Techno-Economic Study of CO$_2$ Capture of a Thermoelectric Plant Using Microalgae (*Chlorella vulgaris*) for Production of Feedstock for Bioenergy

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Abstract: A current concern is the increase in greenhouse gas emissions, mainly CO$_2$, with anthropogenic sources being the main contributors. Microalgae have greater capacity than terrestrial plants to capture CO$_2$, with this being an attraction for using them as capture systems. This study aims at the techno-economic evaluation of microalgae biomass production, while only considering technologies with industrial scaling potential. Energy consumption and operating costs are considered as parameters for the evaluation. In addition, the capture of CO$_2$ from a thermoelectric plant is analyzed, as a carbon source for the cultivation of microalgae. 24 scenarios were evaluated while using process simulation tools (SuperPro Designer), being generated by the combination of cultivations in raceway pond, primary harvest with three types of flocculants, secondary harvest with centrifugation and three filtering technologies, and finally the drying evaluated with Spray and Drum Dryer. Low biomass productivity, 12.7 g/m^2/day, was considered, achieving a capture of 102.13 tons of CO$_2$/year in 1 ha for the cultivation area. The scenarios that included centrifugation and vacuum filtration are the ones with the highest energy consumption. The operating costs range from US $ 4.75–6.55/kg of dry biomass. The choice of the best scenario depends on the final use of biomass.

Keywords: microalgae; cultivation; harvest; drying; bioprocess simulation; energy demand; production cost

1. Introduction

In the last ten years, the main contribution to the increase of greenhouse gas (GHG) emissions has been the growing energy demand. In 2017, the annual global greenhouse gas emissions (excluding emissions from climate change in land use) reached a record 49.2 Gton CO$_2$eq, that is, 1.1% more than the previous year [1]. In the reference scenarios evaluated in the Fifth Evaluation Report that was conducted by the IPCC, the projections indicate that direct CO$_2$ emissions from the energy supply

sector will almost double or could even triple in 2050, when compared to the concentration of CO_2 in 2010 [2].

Brazil, Mexico, Argentina, and Venezuela (Figure 1) are those responsible for most of the emissions in Latin America, contributing 78% of the total emissions in this region. Regarding Mexico, CO_2 emissions have increased considerably from 1970 to 2015. According to the National Inventory of Gas Emissions and Greenhouse Compounds (INEGyCEI), of the National Institute of Ecology and Climate Change (INECC), in 2015 emissions of 537 Mton (Megatons) of CO_2 were recorded, of which 125 Mton were coming from the electric power production industry (from conventional technologies), representing 23.38% of the total CO_2 emissions in the country, being the second activity with greater impact on the environment after mobile sources [3].
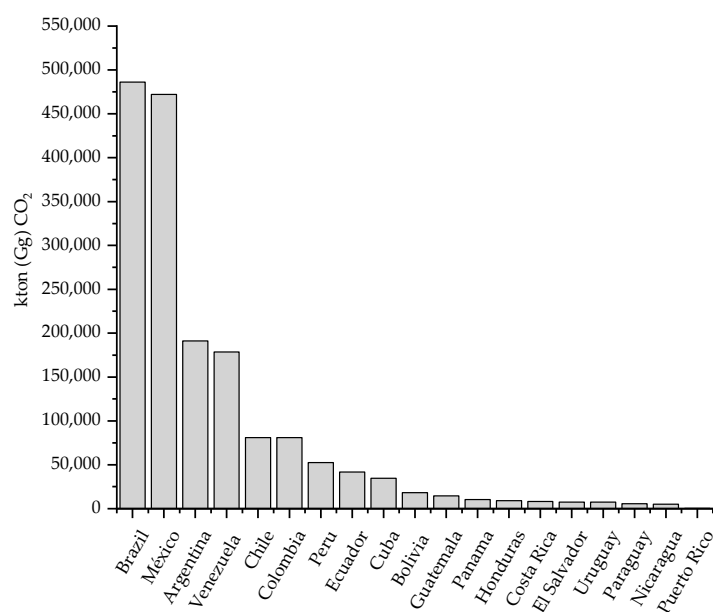
Figure 1. American Latin CO_2 emissions from fossil fuel use and cement production, 2015 [4].

The energy sector in Mexico has an electricity production capacity of 68,044 MW (registered in 2015), of which 71.7% comes from conventional power plants and the rest is generated with clean technologies [5]. Thermoelectric plants only represent 18.7% of the total installed capacity in the country and produce on average 680 kg of CO_2 per MWh generated within conventional energy production technologies, becoming one of the largest emitting sources. The emissions of the largest installed power plant in Mexico have an average of 10.75 Mton of annual CO_2. The typical composition of these emissions not only contains large amounts of CO_2, but also NOx and SOx, and its treatment is important in reducing the negative effects of these emissions into the atmosphere.

In general, and not only in the energy sector, worldwide the strategies that have been followed to mitigate CO_2 emissions include the need for: greater energy efficiency, that is, a decrease in the use of energy per unit of product, process, or service; increased use of clean fossil energy, this is the use of fossil fuels by coupling CO_2 capture from flue gases; and, greater use of renewable energies and the development of neutral energy resources in CO_2 [6–8]. The capture of CO_2 as a source of carbon in the production of microalgae biomass has also been considered to be an option for reducing these emissions. Due to their high photosynthetic capacity, as compared to terrestrial plants [9], they are able to capture up to 1.7 kg of CO_2 per kilogram of biomass produced [10]. Microalgae accumulate significant amounts of fats, carbohydrates, proteins, and other compounds of great economic importance, such as pigments and vitamins [11–13].

1.1. Microalgae

Microalgae are distinguished due to their high performance in terms of oil productivity per area, as compared to biomass that is derived from other sources, being approximately 10 times higher than that obtained with other oil crops [14,15]. Another advantage of microalgae biomass is that it does not belong to edible crops and does not compete for the use of arable or forested land, since they do not require fertile land for cultivation, guaranteeing food security and land use [16,17]. Microalgae have high growth rates, they can double their biomass in periods as short as 3.5 h and a greater amount can be produced continuously compared to land crops [18]. On the other hand, important aspects must be considered before selecting a species for its use, it must be evaluated based on certain parameters, such as being resistant to environmental changes, withstanding high concentrations of CO_2, NOx, and SOx in the cultivation stage (capture them if the purpose is their use as bioremediation), a high growth rate, a high content, and good quality of oils.

One of the most promising species for the capture of CO_2 from combustion gases is *Chlorella*. It has been reported that certain *Chlorella* species could grow in an atmosphere that contains up to 40% (v/v) CO_2 [6], with a CO_2 fixation rate between 0.73 to 2.22 g/L/day [19]. In addition, it has been found that other compounds present in the fed CO_2 stream, for example, NOx and SOx, do not affect the production of microalgal biomass from *Chlorella* [19–21]. Kao et al. [22] and Duarte et al. [23] analyzed the cultivation of the *Chlorella* species as a bioremediation option not only for CO_2 in combustion gases from power plants, but also for other components, finding that the NOx and SOx content in these currents is also reduced. Both of the authors agree that part of the NOx dissolves in water forming nitric acid or nitrous acid and, thus, the microalgae can use it in their metabolism, contributing to the saving of nutrients during cultivation. This shows the great potential of microalgae (especially the *Chlorella* species) as a bioremediation option, not only for CO_2, but also for other greenhouse gases.

The content of lipid oils in microalgae varies from 2% to 75% by weight of dry biomass; however, species that reach high lipid content have low productivity (for example, *Botryococcus braunii*). In contrast, species, such as *Chlorella, Crypthecodinium, Cylindrotheca, Dunaliella, Isochrysis, Nannochloris*, and *Nannochloropsis* have oil levels between 20 and 50%, but they are more productive [11]; that is why the latter are mostly chosen for the production of oils [18]. Lipid productivity considers both the concentration of lipids within cells and the biomass produced by these cells; therefore, it is a more useful indicator for the evaluation of potential costs in the production of liquid biofuels or other uses of lipids. The constitution of microalgal lipids is like vegetable oils; these are mainly triglycerides, where their chemical structure consists of three hydroxyl groups that are esterified with carboxyl groups of straight chain fatty acids. Regarding the composition of fatty acids, this differs in each species of microalgae; this is another important factor, since it provides the quality of lipids [24]; for example, in the production of biodiesel, species that produce mostly neutral lipids must be selected [25].

1.2. Production of Microalgal

There are different types of microalgae production, including photoautotrophic, heterotrophic, and myxotrophic culture. Photoautotrophic production is an autotrophic photosynthesis, where the carbon source is CO_2, heterotrophic production requires organic substances (for example, glucose) to stimulate growth, some strains while of algae can combine autotrophic photosynthesis and heterotrophic assimilation of organic compounds in a mixotrophic process. Currently, photoautotrophic production is the most common form of microalgae culture and the only method that is technically and economically viable for large-scale microalgae biomass production, since carbon consumption costs are low due to the use of CO_2 from of waste effluents from various industrial processes [6,26]. The cultivation stage consumes more process time; it can be operated in continuous or batch mode. As for the systems for the cultivation of microalgae, they can be open systems (system of channels or ponds), closed systems (photobioreactors), or a combination of the above. Several factors strongly influence the option for one or the other alternative, such as the species of microalgae in question, the desired metabolic regime, temperature, and the compound of interest.

The quantity and quality of oils from microalgae vary according to species, cultivation techniques, and oil extraction technologies. Obtaining lipid oils from microalgae for the production of biofuels on a commercial scale is currently not economically viable [27,28]. The high energy consumption in the processes of harvesting and extraction of oils, the low growth efficiency of microalgae, and the consumption of nutrients for their cultivation are some of the limitations. Studies have reported that the harvest stage can represent approximately 20–33% of total production costs [6,25,29]. One of the reasons why this occurs is because the concentration of the cells in the culture is low, typically around 0.1 to 8 g/L in dry weight. In addition, they are cells of very small size (1–10 μm in diameter), and with a density that is similar to that of the culture medium (1020 kg/m^3), which can make the harvest even more difficult [28,30]. Some technologies for this stage are flocculation, flotation, sedimentation, filtration, and centrifugation, although, in some, their energy requirement is high. The selection of dewatering technology is crucial for the economical production of microalgae biomass [31], although the selection of suitable strains is also an important consideration, since certain species of microalgae are much easier to harvest. The collection technique depends on the characteristics of the microalgae, such as size, cell density, value, and specifications of the products obtained from this biomass; however, an optimal collection method should be independent of the species, use less chemicals and energy, and, if possible, it should also release intracellular materials [29].

The biomass collected (approximate concentration of biomass of 200 g/L and with an approximate content of 80% humidity) is perishable and must undergo additional processes for storage or convert it to other products immediately [32]. A drying or dehydration stage is necessary [33], which must reach a concentration of approximately 90% in dry solids of biomass, to increase the stability of the biomass and obtain greater efficiency in the extraction of oils (or any other use). The above can be achieved by drying in the sun, in a drum dryer, spray drying, freeze drying, or any other technique that allows for moisture to be removed from the biomass [6,28]. Drying in the sun requires large areas, a lot of time, and there is a risk of material loss; spray drying is very expensive, which only makes it viable for high value products; lyophilization is equally expensive, especially for large-scale operations, but it facilitates the extraction of oils. When the bulk microalgae biomass is not the desired product, it must undergo further processing to obtain one or more cell fractions. Some microalgae have a rigid cell wall, which leads to cell breakdown being necessary for releasing internal compounds, such as lipids and pigments that are contained in the cytoplasm and carbohydrates stored in the cell wall [34]. For the extraction of microalgal oil, there are mechanical (pressing), chemical (solvent extraction), and supercritical fluid extraction methods [17,25]. It has been reported that the combination of methods can increase the yield of microalgae oil extraction [35].

Several reports analyze the possible technological routes to produce microalgae oil; however, several of these analyzes include the evaluation of technologies with little viability to be implemented on an industrial scale. Some of these technologies are highly efficient, however, their energy consumption is high, which considerably increases the operating costs and decreasing the technical and economic viability of the process. Other reports only include the evaluation of a single process unit, focusing on energy efficiency and demand [32,36–38].

On the other hand, recent researches to improve the cost of obtaining microalgae has focused on the use of waste and integrating the co-production of high-value compounds [39]. CO_2 sequestration using a biorefinery approach, through interconnection with the cultivation of microalgae, is an interesting idea, since the waste generated from power plants or other industrial facilities is used [34,40]. The residual microalgae biomass, which was rich in protein and carbohydrates, could still be used as a carbon source for anaerobic fermentation in the production of volatile fatty acids, biohydrogen, CO_2, among others. The resulting CO_2 and volatile fatty acids can be reused to produce bioplastics, bioelectricity, and biohydrogen [41]. The biorefinery models analyzed in this context could open new avenues to convert CO_2 into several valuable products, materials, and fuels, which could help to close the carbon cycle and contribute to the bioeconomy of the process [42,43].

Recently, there is a growing need for energy and materials, which forces humanity to move from a linear economy that is based on fossil sources to a sustainable circular bioeconomy [44]. The production of energy or valuable products from microalgae biomass is an example of circular bio-economics, since CO_2 emissions can be used as a carbon source for biomass production, contributing to mitigating sources of greenhouse gases. Electric power generating plants, one of the industries with the highest CO_2 emissions, could well consider installing a microalgae cultivation plant at or near their facilities and, thus, feed their effluents both gaseous and wastewater. On the other hand, the biomass obtained (rich in carbohydrates, lipids and proteins) could well be a raw material for the production of bioenergetics, biolubricant oils and other by-products [11,45–47], which can be consumed by themselves or commercialized. These reasons increase the interest in cultivating microalgae as a raw material for obtaining valuable products, providing alternative methods for the use of carbon dioxide emitted by power plants.

Given the great potential of use that microalgae have, the objective of this work is the techno-economic evaluation of biomass production from these, considering only production scenarios with scaling potential at the industrial level. In addition, the capture of CO_2 from a thermoelectric plant is analyzed as a carbon source for the cultivation of microalgae. The production scenarios that were analyzed include several technologies in the harvest and drying stage. A bioprocess simulation tool was used to carry out the evaluation of the production models (SuperPro Designer v10®). The *Chlorella* microalgae was selected as a reference species to establish the operating conditions for each technology involved in the process. The stage of cultivation in the raceway pond was evaluated, while the harvest was divided into two stages, as a strategy to reduce costs [48]; subsequently, two technologies for biomass drying were included. Figure 2 shows the evaluated routes. The criteria for evaluation are energy requirements and operating costs.
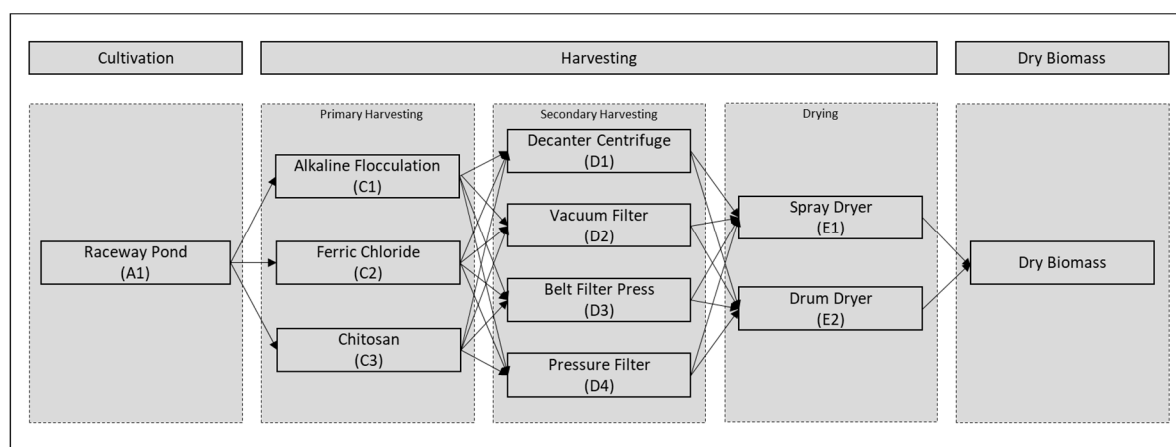

Figure 2. Technologies for microalgal lipid production scenarios.

2. Materials and Methods

2.1. Process Flowsheet and Scenarios Description

For this study, the open pond culture system (raceway pond) was selected due to its lower construction and operation cost (as compared to photobioreactors), and its greater industrial application [28,49].

It is necessary to select the species of microalgae that will be taken as a reference for the simulation before searching and establishing the operating conditions for each of the technologies involved in the production of oils. The species *Chlorella vulgaris* was selected, since, according to the review of the literature, the lipid oils of this species are mostly of high quality, in addition to being a species that are easily adaptable to different cultivation and substrate conditions (desirable characteristics for cultivation large scale) [50]. It also has a short growth cycle, so the cultivation time is much shorter,

which reduces the risk of contamination with unwanted species. The wide availability of information on this species, the great capacity to grow under high concentrations of CO_2, and the high capture efficiency are other important reasons for the choice of this microalgae i [19]. After the selection of the microalgae species, the operating conditions reported in the literature were searched for each of the technologies to be evaluated. Technologies applicable to industrial scale were considered, discarding those with high energy consumption, or little applicable on a large scale. Subsequently, the process models for the production of microalgae biomass were simulated in SuperPro Designer v10®for evaluation.

2.1.1. Model Design and Case Descriptions

1 ha was established as the cultivation area. The mass and energy balances were modeled while considering a biomass productivity per area of 12.71 g/m^2/day, a low productivity when compared to other authors, such as Musa et al. [51], which considers in its analysis 20 g/m^2/day, and Juneja et al. [52], with 25 g/m^2/day. The concentration of algae going out the pond was 0.9 g/L (12 days retention time). The operating conditions for the culture were taken from the experimental data that were reported by Sharma et al. [53]. It was considered an aeration to the system (fed at 0.03 vvm) mixed with the combustion gases from a thermoelectric plant, with a typical composition of 11% v/v CO_2 [23], and the selected species captures 46% w/w of the CO_2 fed and 1.83 kg of CO_2 can be fixed by kg of biomass, as reported by Cheah et al. [19] and Chisti et al. [54]. For this study, the cost of transporting CO_2 to biomass cultivation facilities is not considered; further studies will analyze the possibility of installing microalgae production systems near CO_2 effluent facilities. The inoculum preparation in a photobioreactor with a final concentration of 1.5 g/L of biomass was considered as fresh feed to the raceway pond. This stream is mixed with the stream that contains the nutrients that are needed for the culture.

Harvesting is necessary after the cultivation of the microalgal biomass. In this analysis, the harvest stage is divided into two: the first one has the purpose of concentrating the biomass to 50 g/L (approximately, 5% w/w), while the second concentrates the biomass to 200 g/L (approximately, 20% w/w). The first stage includes flocculation in a clarifier. Three flocculants, NaOH, $FeCl_3$ and Chitosan were evaluated, generating three cases for this stage (C1, C2, and C3, respectively). The minimum doses and separation efficiencies were taken from a study conducted by Lama et al. [55] for the flocculation of several species of microalgae, including the species *Chlorella vulgaris*. Table 1 reports the operating conditions. In the second harvest stage, which is fed by the previous stage, three filtration technologies and one centrifugation technology were evaluated, generating four case studies (D1, D2, D3, and D4). For the evaluation of these technologies, it was established that the biomass could be concentrated to approximately 20% w/w, with efficiencies of 90% biomass removal for all of the technologies evaluated at this stage. Removal efficiencies and the final concentration reached at this stage were established based on what was reported by the literature [48,52]. There are some other technologies for the two harvest stages; however, they are technologies that lead to high energy consumption, some of them due to the need for high operating time. Table 2 summarizes the operating conditions that were used for the simulation and evaluation of technologies for harvesting in stage 2.

Table 1. Considerations for the first harvest (Flocculation) [55].

| Variable	Case C1	Case C2	Case C3
Flocculant	NaOH	$FeCl_3$	Chitosan
Flocculant dose (mg/L)	125	30.52	36.36
Initial biomass concentration (g/L)	0.9	0.9	0.9
Final biomass concentration (g/L)	50	50	50
Removal efficiency (%)	94.28	95.71	95.71

Table 2. Considerations for the second harvest (Centrifugation and Filtration) [51,56,57].

Variable	Case D1	Case D2	Case D3	Case D3
Technology	Decanter Centrifuge	Vacuum Filter	Belt Filter Press	Pressure Filter
Initial biomass concentration (g/L)	50	50	50	50
Final biomass concentration (g/L)	200	200	200	200
Final humidity (% w/w)	80	80	80	80
Removal efficiency (%)	90	90	90	90
Energy (kWh/m^3)	8.7	5.8	0.88	0.9

The collected microalgae biomass is still quite wet (approximately 80% w/w of humidity) and the biomass is highly perishable under these conditions. To prevent the decomposition of biomass, it must be processed immediately after harvest or dried for later use. This study analyzes two drying technologies, Spray dryer (Case E1) and Drum dryer (Case E2). These two technologies were selected due to their use on an industrial scale. Drying in the sun is not viable, due to the large areas used and the possible loss of biomass [6,28]. For the evaluation of drying technologies, it was established as a maximum final humidity of 5% w/w and 40 °C as an outlet temperature, since it has been reported that, if the temperature is higher, this can cause important changes in the composition of biomass [57]. Table 3 summarizes the operating conditions. Figure 3 presents the Flowsheet made in SuperPro Designer for scenario 1.

Table 3. Drying stage considerations [57].

Variable	Case E1	Case E2
Technology	Spray Dryer	Drum Dryer
Initial biomass concentration (g/L)	200	200
Final biomass concentration	992.74	992.74
Final humidity (% w/w)	5	5
Outlet temperature (°C)	40	40
Energy (kWh/kg evaporated)	1.16	0.89
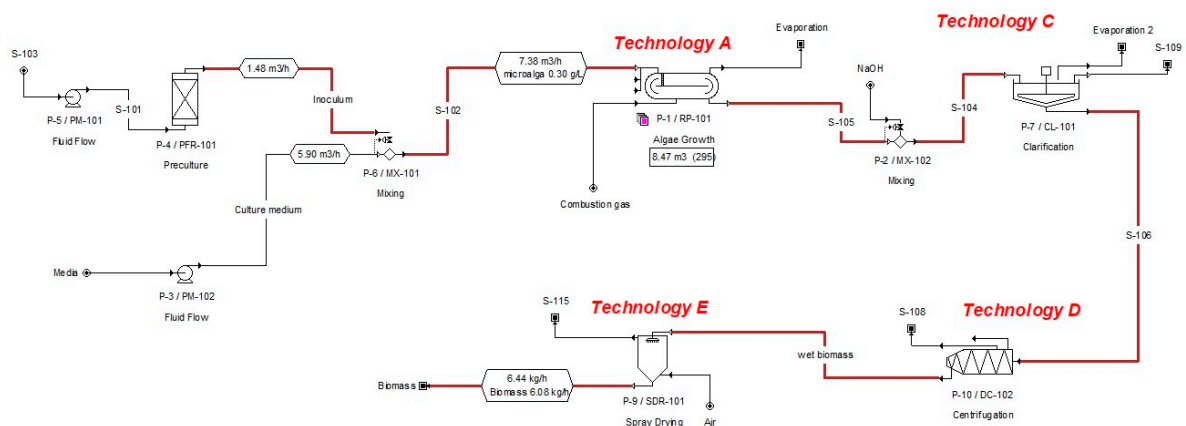
Figure 3. Flowsheet for the production of microalgae biomass.

2.1.2. Techno-Economic Analysis

SuperPro Designer v10®simulated the evaluation of established models for microalgae biomass production routes. 330 working days were considered, in continuous operation mode. 24 production routes resulted in combining the various technologies that were established for each process stage (Table 4). Each process model contains four sections: preculture, growth (cultivation), harvesting, and dry, Figure 3. For each technology included in the process, the simulator performed the balance

of matter and energy, in addition to the evaluation of the equipment size. Table 5 reports the costs associated with the services for the process. The energy consumption was evaluated by process stage and scenario, as well as the operating costs, including the costs that are associated with the consumption of raw material, services, and labor mainly.

Table 4. Technological scenarios for the production of microalgal oil.

No.	Scenario	No.	Scenario	No.	Scenario
1	A1-C1-D1-E1	9	A1-C2-D1-E1	17	A1-C3-D1-E1
2	A1-C1-D1-E2	10	A1-C2-D1-E2	18	A1-C3-D1-E2
3	A1-C1-D2-E1	11	A1-C2-D2-E1	19	A1-C3-D2-E1
4	A1-C1-D2-E2	12	A1-C2-D2-E2	20	A1-C3-D2-E2
5	A1-C1-D3-E1	13	A1-C2-D3-E1	21	A1-C3-D3-E1
6	A1-C1-D3-E2	14	A1-C2-D3-E2	22	A1-C3-D3-E2
7	A1-C1-D4-E1	15	A1-C2-D4-E1	23	A1-C3-D4-E1
8	A1-C1-D4-E2	16	A1-C2-D4-E2	24	A1-C3-D4-E2

Table 5. Data of service and raw material costs.

Kind of Service	Cost	Unity
Electrical power	0.1	US $/kWh
Steam (Heat)	12	US $/ton
Cooling water	0.05	US $/ton
NaOH	350	US $/ton
$FeCl_3$	650	US $/ton
Chitosan	1680	US $/ton

3. Results and Discussions

3.1. Technical Evaluation, Mass, and Energy Balances

3.1.1. Microalgal Growth

1 ha was established as a cultivation area, with a productivity of 12.7 $g/m^2/day$, while considering a low rate for any circumstance that could occur during cultivation. A production of 57 ton/ha/year is achieved under the operating conditions considered. Some studies consider production rates of up to 30 $g/m^2/day$ [58]; however, the microalgal biomass production rates in the raceway pond system (averaged over a year) have reached a value of around 20–22 $g/m^2/day$ [59]. Higher production rates can be achieved, but this for short periods of production, because the environmental conditions for a year are changing. According to the conditions that are considered for the design, 295 raceway pond system of 6.51 m $\times$ 2.6 m $\times$ 0.5 m (length, width and depth) each are required (according to the operating conditions used) [53]. For the arrangement of the cultivation systems, not only the footprint of the area occupied by each system was considered, but also the shadows that they cast, since this area is not used to install other bioreactors. Table 6 summarizes some results.

Table 6. Results for the cultivation stage.

Variable	Value	Unity
Annual CO_2 capture	102.13	ton/year
Annual fresh water consumption	58,061	$m^3/year$
Raceway pond units	295	units
Annual biomass production	56.81	ton/ha/year
Energy consumed (Preculture, tubular photobioreactor)	16,958	kWh/year
Energy consumed (Cultivation, raceway pond)	21,617	kWh/year

CO_2 and nutrients are necessary to maintain this biomass production. Cheah et al. [19] reports that the cultivation of the *Chlorella* species in raceway pond has CO_2 removal efficiencies of up to 46%, that is, the difference in CO_2 concentration of the influent and effluent. A capture of up to 102.13 ton/year of CO_2 in the system is calculated (Table 6) based on these data and that the aeration to the system (supplied at 0.03 vvm) contains 11% v/v of CO_2. Under the conditions established for this study, a requirement of 105,747.58 ha is calculated for the capture of 10.8 Mton of CO_2 emitted by the largest power plant in Mexico, with a capacity of 2778 MW, the Plutarco Elías Calles thermoelectric plant, located in the municipality de La Unión de Isidoro Montes de Oca, Guerrero, México [60]. Gonçalves et al., reported a capture 110 tons of CO_2/year in 1 ha of cultivation, similar to what was obtained in this study [61]. This CO_2 capture depends on the species selected, biomass productivity, and capture efficiency. Manickam et al. report that approximately a 40 ha algal pond is required for mitigating the CO_2 emitted from 1 MW coal based power unit, at 50% capture efficiency [62]. Behera et al. reported the requirements of 279 ha algal ponds to capture the flue gas from the 240 MW power Plant in Odisa [63]. The established area also depends on the total emissions of each power plant, and not all of them emit the same amounts of CO_2, since these depend on the fuel and technology used for energy production. On the other hand, using photobioreactors for cultivation could increase the biomass productivity of microalgae; this also significantly reduces the cultivation area.

The results show that the consumption of fresh water for the culture is 58,061 m^3/year. The use of wastewater is an option for reducing water consumption; it is also a source of essential nutrients to produce microalgae biomass, which would contribute to the saving of nutrients for the culture. In several case studies, the *Chlorella* species has been isolated from wastewater treatment plants, which gives it advantages to be cultivated while using wastewater effluents [64].

Several similar studies only consider the model for the cultivation of biomass and leave out the preparation of the preculture that is necessary for feeding the raceway pond. In this study, it was established that the preculture was performed in a tubular photobioreactor, achieving a final biomass concentration of 1.5 g/L [65], which is then mixed with the culture medium and fed to the raceway pond. It has been reported that the cultivation of biomass in photobioreactors is more efficient in biomass production, but the energy consumption is higher in these systems [66–68]. In this case, the preculture consumes 44% of the total energy consumption for the cultivation of biomass, while the rest is associated with the raceway pond (56%).

3.1.2. Harvest

For the harvest of the microalgae biomass, there are several ways to achieve it; however, the options are reduced if the purpose is its application at the industrial level. The total flow from the ponds to the harvesting section was 7841 L/h, with a concentration of 0.91 g/L of microalgal biomass. The biomass harvest, which generally requires one or more solid-liquid separation steps, can be a great technical and economic obstacle in the cultivation of microalgae biomass, since it can represent between 20–33% of the total biomass production cost [25,29]. To reduce costs due to high energy consumption, it has been reported that harvesting in two stages minimizes the costs that are associated with energy [69].

The first stage evaluates the primary concentration of biomass by flocculation, evaluating three flocculants with different operating mechanisms. Flocculation concentrates the diluted biomass from 0.9 g/L to 50 g/L (5% w/w). There are different flocculation mechanisms and a wide variety of flocculants that can be used. The flocculant usually used depends on the selected microalgae species, since each specie has specific physicochemical characteristics that must be taken into account [70]; or, the design of the first harvest stage, chemical flocculation is analyzed, being induced by an increase in pH (also known as auto-flocculation) by adding sodium hydroxide to the culture (Case C1), a second case by adding an iron salt, because it is an efficient flocculant, and does not require a modification of the culture medium (Case C2), and a third case flocculated with Chitosan (natural biopolymer), since it does not contaminate the biomass and shows successful flocculant activity (Case C3). The results that

were obtained by Lama et al. [55] were taken as a basis. It is assumed that the production of microalgae is constant throughout the year.

The removal efficiencies in flocculation are not the same for the three cases analyzed, which is why the small variation in biomass production. Although in Case C1 the consumption of flocculant is higher, the cost that is associated with the raw material is even higher for Case C3, since the flocculant (in this case the Chitosan) is, respectively, 2.6 or 4.8 times more expensive than the other two flocculants, significantly increasing the operating costs for Case C3. The selection of the appropriate flocculant depends on the final use of the biomass, since it can often be contaminated by the chemicals used for flocculation, which limits its application [71]. For example, the use of ferric salts might contaminate the biomass due to the metals used; it has been shown to cause brown-yellow coloration in the microalgae, causing pigments to not be extracted, and makes it difficult to apply as biomass for biofuel or animal feedstock [69]. The consumption of Chitosan as a flocculant has been reported as effective and it does not contaminate the biomass; however, its high cost avoids its implementation if its purpose is not to obtain a higher quality biomass [72]. On the other hand, if the objective is to reduce the overall cost of production, the $FeCl_3$ salt should be applied, since the required quantities and the costs of the flocculant are low when compared to the others. Another option, for alkaline flocculation, sodium hydroxide could be replaced by slaked lime, which costs 50% less [73]. A great advantage of flocculation is that this method allows for almost 90% of the culture medium to be recycled after sedimentation that is caused by a flocculant; however, some considerations must be taken into account [36]. Even so, it is desirable that the harvest method allows recycling of the culture medium and thus reduce the nutrient costs for the culture [69]. In this study, the recycling of the clarifier supernatant is not evaluated. The energy consumption in the three cases analyzed are the same; however, the operating costs do significantly vary (Table 7), mainly due to the flocculant necessary for each case analyzed.

Table 7. Results for the first harvest (Floculation).

Variable	Case C1	Case C2	Case C3
Harvest area (m^2)	5.92	5.92	5.92
Tank Depth (m)	3	3	3
Biomass Production (kg/year)	53,495.11	54,306.51	54,306.51
Annual flocculant consumption (kg/year)	7809.12	1900.8	2273.04
Material Cost (US $/year)	3819	1866	4990
Electrical Power (kWh/year)	5837	5836	5837
Operating Cost (US $/year)	13,000	11,000	14,000
Unit Production Cost (US $/kg)	0.25	0.21	0.26

The second stage is intended to dehydrate the biomass that is concentrated in the previous stage, from 50 g/L to 200 g/L (approximately 20% w/w). The second harvest stage evaluates centrifugation and three different filtration technologies, that is, four case studies (Table 8). Centrifugation (Case D1) is effective in the collection of microalgae, with a recovery greater than 90% and it can be obtained in a short time; the fast and efficient nature of this method makes it one of the preferred methods for collecting [29,57,71]. Filtration is usually applied after flocculation. Its application requires maintaining a pressure drop through the system to force the flow of fluid through a membrane [69]. There are different filtering technologies that are applicable to the microalgal biomass dehydration process. Vacuum filtering (Case D2), filtering with a band press (Case D3), and plate press filter (Case D4) were evaluated. The use of membrane filtration technologies was discarded, due to the high cost of operation and consumables required, and that their large-scale application is limited [69]. Efficiencies of 99.99% have been reported for centrifugation and 90% for filtering for the *Chlorella* species [48,52]. Based on this information, efficiency in all technologies was set at 90%, achieving biomass concentrations of 200 g/L.

Table 8. Results for the second harvest (Centrifugation and Filtration).

Variable	Case D1	Case D2	Case D3	Case D4
Biomass Production (kg/year)	48,145.6	48,145.6	48,145.6	48,145.6
Electrical Power (kWh/year)	9308	6213	941	963
Operating Cost (US $/year)	75,000	14,000	71,000	11,000
Unit Production Cost (US $/kg)	1.55	0.29	1.47	0.23

The production of biomass in each of these technologies depends on what is fed, since flocculation does not have the same removal efficiencies for all cases evaluated. Belt filtering technology (Case D3) is the one with the lowest energy consumption, while centrifugation is the one with the highest energy consumption. All of the technologies were evaluated under the same removal efficiency (90%) in order to make the comparison. The operating cost includes costs that are related to the demand for a number of resources (i.e., raw materials, consumables, labor, utilities, and power), as well as additional operational cost, such as the costs that are associated with equipment maintenance, taxes, and others expenses that might be occurred in the process. In this evaluation, the operating costs are higher for Case D1 and D3, due to the high cost of equipment, which implies an increase in the costs that are associated with maintenance, and the longer operating time that is necessary to operate Case D3.

3.1.3. Biomass Drying

The microalgae biomass is perishable; it is therefore necessary that, immediately after the previous stage (dewatering), it is processed. On the other hand, if the storage of the biomass is necessary, or if the oils will be extracted by chemical solvents, then it must be dried to increase the extraction efficiency. Two technologies for drying biomass were evaluated, being considered for their industrial applicability. For Case E1, spray drying is analyzed, while, for Case E2, Drum Dryer technology is analyzed. Table 9 shows the results.

Table 9. Results for drying microalgae biomass.

Variable	Case E1	Case E2
Biomass Production (kg/year)	48,145.6	48,145.6
Electrical Power (kWh/year)	1938	1497
Operating Cost (US $/year)	34,000	18,000
Unit Production Cost (US $/kg)	0.71	0.37

According to the results, the operating costs are almost double for Spray Dryer (Case E1) with respect to Drum Dryer; this due to the high temperature in the air for drying, demanding too much energy in the form of heat [32]. On the other hand, a disadvantage of the Drum Dryer (Case E2) is that the temperature of the product might exceed the denaturation temperature of the proteins; therefore, these systems are not preferred if their purpose is the drying of biomass with high proteins quality [57]; however, if the purpose of biomass is for the production of biofuels, this technology can be considered, due to its lower energy consumption when compared to Spray Dryer. The selection of technology for drying depends on both the scale of production and the purpose for which dry biomass is destined [74]. As an alternative for the reduction in energy consumption in the drying of microalgal biomass, the residual heat of the power plant from which CO_2 is obtained should be used [75]. On the other hand, some methods of obtaining energy or products from microalgae are carried out with wet biomass, which would avoid energy consumption by drying the biomass.

3.2. Evaluation of Biomass Production Routes

The combination of the different technologies that were evaluated at each stage of the process generated 24 scenarios to evaluate (Table 4). One of the main parameters to consider in the design of processes is energy consumption. Energy consumption is mainly associated with the need for

continuous feeding of water, nutrients, the circulation of the culture medium in the raceway pond, and the energy requirement for harvesting and drying biomass. The 24 scenarios are compared according to energy consumption, as in Figure 4. Scenario 6 is the one with the lowest energy consumption, with 46,840 kWh, for a 48.15 ton/year production of biomass. This scenario includes the cultivation in raceway pond, flocculation with NaOH, Belt Filter Press, and Spray Dryer. On the other hand, scenario 17 (producing 48.8 ton/year of biomass and consuming 55,740 kWh) is the one with the highest energy consumption; the cultivation is in raceway pond, flocculation with Chitosan, Centrifuge, and Spray Dryer. In general, it is observed that those routes that consider the Centrifuge and Vacuum Filter for dewatering are those with the highest energy consumption, while those that use Belt filtration and Pressure Filter are the ones with the lowest energy consumption. The total energy consumption of the evaluated routes is distributed, as follows: for the cultivation stage including pre-cultivation, they range from 69% to 82%, from 14% to 27% for the harvest, and 2.7% to 4% for the drying of the biomass, as in Figure 5.
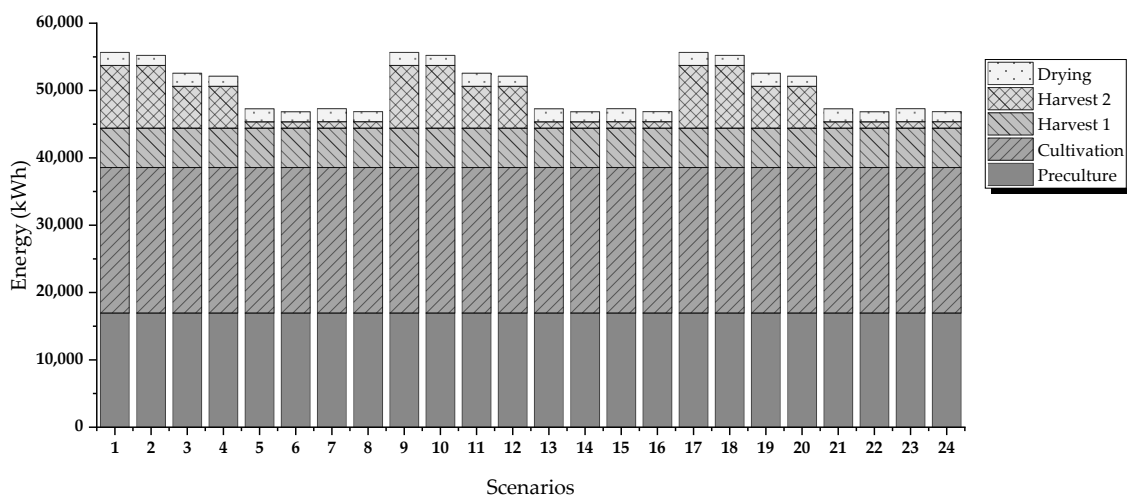

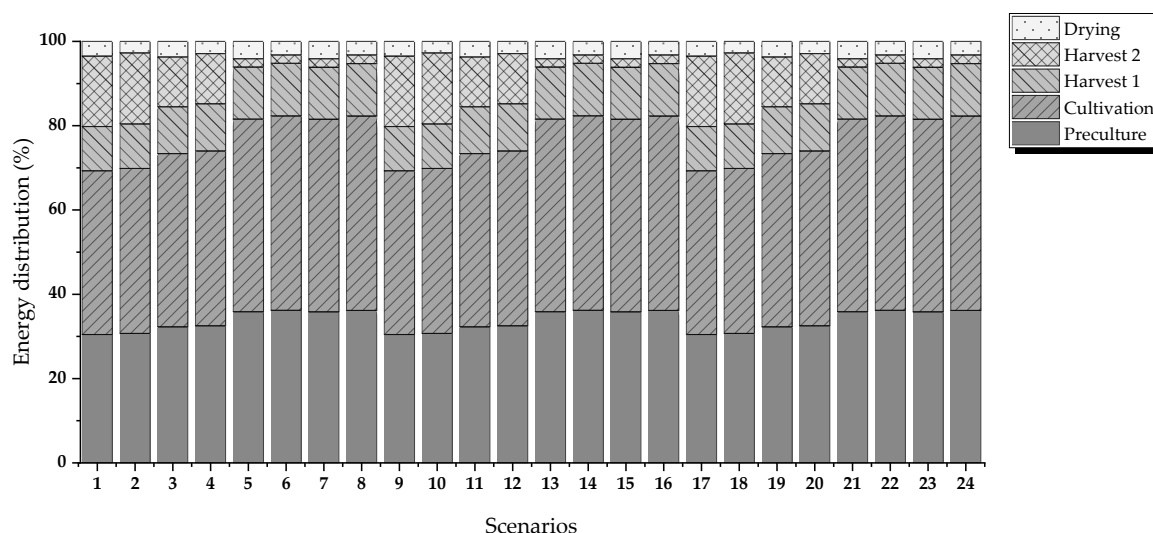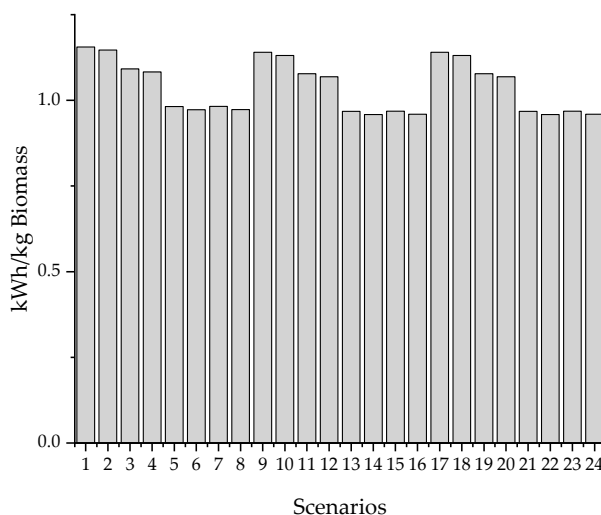**Figure 4.** Total energy consumption per scenario evaluated.

Figure 5. Distribution of total energy consumption per scenario evaluated.

The routes with the lowest energy consumption are 14, 16, 22, and 24W when the scenarios are compared with respect to their energy consumption per kilogram of biomass produced (Figure 6). These scenarios have the harvest by flocculation with $FeCl_3$ and Chitosan (higher flocculation efficiencies), Belt filtration and Pressure Filter (lower energy consumption), and drying of biomass

in Drum Dryer (lower energy consumption) in common. Scenario 1 is the worst evaluated, since the amount of biomass produced is the lowest and includes in its collection the Centrifugation and Spray Dryer (technologies with the highest energy consumption). Weschler et al., [76] performed an energy analysis for algae biomass production while using different production scenarios. They included two cultivation technologies, two technologies for primary harvest, four technologies for secondary harvest, and one technology for drying. Weschler et al. calculated an energy consumption of 2600 kWh/1000 kg of dry biomass produced for one of the evaluated scenarios (Raceway pond for cultivation, flocculation for primary harvest, chamber filter press for secondary harvest, and mechanical steam recompression dryer for thermal drying), in our study scenario 15 (Raceway pond, flocculation, pressure filter, and spray dryer) is comparable, obtaining an approximate energy consumption of 970 kwh/1000 kg of dry biomass produced, being 62.69% less. In both studies, the energy consumption for each stage of the process is similar, but the concentrations that were specified in each stage of the process change. As Weschler et al. mentions, the selection of technological parameters shows the sensitivity in the energy demand of these processes, and, therefore, the difference between the results in both studies. Other studies have reported that the increase in biomass productivity considerably reduces energy consumption [77], so we must look for alternatives to have higher biomass productivity in the cultivation.

Figure 6. Total energy consumption per kg biomass produced for the scenarios evaluated.

Microalgae Production Cost of Case Study

Operating costs are mainly associated with energy consumption and raw materials for the process. In general, a behavior in operating costs, like energy consumption, is shown (Figure 7). The highest operating cost in all of the scenarios evaluated is associated with the microalgae culture stage (including the preparation of the pre-culture in photobioreactor and the cultivation in raceway pond), these represent between 61% and 82%, while 9 % to 30% are associated with the harvest and from 6% to 14% to the drying of the biomass (Figure 8). The productivity set for this study was 12.7 g/m^2/day, under this condition, scenario 8 (consisting of cultivation in raceway pond, harvesting with NaOH as flocculant, Pressure Filter, and Drum Dryer for drying) has the lowest cost of operation, US $ 4.75/kg, while scenario 1 is the one with the highest cost, US $ 6.55/kg. The energy consumption for scenario 1 is 1.16 kWh/kg, being the highest energy consumption per kilogram of biomass produced, which causes it to be the route with the highest operating cost. If it were possible to increase productivity in biomass cultivation, the operating costs of the process route would be significantly reduced. Hoffman et al. [78] have reported the production cost of wet biomass (does not include drying) at 0.673 US $/kg, under a productivity of 20 g/m^2/day, being much higher than the one that is assumed in this study.
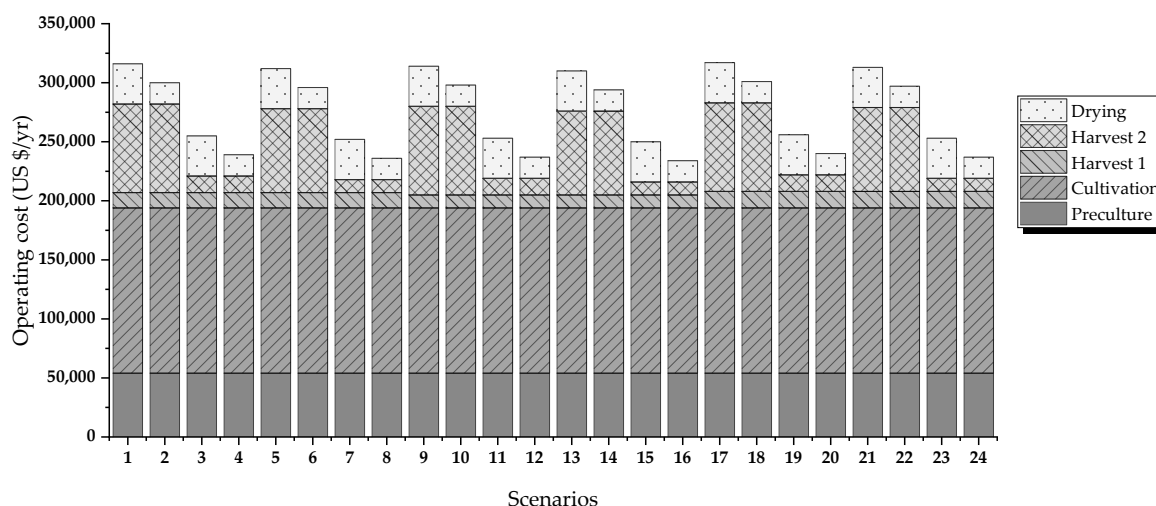
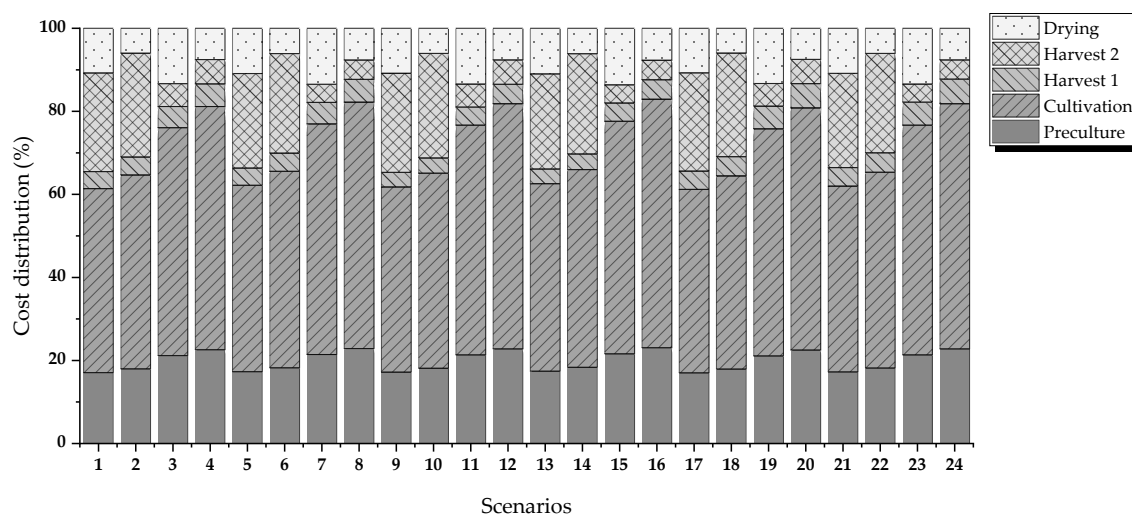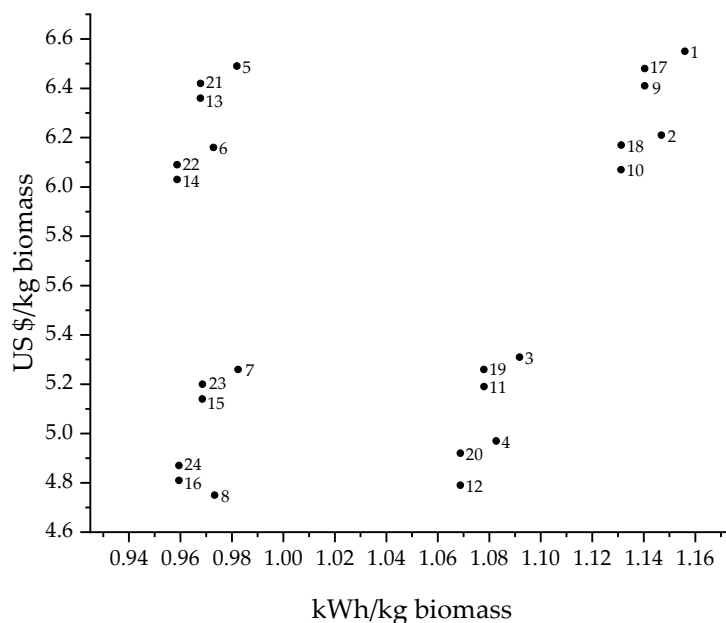**Figure 7.** Total operating costs per scenario evaluated, US $.

Figure 8. Distribution of total operating costs per scenario evaluated.

The choice of the appropriate parameter for your election is one of the great challenges in selecting a better process path. A comparison of both parameters was made to establish the best evaluated scenario, while considering energy consumption and production cost. Figure 9 shows the energy consumption and the total operating cost per kg of dry biomass produced for each scenario formed with the technologies shown in Figure 2 and the combinations that are shown in Table 4. As we can see, the best-evaluated scenarios are 8, 16, and 24 (found in the lower left corner of Figure 9), which have lower energy consumption and operating cost. The three scenarios have the Pressure Filter and Drum Dryer technologies in common, while the flocculant is NaOH, $FeCl_3$, and Chitosan, respectively. The Pressure Filter is not the technology with the lowest energy consumption; however, its maintenance cost is lower when compared to the Belt Filter Press. Maintenance costs are associated with the purchase cost of the equipment and, in this case, the Belt Filter Press is approximately 6.5 times more expensive than the Pressure Filter, which causes a higher maintenance cost. The higher energy consumption of scenario 8 is due to the lower removal efficiency in the flocculation considered (1.5% less than Case C2 and C3), which causes the amount of collected biomass to be lower, under the same energy consumption as the other two scenarios. If only the production cost is considered, scenario 8 has the lowest cost (US $ 4.75/kg), however, because higher energy consumption is associated with higher CO_2 emissions, the scenario of lower energy consumption is preferable, in this case, scenario 16

(0.96 kWh/kg and 4.81 US $/kg). An environmental impact assessment is necessary to have a clearer idea about the emissions generated in the process.

Figure 9. Total energy consumption vs. total operating costs per kg biomass produced.

The group of scenarios that appear in the upper left corner considers a Belt Filter Press. This technology has low energy consumption, but with a high maintenance cost, which results in high operating costs, as mentioned earlier. In the lower right corner are the scenarios that consider a Vacuum Filter; these have high energy consumption and low operating costs, which is due to its low maintenance cost. On the other hand, those scenarios that consider a Centrifuge as the second stage of harvest, have high-energy consumption and a higher operating cost, which is due to the nature of the centrifuge's operation. The costs of the Decanter Centrifuge and Belt Filter Press equipment are similar, so maintenance costs are also similar; however, the energy consumption of the Centrifuge is 9308 kWh/year versus 941 kWh/year consumed by the Belt Filter Press, almost 10 times more, which is clearly reflected in the operating costs in each group of scenarios. The obtained results clearly show the direct contribution of the technologies that are involved in the process of obtaining microalgae biomass, both energy consumption and operating costs.

4. Conclusions

Microalgae have great capacity to capture CO_2; however, the cultivation in open systems entails a low capture efficiency when compared to closed systems. Conditions should be sought to increase biomass productivity and thereby increase CO_2 capture and, thus, reduce the area required for cultivation, and the operating costs associated with the biomass harvest would be reduced. The operating costs for the cultivation stage are high, mainly due to the energy consumption in the preparation of the preculture that uses a tubular photobioreactor. It has been reported that Flat Plate Photobioreactors can even achieve higher productivity [57] and their energy consumption is lower [79], being an option to consider for its implementation in preculture preparation. The selection of technologies for harvesting depends on the final use of biomass; however, technologies, such as centrifugation and vacuum filtration are those with the highest energy demand. Scenarios 8, 16 and 24, are the best evaluated, since they have lowest energy consumption (0.97, 0.96, and 0.96 kWh/kg, respectively) and lower operating costs (4.75, 4.81, and 4.87 US $/kg, respectively). Scenario 12 presents an operating cost that is similar to scenario 8; however, energy consumption is 12% higher than scenarios 16 and 24. For the choice of a single route as the best one, it must be selected in terms of

energy consumption or lower operating cost, whereas, if the objective of implementing these biomass production systems, process routes with the lowest energy consumption should be selected and, thus, reduce the emissions that are associated with the process.

The results of this study generate a basis for the development of future research that wishes to deepen, in detail, the production of *Chlorella* microalgae biomass, since it shows a direct interaction of the combination of technologies that can be applied, also shows the potential to capture CO_2 that can be obtained by implementing these systems.

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