industrial-scale use. One of the most significant challenges in this research was gathering the necessary data for simulating the models of the various lipid production scenarios from microalgae, ultimately enabling a comparison of the generated scenarios.

2.1. Description of Microalgae Lipid Production Scenarios

For the cultivation stage, a closed system was considered, consisting of a series of horizontally positioned tubular photobioreactors covering a surface area of 1 hectare designated for cultivation. The model used for simulating the tubular bioreactor in SuperPro Designer (P-4/PFAB-101, Figure 2) was a Plug-Flow Stoichiometric Aerobic BioOxidation (PFAB) Procedure. Stoichiometry was defined with mass coefficients, as shown in Table 1. The reactants included biomass from the inoculum, CO_2 (carbon source), nutrients, and freshwater. Only a few nutrients were considered in the reactants to facilitate calculations (e.g., N and P sources). For the products, only three compounds were considered: biomass produced in the culture, culture medium, and oxygen generated in photosynthesis. The design of

the horizontal tubular photobioreactors involved a diameter of 0.09 m, and this design specification was used to calculate a length of 555 m. By setting the diameter, stoichiometry, and residence time in the equipment model, the simulator determined the required length to achieve the experimental biomass concentration. Consequently, it also calculated the quantity of photobioreactors needed to cover the specified area. The arrangement of the photobioreactors took into account not only the footprint of each cultivation system but also the shadows cast. This consideration was important as the shaded area would become unusable for installing other bioreactors. In this stage, two cultivation options were evaluated. The first option involved the use of a nutrient-rich growth medium with freshwater (case B1), while the second option considered the partial use of wastewater from pig farms (case B2) to obtain a portion of the nutrients. All conditions and data for simulating the cultivation stage were based on what was reported by Kuo et al. [27]. The composition of the wastewater was derived from the information provided by Garzón-Zuñiga et al. [28], and its composition is shown in Table 2. In the case that involves wastewater (case B2), a 25:75 (% v/v) mixture of wastewater and fresh nutrient solution was supplied. This mixture was selected because, as reported by Kuo et al. [27], it yields the best results in biomass production and desired lipid quality. The simulated scenarios did not take into account the pretreatment that wastewater must undergo before being fed to the microalgae cultivation, nor did they consider the cost of this. However, in reality, it is important to consider the cost of acquiring water and its treatment.

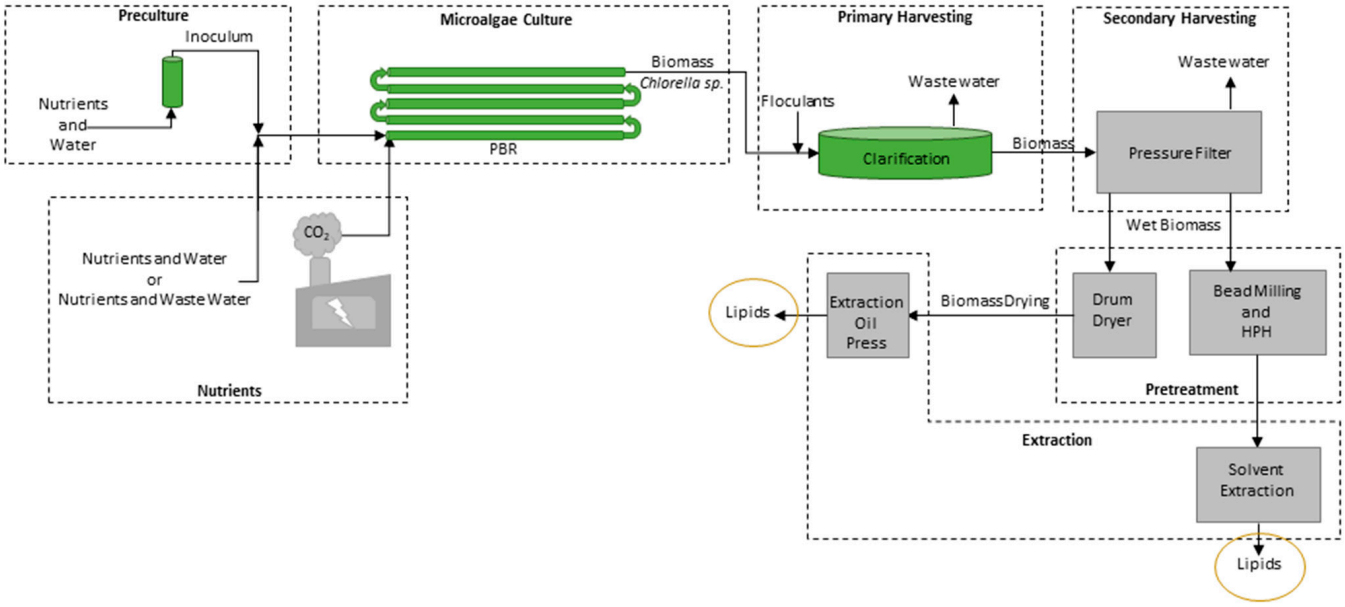

Figure 1. Flowsheet for the simulation of the lipid production from microalgae *Chlorella* sp. biomass.

Table 1. Stoichiometry Balance for Reaction in P-4/PFAB-101.

Reactants		Products	
Component	**Mass Coef.**	**Component**	**Mass Coef.**
Biomass 1	94.6300	Biomass 2	1528.7300
CO_2	66,783.7140	Culture medium 2	127,413.5640
$MgSO_4 \cdot 7H_2O$	251.4700	O_2	1528.7300
Culture medium 1	62,335.0150		
KNO_3	313.1000		
KH_2PO_4	313.0800		
Water	380.0150		
Total mass	130,471.0240	Total mass	130,471.0240

Table 2. Composition of flue gas from a thermal power plant and of wastewater in the cultivation.

Composition of the Wastewater [26]				Composition of the Flue Gas [29]	
N-total	524 mg/L	COD	3478 mg/L	CO_2	10–12% (v/v)
N-NH_4^+	200 mg/L	BOD_5	996 mg/L	NOx	680 ppm
SST	942 mg/L	P-total	27.4 mg/L	SOx	1700 ppm
SSV	2981 mg/L			Ash	265 ppm

N: Nitrogen, NH_4^+: Ammonium, SST: Total Solids, SSV: volatile solids, COD: Chemical oxygen demand, BOD_5: Biological oxygen demand (5 days), P: Phosphorus.

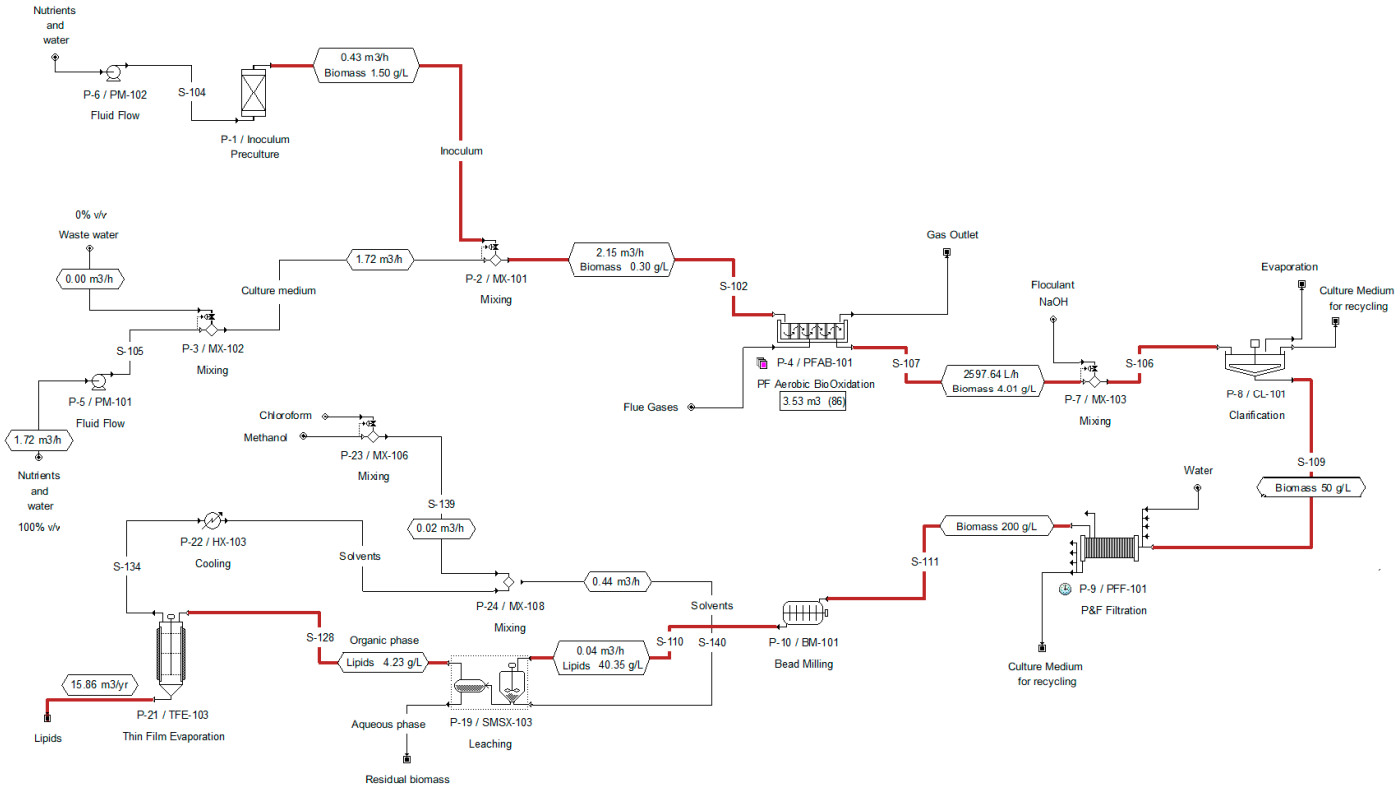

Figure 2. Process flowsheet in SuperPro Designer for lipid production for scenario 1.

To evaluate the annual biomass production achievable, an average productivity rate of 25.15 and 28.28 g/m^2/day was set for the cultivation without the use of wastewater (case B1) and for the cultivation using wastewater (case B2), respectively. For photobioreactors operated in continuous mode, production rates typically range from approximately 15 to 45 g/m^2/day [29]. These productivity rates depend on cultivation conditions, climate, and various other factors that can vary throughout the year. Hence, it's important not to consider values that are too high or too low. It was established that the achieved concentrations were 4 and 4.85 g/L in the effluent stream from the cultivation for cases B1 and B2, respectively.

To assess CO_2 capture, it was considered that 60% (w/w) of the CO_2 supplied to the cultivation was consumed, in accordance with literature reports [30,31]. This study did not analyze the capture of NOx and SOx in the mass balances. For the composition of the flue gas stream supplied to the cultivation, the composition reported by Duarte et al. [31] in Table 2 was considered. The composition of the fresh growth medium was taken from data reported by Kuo et al. [27] in Table 3.

To initiate biomass cultivation, a preculture stage is necessary. For this stage, a vertical tubular photobioreactor that achieves a biomass concentration of 1.5 g/L was considered. The biomass generated in the preculture will be used to inoculate the large-scale photobioreactors in the cultivation and initiate biomass production. The nutrients considered in the preculture were the same as those used in biomass cultivation.

Table 3. Source of nutrients and micronutrients for the culture.

Composition of the Fresh Culture Medium [27]					
KNO_3	1250 mg/L	$CaCl_2 \cdot 2H_2O$	83.5 mg/L	$MnCl_2 \cdot 4H_2O$	14.4 mg/L
KH_2PO_4	1250 mg/L	H_3BO_3	114.2 mg/L	$CuSO_4$	10 mg/L
$MgSO_4 \cdot 7H_2O$	1000 mg/L	$FeSO_4 \cdot 7H_2O$	49.8 mg/L	Na_2MoO_4	7.1 mg/L
$EDTA \cdot 2H_2O$	500 mg/L	$ZnSO_4 \cdot 7H_2O$	88.2 mg/L	$CoCl_2 \cdot 6H_2O$	4 mg/L

After cultivation, biomass is first harvested using flocculation, and three flocculants were considered for this stage: NaOH to induce autoflocculation by increasing pH (case C1), $FeCl_3$ (case C2), and chitosan (case C3). In this stage, the biomass needs to be concentrated to 50 g/L, and the flocculant doses were 125 mg/L, 30.52 mg/L, and 36.36 mg/L for cases C1, C2, and C3, respectively. The removal efficiencies were established at 94.28%, 95.71%, and 95.71%, based on what was reported by Lama et al. [32]. In the secondary harvest, only the biomass filtrate was considered using a filter press, as it had been evaluated earlier as a low-energy consumption technology, and the equipment is cost-effective compared to other technologies [33]. The goal of this stage is to concentrate the biomass from 50 g/L to 200 g/L.

Once the biomass is harvested, it undergoes pretreatment to disrupt the cell wall. Three mechanisms were considered to provoke cell wall disruption: bead milling (case F1), high-pressure homogenization (HPH) (case F2), and pressing of the biomass (case F3). In cases F1 and F2, wet biomass feed is required, so there is no need to consider a drying stage before pretreating the biomass. However, in the case of F3, dry biomass is necessary to achieve a higher lipid extraction yield. Therefore, for scenarios involving pressing to provoke cell disruption, it was assumed that the biomass is dried (until it reaches 5% w/w moisture) in a drum dryer (case E1) and then fed into the press (case F3). The lipid recovery for each technology was established at 75% when using milling (case F1) [34], 85% when using HPH (case F2) [35], and 70% for pressing (case F3) [36]. In the cases of biomass pretreatment using milling (case F1) and HPH (case F2), a mixture of lipids, proteins, cellular debris, and water is generated, from which it is necessary to separate the lipids using chemical solvents. For this extraction stage (case G1), a mixture of chloroform and methanol (2:1, v/v) as solvents was considered, with a solvent-to-biomass ratio of 10:1 (v/v) applied for 8 h. The overall timeframe encompassed 4 h for the biomass to be mixed with the solvent and an additional 4 h for the subsequent decantation and separation of the organic phase (comprising lipids and solvents) from the aqueous phase and biomass (including cellular debris). Following this, the organic phase undergoes evaporation in an evaporator at a temperature of 60 °C [37]. This specific temperature was chosen because higher temperatures tend to accelerate oxidative lipid degradation. An advantageous aspect of this extraction method is its capability to extract lipids from solutions characterized by high moisture content.

2.2. Simulation and Definitions of the Assumptions Necessary for the Technical and Economic Analysis

After collecting data from the literature, the selected technologies were evaluated by simulating them in the commercial simulator SuperPro Designer v10®. In the first stage, all technologies were simulated to analyze their individual impact. Afterward, the technologies employed in each stage were integrated to formulate process flow sheets for different scenarios, which were then subjected to analysis (a total of 18 scenarios, as detailed in Table 4). Mass and energy balances were conducted for each technique or technology utilized in the process, the required equipment sizes were determined, and production costs were calculated.

Table 4. Technological scenarios for microalgal oil production.

Cultivation	Primary Harvesting (Flocculation)	Secondary Harvesting	Pretreatment (Cell Disruption or Dry)	Extraction	Scenario	No.
Freshwater (B1)	NaOH (C1) $FeCl_3$ (C2) Chitosan (C3)	Pressure filter (D)	Bead milling (F1)	Extraction (G)	B1-C1-D-F1-G B1-C2-D-F1-G B1-C3-D-F1-G	1 2 3
Waste water (B2)	NaOH (C1) $FeCl_3$ (C2) Chitosan (C3)	Pressure filter (D)	Bead milling (F1)	Extraction (G)	B2-C1-D-F1-G B2-C2-D-F1-G B2-C3-D-F1-G	4 5 6
Freshwater (B1)	NaOH (C1) $FeCl_3$ (C2) Chitosan (C3)	Pressure filter (D)	High-pressure homogenization (F2)	Extraction (G)	B1-C1-D-F2-G B1-C2-D-F2-G B1-C3-D-F2-G	7 8 9
Waste water (B1)	NaOH (C1) $FeCl_3$ (C2) Chitosan (C3)	Pressure filter (D)	High-pressure homogenization (F2)	Extraction (G)	B2-C1-D-F2-G B2-C2-D-F2-G B2-C3-D-F2-G	10 11 12
Freshwater (B1)	NaOH (C1) $FeCl_3$ (C2) Chitosan (C3)	Pressure filter (D)	Drum dryer (E)	Oil press (F3)	B1-C1-D-E-F3 B1-C2-D- E-F3 B1-C3-D- E-F3	13 14 15
Waste water (B1)	NaOH (C1) $FeCl_3$ (C2) Chitosan (C3)	Pressure filter (D)	Drum dryer (E)	Oil press (F3)	B2-C1-D- E-F3 B2-C2-D- E-F3 B2-C3-D- E-F3	16 17 18

In the technical analysis, the primary indicator of interest was to evaluate energy consumption for each stage of the process as well as for the scenarios created in lipid production. One of the motivations for using microalgae biomass is its ability to capture CO_2, and assessing the energy consumption required for its cultivation could provide us with fundamental information for evaluating the impact on CO_2 emissions resulting from the energy consumption in the process. Energy consumption for each technology involved in the process was determined based on data reported in the literature; energy consumption for the photobioreactors during the preculture and cultivation stage, it was 15 kWh/m^3 feed [29], for the pressure filter (secondary harvest), it was 0.9 kWh/m^3 feed [33], for the drum dryer, it was 0.89 kWh/kg of evaporated water [33], for bead milling, it was 0.72 kWh/kg of dry weight (DW) of the fed biomass [38], for HPH (high-pressure homogenization), it was 0.4 kWh/kg of DW [39], and for oil press it was 0.1375 kWh/kg of DW, this data was taken from what was reported in a device with similar characteristics published on Alibaba.com [40]. Default values from the simulator were used for extraction and evaporation.

As for the economic analysis, the total and unit production costs were evaluated. The production cost is assessed using a simulator, encompassing expenses tied to raw materials, labor, services, and supplementary operational costs linked to facility usage. The raw materials for preculture and cultivation align with those documented by Valdovinos et al. [33], with considerations given to costs reported for the year 2018. Table 5 outlines the costs associated with process services, directly sourced from the simulator. The remaining costs are estimated by the simulator using parameters related to capital investment. This method uses the equipment purchase cost as a reference to calculate (indirectly, with percentages) the fixed capital investment cost and some costs included in the operating cost, such as facility-dependent costs. The latter includes maintenance and depreciation, among others, like insurance, local taxes, and factory expenses. These percentages are already defined in the simulator but have the option to be modified if the user prefers. Furthermore, the simulator incorporates a comprehensive database facilitating the adjustment of costs over the years (Intelligen, Inc., Scotch Plains, NJ, USA). The assessment was conducted based on 330 working days, assuming continuous operation mode.

Table 5. Cost of services.

Services	Cost	Unit (US)
Energy	0.1	$/kWh
Steam (heat)	12	$/ton
Cooling water	0.05	$/ton
NaOH	350	$/ton
$FeCl_3$	650	$/ton
Chitosan	1680	$/ton

3. Results and Discussion

The selected technologies for microalgal biomass production and lipid extraction were simulated using SuperPro Designer v10.0. Data reported in the literature were considered to establish the operating conditions for each of the evaluated technologies, and only technologies with the potential for industrial-scale application were selected. Technologies with high energy consumption or limited applicability on a large scale were discarded. All scenarios were evaluated under the assumption of continuous operation mode, considering 330 days of annual operation. Figures 2 and 3 depict the process flowsheets developed in the SuperPro Designer v10 simulator for the evaluation of scenarios 1 and 4, respectively.

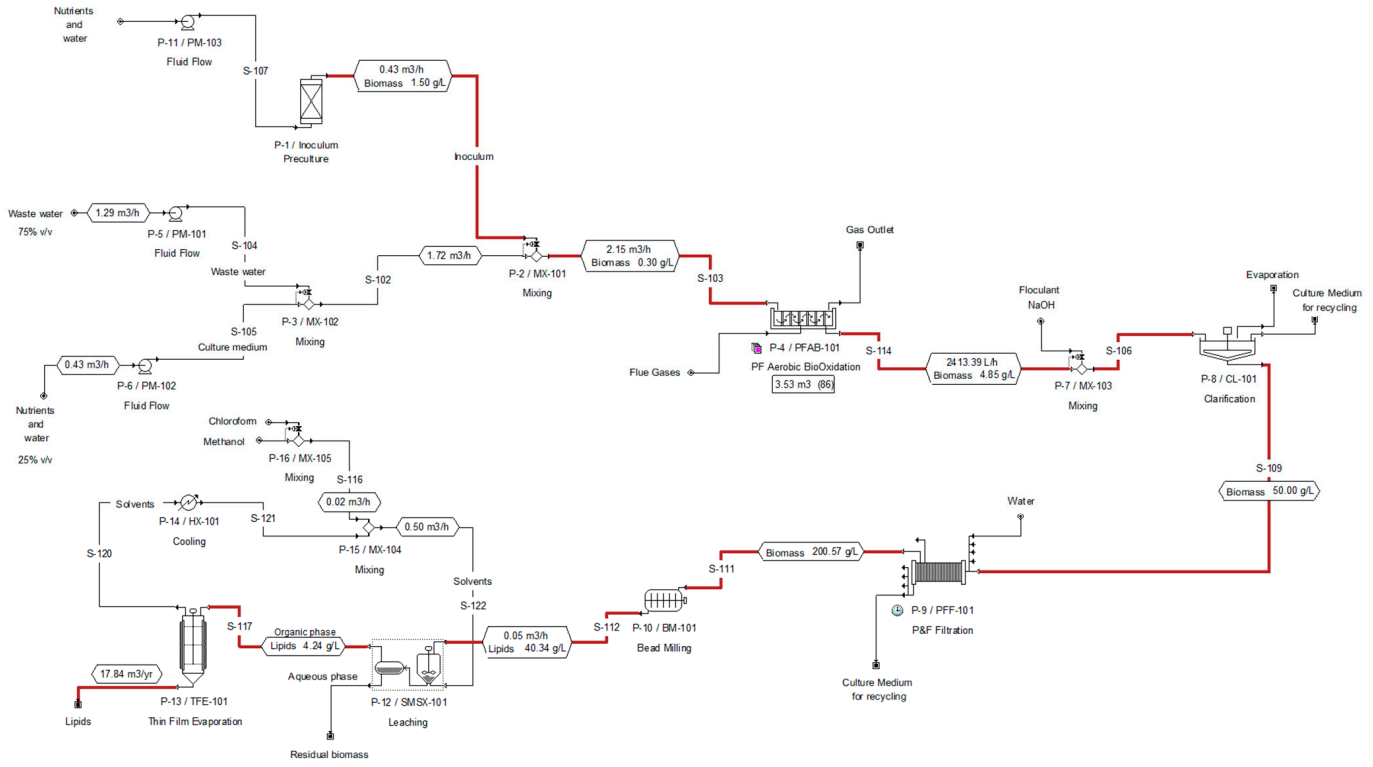

Figure 3. Process flowsheet in SuperPro Designer for lipid production for scenario 4.

Figures 4 and 5 display the flowsheets for scenarios 7 and 10, and Figures 6 and 7 depict the flowsheets for scenarios 13 and 16. Similar process flowsheets were developed for the remaining scenarios. All the technologies included in each scenario are described in Table 4. The results were divided into two sections: first, the technical evaluation, which assessed CO_2 capture, fresh and wastewater consumption, as well as the energy consumption of the scenarios and the impact of process stages. In the second section, the results of the economic evaluation are presented; in this case, only the production cost per unit of production was determined, that is, per kg of lipids produced.

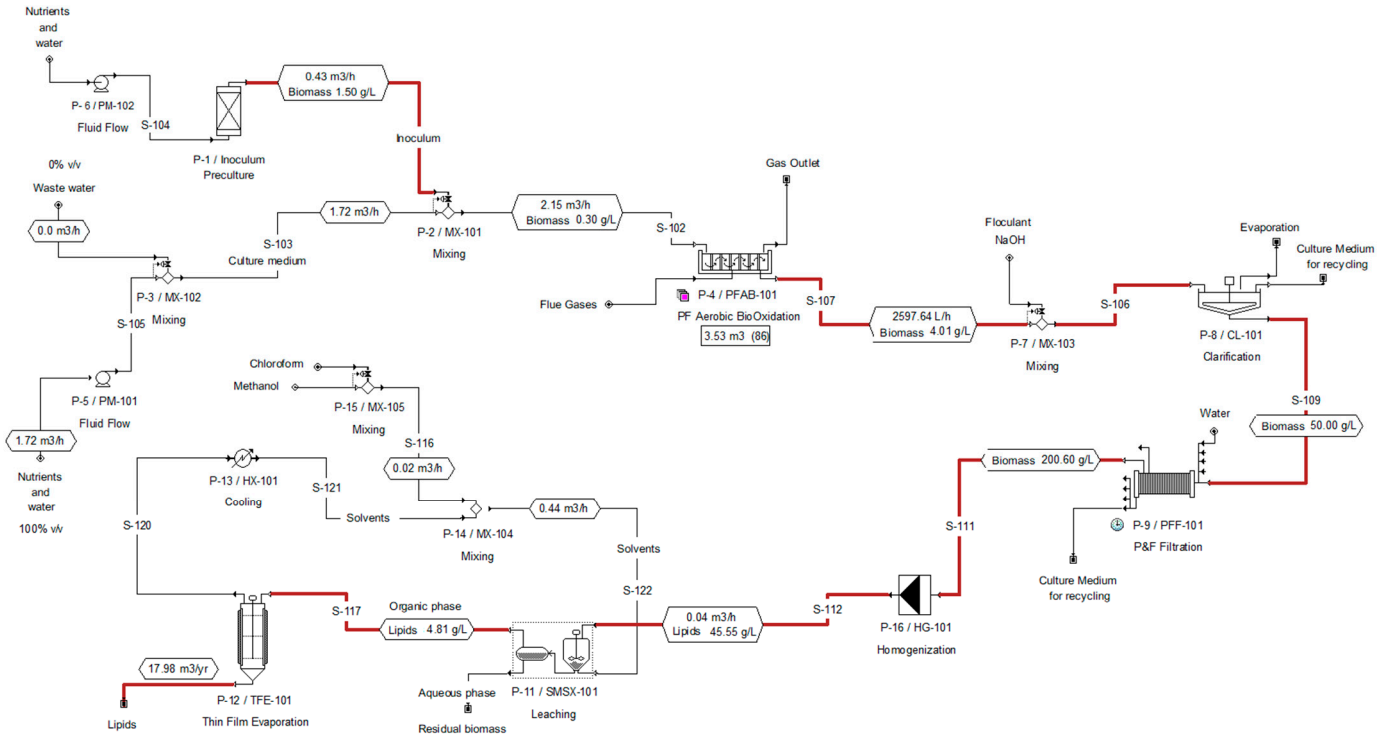

Figure 4. Process flowsheet in SuperPro Designer for lipid production for scenario 7.

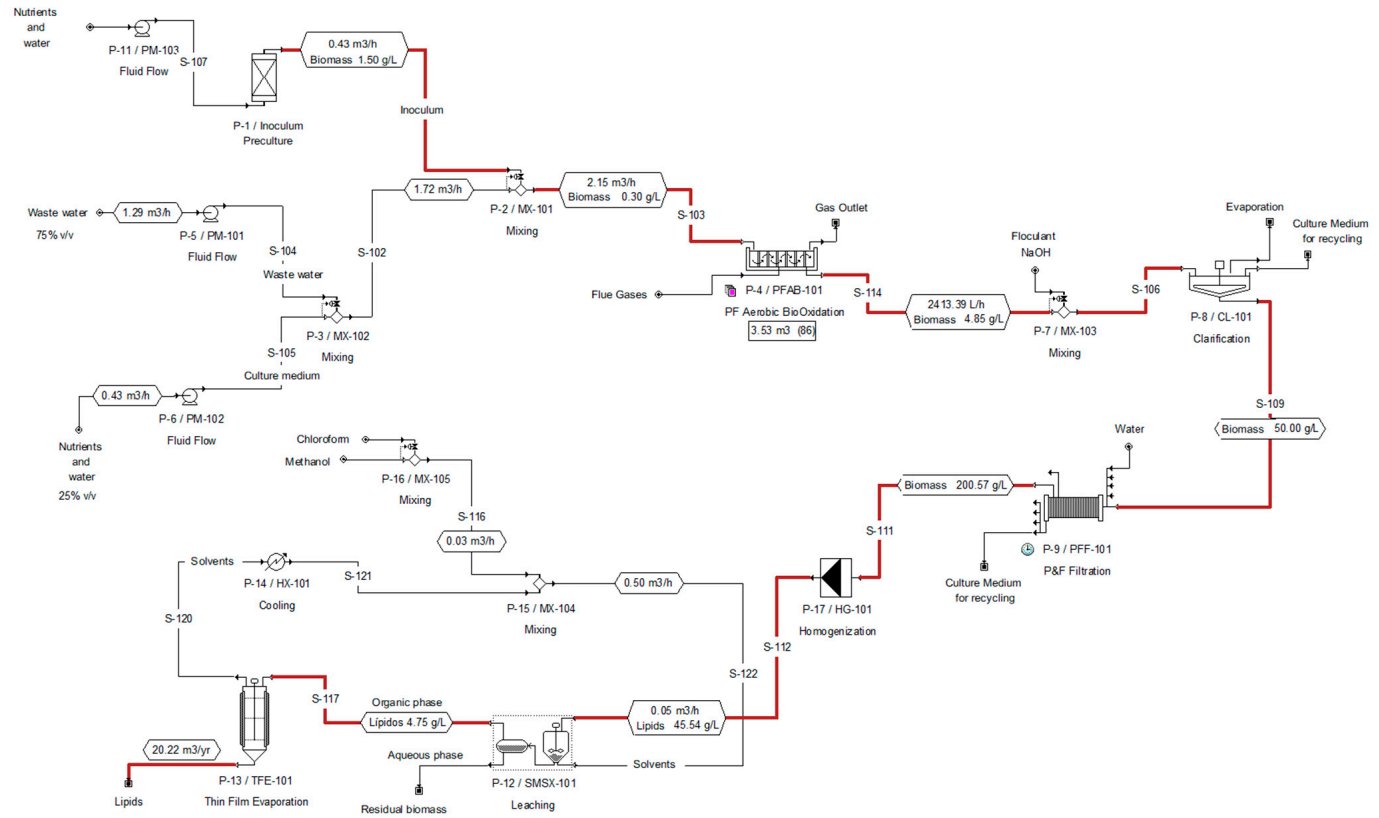

Figure 5. Process flowsheet in SuperPro Designer for lipid production for scenario 10.

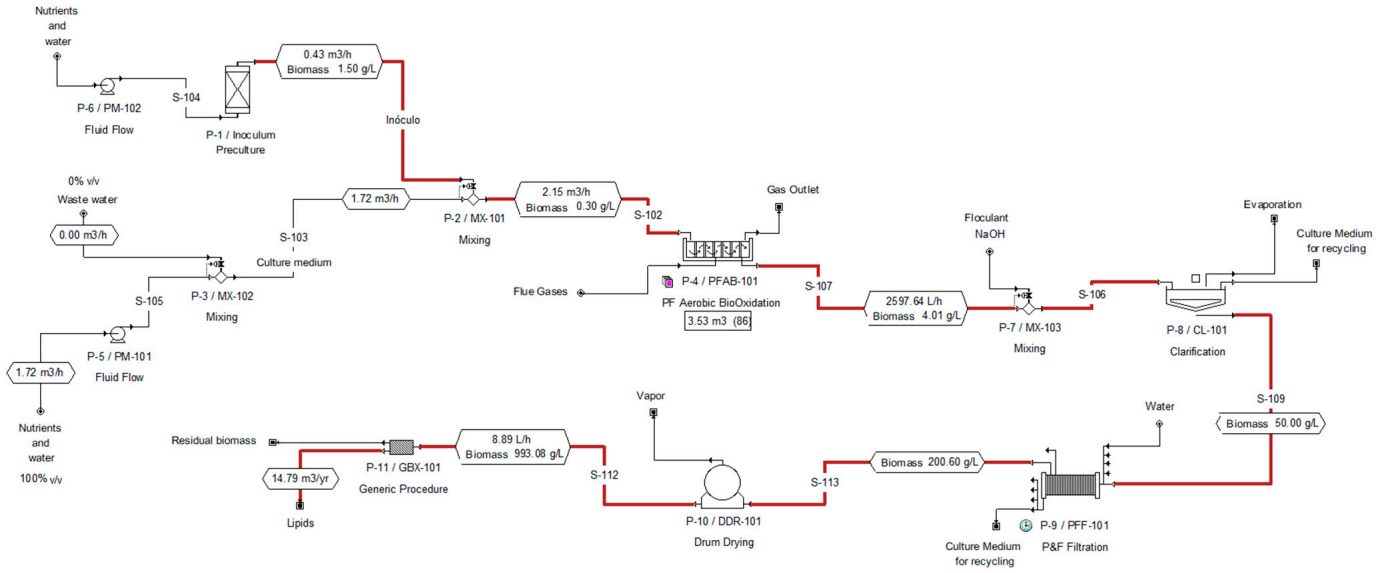

Figure 6. Process flowsheet in SuperPro Designer for lipid production for scenario 13.

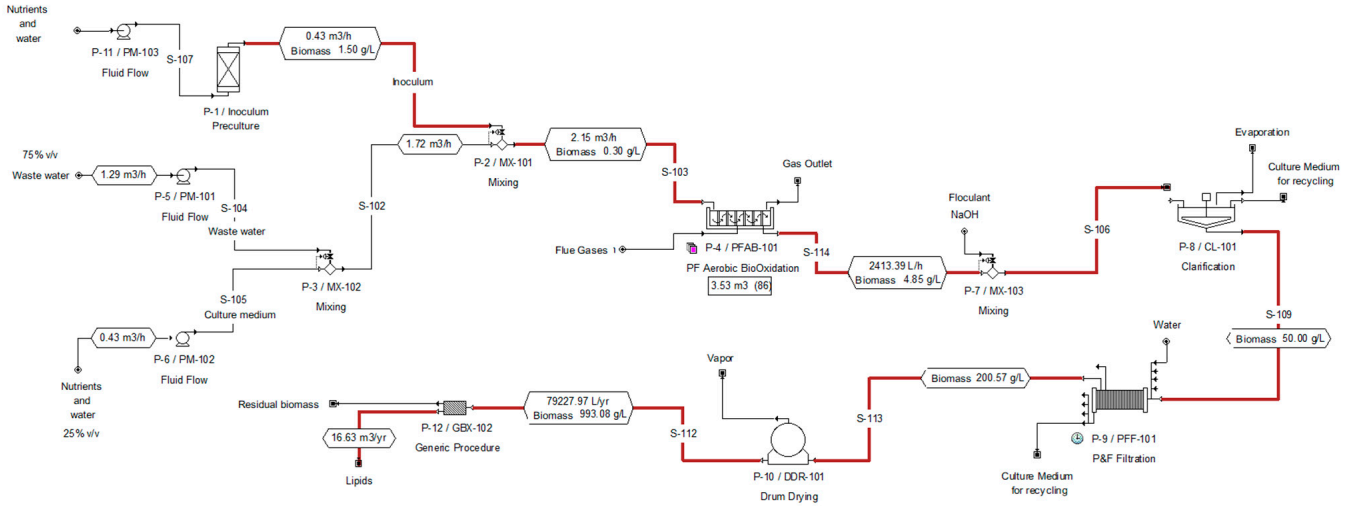

Figure 7. Process flowsheet in SuperPro Designer for lipid production for scenario 16.

3.1. Technical Evaluation of Microalgal Lipid Production Scenarios

The simulation results show that lipid production would range from 13.2 tons/ha/year (scenario 13) to 18.3 tons/ha/year (scenarios 11 and 12), as shown in Figure 8. In general, it can be observed that scenarios that included wastewater had higher lipid production (scenarios 4, 5, 6, 10, 11, 12, 16, 17, and 18). This is due to the higher biomass productivity in those scenarios that consider porcine wastewater. According to Kuo et al. [27], this may be because wastewater contains many nutrient compounds for microalgal growth, such as NH_4^+-N, N, and P. For this study, biomass productivities were set at 25.15 and 28.28 g/m^2/day. In continuous-mode photobioreactors, biomass production rates are typically around 15 to 45 g/m^2/day [30]. To assess the lipid production achievable in the biomass produced, it was considered that *Chlorella* microalgae contained 27% lipids, 21% proteins, and 35% carbohydrates, and the remaining percentage was attributed to pigments and other compounds [34]; all percentages are in weight/weight (*w*/*w*). It's important to clarify that not all the technologies considered for the cell disruption stage (pretreatment stage, technologies in cases E, F1, and F2) have the same efficiency in lipid recovery, which leads to diversity in the lipid production scenarios. Another parameter contributing to the diversity in biomass and lipid production is the type of flocculant used.

For example, for pH-change flocculation with NaOH, a biomass removal efficiency of 94.28% was considered, while for $FeCl_3$ and chitosan, it was set at 95.71%.

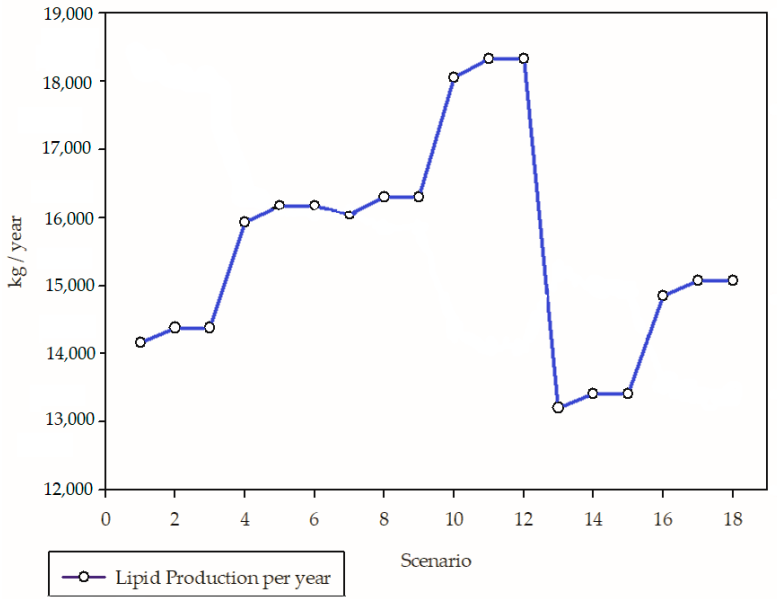

Figure 8. Unit lipid production per scenario (kg/year).

On the other hand, the selection of the type of flocculant to use must be considered to determine the ultimate use of biomass, as some flocculants can be toxic and limit the use of biomass and, therefore, lipids [41]. Furthermore, it is desirable that the wastewater generated during the primary and secondary harvest stages be utilized, either for alternative purposes such as irrigation water or for recirculation back into the cultivation system to minimize nutrient use. However, this can also be limited by the type of flocculant [40].

The introduction of NaOH increases the pH of the culture, resulting in the generation of concentrated microalgal biomass. This method has the advantage of using an economic substance and also reduces the bacterial load that may be present in the biomass culture. All or part of the cell-free medium after flocculation can be recycled back into the cultivation system after adjusting the pH, as reported in the literature [41,42]. In the case of using iron salts (such as $FeCl_3$), it has been reported in the literature that the use of ferric salts can lead to a yellow-brown discoloration of microalgae, which could limit the use of biomass for the co-production of pigment extraction. Additionally, it could become contaminated by metals and hinder its application as a raw material for biofuels or animal feed [43]. Moreover, employing such flocculants may cause the precipitation of undesirable metals, restricting the suitability of wastewater for irrigation. The utilization of chitosan as a flocculant has been identified as effective and does not introduce contaminants to the biomass. Nevertheless, its elevated cost might curtail its application if the objective is not geared toward producing high-quality biomass and oils [42,43]. In the literature, it has been reported that the use of chitosan allows for the utilization of wastewater obtained from primary and secondary harvesting because it can sustain the growth of biomass by inoculating fresh algal cultures [44]. Furthermore, chitosan is produced from chitin, a component in the exoskeletons of shrimp and crabs, which allows for more sustainable production compared to other synthetic organic polymers [45]. This contributes to producing biomass that is free from undesirable and potentially toxic contaminants. In conclusion, the use of certain flocculants should be analyzed to assess the potential impact on the target compound to be produced from biomass, as well as the feasibility of recycling the wastewater obtained from primary and secondary harvesting. This recycling can help minimize the consumption of fresh nutrients in the cultivation, directly impacting cost savings in the process.

Another interest in cultivating microalgae, in addition to the production of commercially valuable compounds, is their capacity to capture CO_2. Under the operating conditions established in this study, it was determined that 86 PBRs (Photobioreactors) are required to cover 1 ha of cultivation area. The achieved biomass productivity is 82.45 and 92.73 tons/ha/year for case B1 (using only fresh culture medium) and case B2 (using culture medium mixed with wastewater), respectively. To maintain this level of biomass productivity, CO_2 and nutrient supplementation is necessary. Considering that the cultivation of the *Chlorella* species in closed cultivation systems could achieve CO_2 removal efficiencies of up to 60%, it is estimated that the cultivation stage would capture up to 148.4 tons of CO_2 per year in the case of B1 and 166.90 tons of CO_2 per year in the case of B2. Closed cultivation systems offer better control over CO_2 capture and achieve higher biomass production compared to open cultivation systems. This is especially advantageous when CO_2 capture is an additional goal alongside biomass and lipid production. In a previous study where CO_2 capture was evaluated using the cultivation of microalgal biomass in an open system (raceway pond), it was estimated that these systems could achieve capture of up to 102 tons of CO_2 per year [46]. Comparing this result, the closed cultivation systems evaluated in this study capture 45.3% and 63.4% more CO_2 than the open cultivation system. Figure 9 illustrates the kg of CO_2 captured annually per kg of lipids produced for each scenario. All scenarios capture the same amount of CO_2; however, when compared per kilogram of produced lipids (Figure 9), scenarios with high productivity will have a lower CO_2 capture value.

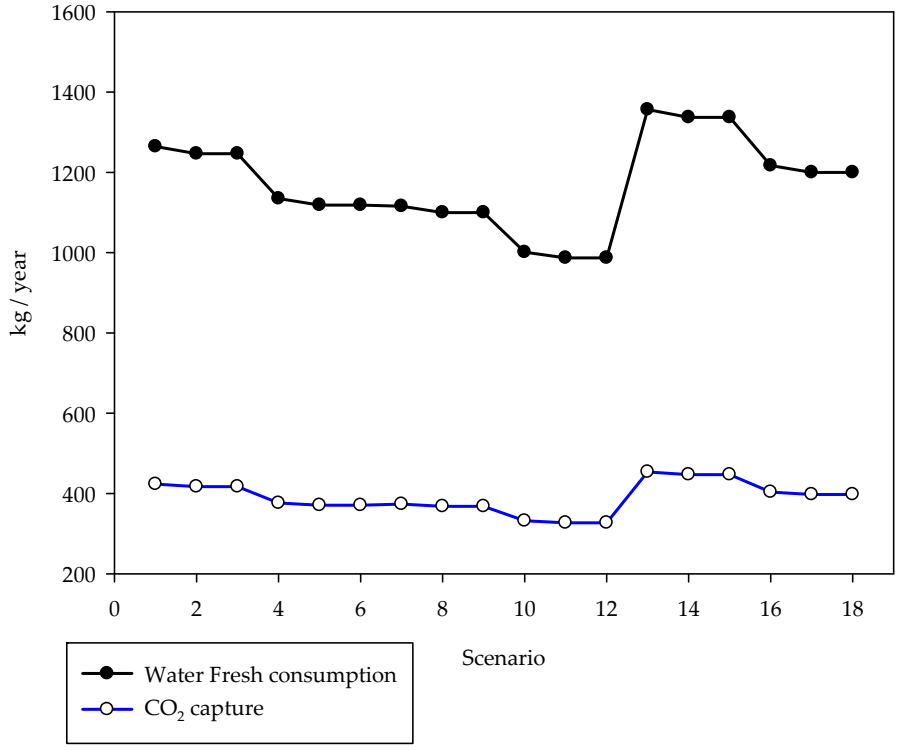

Figure 9. Freshwater consumption and CO_2 capture per kg of lipids produced for each scenario.

It is known that with high CO_2 dissolution, an increase in pH is inevitable due to the presence of CO_2, bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}), and therefore, the tolerance of microalgae to these conditions has been investigated. Kuo et al. [47] report that the microalga *Chlorella* sp. AT1 is tolerant to alkali conditions and was cultivated in an alkaline medium (pH = 11) with 10% CO_2 aeration.

The evaluation of CO_2 capture allows us to project the required surface area for capturing CO_2 from a thermal power plant if closed cultivation systems (PBR) like the ones designed in this study were used. Under the operating conditions established in

this study, an area of 72,776.28 hectares and 64,709.4 hectares is estimated to be required if the cultivation system of case B1 and case B2, respectively, is employed for capturing 10.8 million tons of CO_2 emitted by the largest capacity thermal power plant in México [48], the Plutarco Elías Calles thermoelectric plant, located in the municipality of Unión de Isidoro Montes de Oca, Guerrero, México. The estimates in this study show that for capturing the CO_2 emissions generated by the production of 1 MW at the Plutarco Elías Calles thermoelectric plant, 26.2 hectares would be needed if the B1 cultivation case were implemented, and 23.3 hectares if it were the B2 case, with a 60% capture efficiency of the supplied CO_2. Sudhakar et al. [49] report that approximately a 40-hectare algae pond is required to mitigate the CO_2 emitted by a 1 MW coal-based power unit, with a 50% capture efficiency. The amount of required surface area will depend on the conditions set as the basis for the study, such as biomass productivity and CO_2 capture capacity. It is also essential to note that the microalgal species chosen as the basis for the study will significantly influence the CO_2 capture capabilities achievable in accordance with the species used for cultivation and biomass production. Approximately 1.83 g of CO_2 is consumed to produce 1 g of microalgal biomass [47].

The results show that the consumption of freshwater is high, even with the use of wastewater. Wastewater from pig farms is rich in essential nutrients such as N and P, which contributes to nutrient savings for microalgae biomass production. In scenarios that consider wastewater (cultivation case B2, scenarios 4, 5, 6, 10, 11, 12, 16, 17, and 18), a significant reduction in freshwater consumption is observed, which is beneficial for reducing the water footprint in microalgae biomass production processes. For scenarios without wastewater (case B1), the freshwater consumption for this stage was determined to be 16,872 m^3/year, while for scenarios that consider wastewater (case B2), the freshwater consumption is only 6746 m^3/year. However, in the latter case, it should be noted that there is a need for the availability of 10,217 m^3/year of wastewater from a pig farm. Figure 9 shows the consumption of freshwater in kg/year to produce 1 kg of lipids in each of the scenarios evaluated. One of the advantages of using closed photobioreactors is that it prevents water loss due to evaporation, which is not the case in open cultivation systems. In addition, closed systems offer better control over biomass cultivation, reducing the risk of contamination. In a previous study [46], it was estimated that 58,061 m^3/year of freshwater would be required to cultivate microalgae in an open system covering an area of 1 ha just to locate the cultivation systems. Comparing the current results with the previous study, water savings are 71% less when using only freshwater and cultivating in a photobioreactor (case B1) and 89% less when using a combination of freshwater and wastewater (case B2). The idea of using wastewater to reduce nutrient consumption in the microalgae biomass cultivation stage provides a pathway for the removal of chemical and organic contaminants, heavy metals, and pathogens from wastewater. Simultaneously, biomass is produced for oil production with various potential end uses [49]. Savings in chemical remediation requirements and potential reduction in freshwater usage are the primary drivers for biomass production as part of a wastewater treatment process. Some examples of wastewater effluents suitable for microalgae cultivation come from the dairy industry, breweries, municipal wastewater treatment plants, and ethanol distilleries, among others [46]. Many studies have been conducted on microalgae cultivation for biomass and lipid production, as well as nutrient removal, primarily phosphorus (P) and nitrogen (N), using wastewater effluents to prevent eutrophication [25,50–54]. However, most focus solely on the viability of biomass growth during cultivation using various wastewater effluents, leaving aside the techno-economic evaluation.

In terms of energy consumption, it is well known that closed cultivation systems are highly energy-intensive. The results of the evaluation of the cases analyzed in this study show that energy consumption ranges from 48.75 kWh/kg of lipids (scenarios 11 and 12) to 64.8 kWh/kg (scenario 13), as shown in Figure 10. The primary source of energy consumption is the cultivation stage. For example, in scenario 12, 95% of the consumption is attributed to this stage, with the remainder distributed between the two biomass harvesting

stages, biomass pretreatment and lipid extraction (with solvents). In scenario 13, 97.8% of the energy is consumed during the cultivation stage, with the remainder distributed between the two biomass harvesting stages and lipid extraction using a press. Energy consumption is slightly higher for scenarios that do not include solvent extraction, namely scenarios 13 to 18. This is because these scenarios have lower lipid production, as press extraction does not achieve extraction percentages as high as those attained when considering biomass pretreatment with a bead mill (case E1) and HPH (case E2), followed by solvent extraction (case G). In a previous study [55], similar scenarios for lipid production were analyzed, which also considered 1 ha as the cultivation area. However, in that study, microalgal biomass was cultivated in an open system (raceway pond). When comparing the results for energy consumption, it is evident that lipid production systems that employ photobioreactors for biomass cultivation consume approximately nine times more energy.

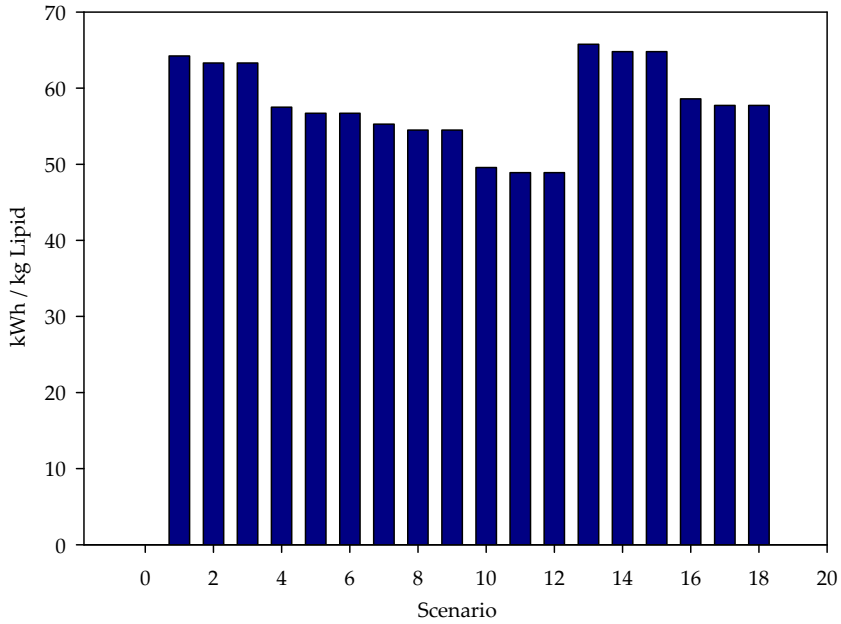

Figure 10. Energy consumption (kWh) per kg of lipids produced per scenario.

3.2. Economic Evaluation of Microalgal Lipid Production Scenarios

Regarding the cost of microalgal lipid production, the results indicate that it is high, ranging from 836.9 US $/kg (for scenario 11 and 12) to 1131.5 US $/kg (for scenario 13), as shown in Figure 11. The operating cost is estimated as the sum of labor, services, raw materials, and additional operating costs related to the use of the facility. For scenarios that include biomass pretreatment before solvent extraction (scenarios 1 to 12), the unit production cost is distributed approximately as follows: 2% for raw materials, 1% for labor-dependent, 96% for facility-dependent, and 1% for utilities. In scenarios that do not consider biomass pretreatment but instead, direct lipid extraction using a press (scenarios 13 to 18), approximately 98.3% of the costs are associated with facility-dependent costs, 0.7% with raw materials, 0.1% with labor-dependent costs, and 0.9% with utilities. The change in the distribution of unit production costs in the two groups mentioned earlier is primarily due to the fact that the first group of scenarios (1 to 12) includes lipid extraction with solvents. The solvent consumption for extraction is high, leading to an increase in the cost associated with the raw materials required for the process.

In scenarios that involve lipid extraction with solvents (scenarios 1 to 12), approximately 60–74% of the raw material cost is attributed to the solvents used for extraction. Within this group of scenarios, those that use wastewater are the ones producing the highest amount of lipids, and consequently, they are also the ones consuming the most solvents. The use of wastewater in this group of scenarios contributes to a 7.84% cost savings associated with nutrients and water for cultivation.

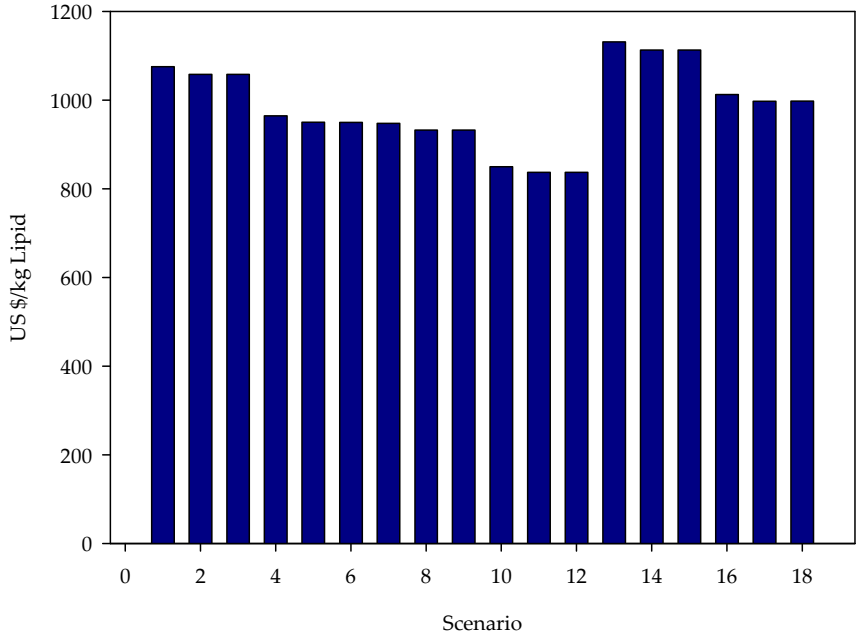

Figure 11. Unit production cost per kg of lipids produced by scenario.

For scenarios that do not involve solvent extraction (scenarios 13 to 18), the use of wastewater significantly reduces the cost related to nutrient consumption. Within this group, scenarios 16, 17, and 18 are approximately 44% less expensive than scenarios that do not include wastewater (scenarios 13, 14, and 15).

Regarding labor costs, these account for slightly less than 1% for all scenarios. In this evaluation, only operators were considered as labor costs because this study is exploratory. However, for a more detailed analysis, it would be advisable to include other labor charges. Facility-dependent costs are similar in all evaluated scenarios (approximately 14,800,000 US $/year). These costs include equipment maintenance, taxes, insurance, and other expenses. Maintenance costs have the most significant impact in this parameter, as they are calculated as a percentage of equipment costs, which are quite high. The use of closed cultivation systems, such as photobioreactors (PBR), is still limited in the industry due to the high operating and construction costs despite the high microalgal biomass productivity [47].

Regarding the annual cost associated with utilities, it is similar for the group of scenarios that include solvent extraction (1 to 12), approximately 182,000–196,000 US $/year. Meanwhile, for scenarios that do not include solvent extraction (13 to 18), the cost is approximately 130,000–133,000 US $/year.

This technical and economic evaluation allows us to identify which stages or operations need to be analyzed in more detail and, therefore, search for alternatives to minimize costs. For example, it may be possible to reduce nutrient or utility consumption, such as energy, heating, or cooling, or to replace one piece of equipment with another. We can observe that one of the factors with the most significant impact on the cost of lipid production in these evaluated scenarios was the solvent consumption for lipid extraction in scenarios 1 to 12. Therefore, it is advisable to explore the use of different solvents or alternative lipid extraction methods. As for energy consumption, the cultivation stage has the most significant impact, so it might be worth evaluating if another type of bioreactor is feasible to achieve these biomass and lipid productivities. As observed in the results, the cost of lipid production is high. However, all these factors impact the final product cost, so it is essential to explore alternatives to reduce costs. For instance, if we examine the process flowsheet (Figure 2), one option to consider is the reuse of the wastewater from the primary harvest stage (stream "Culture Medium for recycling" from equipment P-8/CL-101) and the secondary harvest stage (stream "Culture Medium for recycling" from equipment

P-9/PFF-101) by reintroducing it into the cultivation stage. These streams still contain valuable nutrients. Another alternative could be selling this water as irrigation water for farmland and no longer recycling it for the cultivation stage. Additionally, you might consider implementing a biorefinery scheme where residual biomass after lipid extraction is utilized, or it can be sold as a raw material for biofertilizers since it still contains carbohydrates and proteins. The final residue of microalgae could also find utility as biochar; this implies that carbon fixation technology in microalgae has the potential for real-world application in the industry [47]. According to Kuo et al. [47], from an economic standpoint, it is advisable to extract a broader range of essential compounds from microalgae biomass, such as carotenoids, in order to formulate high-value products. The production of microalgae biomass as a commodity source is not yet viable, with the primary obstacle being production scale and total production and processing costs. As we can see, these costs are largely attributed to energy consumption in various process stages. Vanthoor et al. [56] mention that there is still significant room for improvement in algae research to increase production and extraction efficiency, especially when more products can be obtained from a microalgae production process. This will significantly increase the value of algae and make algae production economically viable.

A large number of techno-economic studies of biorefinery processes using microalgae biomass have been reported in the literature. However, this diversity has led to a wide range of cost evaluations because there is no standardization in the analyses. Some studies design a process based on average values of biomass or lipid production, while others omit the cultivation of biomass and all the necessary processes for harvesting. Instead, they design their process starting from the biomass, among many other process configurations. Additionally, the wide variety of microalgae species available also contributes to specific process requirements and variations.

Figure 12 shows the energy consumption and unit production cost for each scenario. It is evident that scenarios 11 and 12 are the most favorable, suggesting that they might also have a lower carbon footprint due to the CO_2 emissions generated by the energy consumption during the process operation. According to the results, these two scenarios also appear to have the lowest consumption of freshwater.

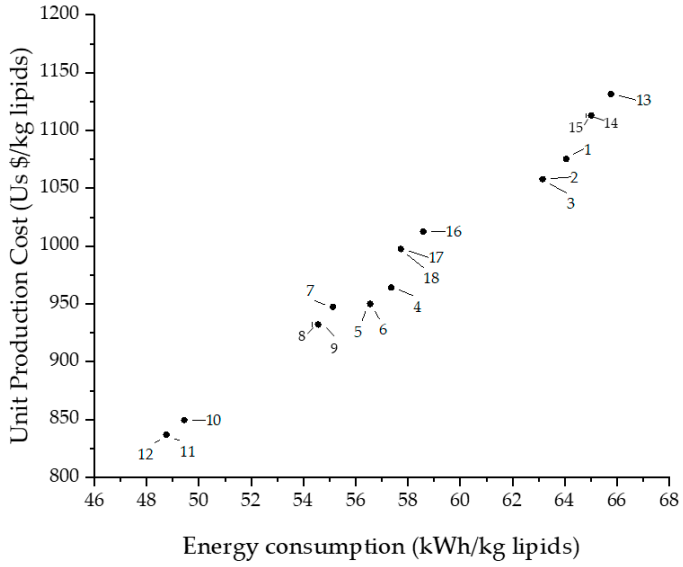

Figure 12. Energy consumption vs. cost of production per kg of lipids produced by scenario (1 to 18).

The increasing demand for energy and materials is pushing humanity towards a shift from a linear economy reliant on fossil fuels to a sustainable circular bioeconomy. The utilization of microalgae for the production of energy or valuable products exemplifies a circular bioeconomy, as it can effectively employ CO_2 emissions as carbon sources for microalgal biomass production. This contributes to the mitigation of greenhouse gas

emissions and serves the dual purpose of wastewater treatment. Power plants, one of the industries with a significant impact on CO_2 emissions, could consider installing a microalgae cultivation facility on their premises or nearby. This could allow them to feed their gaseous and wastewater effluents for treatment, while the biomass obtained, rich in lipids, carbohydrates, and proteins, could serve as raw material for biofuels, biolubricants, and other by-products that can be used in-house or commercialized. Currently, there is a significant interest in the design of sustainable processes driven by factors such as population growth, industrialization, the depletion of natural resources, increased consumption of non-renewable resources, climate change, and more. This interest aims to ensure food security, manage natural resources sustainably, reduce dependence on non-renewable resources, mitigate and adapt to climate change, protect the environment, and create new job opportunities and industries. According to Kuo et al. [47], in Taiwan, a significant portion of livestock wastewater comes from pig farming, and active research has been directed towards the treatment of piggery wastewater. Raw piggery wastewater, without pretreatment, can also be used in microalgae cultivation. It has been reported that the biomass produced contains approximately 20% lipids, making it suitable as a raw material for biodiesel production. These factors enhance the appeal of cultivating microalgae as a raw material for valuable products, offering alternative avenues for utilizing CO_2 emissions from power plants.

4. Conclusions

The choice of the best scenario will depend on the objective to be met. For example, if the goal is to capture CO_2, then the scenario with the highest annual CO_2 capture per kilogram of lipids produced would be the best (scenario 13, 454 kg of CO_2/kg of lipids). However, it would still be necessary to evaluate the carbon footprint to determine if the CO_2 capture is greater than the emissions generated in the process. On the other hand, if the primary interest is to achieve the highest production at the lowest cost, then scenarios 11 and 12 are the best to fulfill this objective (836.9 US $/kg).

The use of wastewater does allow for savings in nutrient and freshwater consumption, which is reflected in the unit production cost, with approximately a 10.33% cost savings in all scenarios. The savings in freshwater are significant when using wastewater, with approximately 60% less freshwater being used.

This study provides an assessment of various scenarios, analyzing the impact of different stages of the process and the technologies employed. Evaluating the energy consumption of the processes is important because this data could be used to assess the carbon footprint and determine whether the processes could be viable for implementation as carbon capture systems. In other words, it helps determine if the carbon capture from the process exceeds the emissions that could be generated by the energy consumed for its operation. Additionally, it evaluates which stages have the highest energy consumption and explores alternatives to reduce it. On the other hand, the operational cost indicates how economically viable it is to produce compounds of interest (in this case, lipids) from biomass cultivated under these production schemes. This information contributes to the literature for comparison with new proposed scenarios.

With the help of process simulation tools, we were able to save time in the evaluation, gain a deep understanding of the functionality of each piece of equipment involved in each stage of the process, identify critical variables for design, and highlight the potential for applying these processes on an industrial scale.

Author Contributions: Conceptualization, E.M.V.-G., M.G.B.-S., J.B.-F. and M.A.P.-P.; methodology, E.M.V.-G.; software, E.M.V.-G. and M.A.P.-P.; validation, C.A.C.-C., M.d.l.Á.O.-A. and J.B.-F.; formal analysis, E.M.V.-G., M.G.B.-S., J.B.-F. and M.A.P.-P.; investigation, E.M.V.-G., C.A.C.-C., M.G.B.-S., J.B.-F., M.d.l.Á.O.-A. and M.A.P.-P.; writing—original draft preparation, E.M.V.-G., C.A.C.-C. and M.A.P.-P.; writing—review and editing, M.G.B.-S., J.B.-F. and M.d.l.Á.O.-A.; supervision, E.M.V.-G., M.G.B.-S., J.B.-F. and M.A.P.-P.; project administration, E.M.V.-G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to content protection.

Acknowledgments: The authors are thankful to their institutions (Universidad Juárez Autónoma de Tabasco and Tecnológico Nacional de México in Celaya) for the support provided for the development of the research.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviation

PBR	photobioreactors
PFAB	Plug-Flow Stoichiometric Aerobic BioOxidation
NOx	nitrogen oxides
SOx	sulfur oxides
MW	megawatts
kWh	kilowatts per hour
NaOH	sodium hydroxide
$FeCl_3$	iron chloride III
HPH	high-pressure homogenization
$MnCl_2{\cdot}4H_2O$	tetra hydrated manganese chloride
$CuSO_4$	copper sulfate II
Na_2MoO_4	sodium molybdate
$CoCl_2{\cdot}6H_2O$	cobalt (II) chloride hexahydrate
$CaCl_2{\cdot}2H_2O$	calcium chloride dihydrate
H_3BO_3	boric acid
$FeSO_4{\cdot}7H_2O$	iron (II) sulfate heptahydrate
$ZnSO_4{\cdot}7H_2O$	zinc sulfate heptahydrate
KNO_3	potassium nitrate
KH_2PO_4	potassium dihydrogen phosphate
$MgSO_4{\cdot}7H_2O$	magnesium sulfate heptahydrate
$EDTA{\cdot}2H_2O$	Ethylenediaminetetraacetic acid dihydrate
N	Nitrogen
NH_4^+	Ammonium
SST	Total Solids
SSV	volatile solids
COD	Chemical oxygen demand
BOD_5	Biological oxygen demand (5 days)
P	Phosphorus

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