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Techno-economic assessment of microalgae production, harvesting and drying for food, feed, cosmetics, and agriculture

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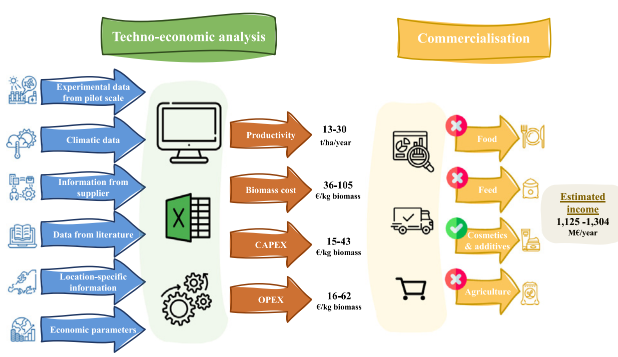
HIGHLIGHTS

- Production of *Nannochloropsis* and *Tisochrysis* + *Phaeodactylum* at 1-ha in Portugal
- *Nannochloropsis* production results in 28 t/ha/y and a cost of 53 €/kg DW.
- *Tisochrysis* + *Phaeodactylum* production results in 13 t/ha/y and a cost of 105 €/kg DW.
- Scale up to 10-ha could reduce production cost in 18% for *Nannochloropsis*.
- *Tisochrysis* + *Phaeodactylum* commercialisation could result in a 22% greater income.

GRAPHICAL ABSTRACT



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ABSTRACT

The objective of this techno-economic analysis is to define the costs for an industrial microalgae production process, comparing different operation strategies (*Nannochloropsis oceanica* cultivation during the whole year or cultivation of two species, where *Phaeodactylum tricornutum* and *Tisochrysis lutea* alternate), production scales (1 and 10 ha), harvesting technologies (centrifugation or ultrafiltration) and drying methods (freeze-drying or spray drying). This study is based on an industrial scale process established in the south of Portugal. The strategy of cultivating *N. oceanica* all year round is more attractive from an economic perspective, with production costs of 53.32 €/kg DW and a productivity of 27.61 t/y for a scale of 1 ha, a 49.31% lower cost and two-fold productivity than species alternation culture strategy. These results are for biomass harvested by centrifugation (10.65% biomass cost) and freeze-drying (20.15% biomass cost). These costs could be reduced by 7.03% using a combination of ultrafiltration and spray drying, up to 17.99% if expanded to 10 ha and 10.92% if fertilisers were used instead of commercial nutrient solutions. The study shows potentially competitive costs for functional foods, food, and feed additives, specialised aquaculture products (live feed enrichment) and other high value applications (e.g., cosmetics).

Abbreviations: EU, European Union; DW, Dry Weight; PBR, Photobioreactors; PHT, *Phaeodactylum Tricornutum*; TISO, Tisochrysis Lutea; NAS, Nannochloropsis Oceanica; HRT, Hydraulic Retention Time; UV, Ultraviolet; UF, Ultrafiltration; PMMA, Polymethyl Methacrylate; CAPEX, Capital Expenditures; OPEX, Operational Expenditures; PE, Photosynthetic Efficiency; MEC, Major Equipment Cost.

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1. Introduction

The European Union (EU) adopted a bioeconomy strategy in 2012 (European Commission, 2012), which was updated in 2018 (European Commission, 2018). This strategy aims to support the innovative use of biological resources to meet the growing demand in the food, energy, and industrial sectors, creating new employment, innovation, and services for a growing population. In this context, microalgae are raising high expectations as a resource for various commercial sectors (food, feed, cosmetics, nutraceuticals, fertilisers, bioenergy, and bio-based products (Fernández et al., 2021)). CO_2 absorption and O_2 production, the content of various compounds of interest, high productivity, the possibility of using waste flows for its cultivation, and the fact that it does not compete with agriculture for resources are reasons for this increased interest. At the same time, they contribute to addressing global and local challenges (climate change and sustainable development) while also committing to some of the Sustainable Development Goals set out in the Agenda 2030 of the EU (UN General Assembly, 2015).

Despite the growing interest and potential of microalgae as an innovative sector within the EU bioeconomy, the production volume and market size are still small. An estimated production volume of 25,000 t per year (Fernández et al., 2021) and a value of the marine biotechnology market (the main component being microalgae) of 2.4 billion euros was estimated (Enzing et al., 2014).

Currently, microalgae are being sold as whole algae or for extraction of their compounds marketed mainly for high-value products (e.g., food supplements or nutraceuticals (Russell et al., 2022)). In contract, products with high production volume and low market value (such as biofuels (Dasan et al., 2019)) are still not commercialised. This is due, on the one hand, to various constraints limiting the expansion of the sector, such as high production costs and technological limitations, variability in biomass supply, and gaps in scientific knowledge of large-scale cultivation of microalgae (Araújo et al., 2021). In addition, the complexity and non-existence of some national and EU regulations are not boosting the development of this sector (Araújo, 2019). On the other hand, establishing a production cost is not straightforward, which is evident in the variability of the results of different studies (2.90 €/kg (Schipper et al., 2021), 5.96 €/kg (Norsker et al., 2011), 12.40 €/kg (Tredici et al., 2016), 69 €/kg (Acién et al., 2012a), 290 €/kg (Oostlander et al., 2020)). Due to the scales of work, assumptions, and lack of homogeneity in the analysis procedure from different sources. For this reason, it is necessary to do a case-by-case study, such as the present one, supported by empirical data, following the same methodology for each of the simulations.

To enable large-scale economic production of microalgae-based products, the production and biorefinery process (separation of the different biochemical compounds) must become an industrialised process in which process stability, reliability, product quality, sustainability, and economic viability, are guaranteed.

In this work, we performed a techno-economic evaluation of an industrial-scale process to produce autotrophic microalgae in closed cultivation systems (vertically stacked tubular photobioreactors (PBRs)). To this end, the effect on costs from varying different inputs was modelled (microalgae strain, final product format and technologies for harvesting and drying, and scale). This resulted in different projections with a detailed cost breakdown. The analysis is based on experimental data obtained in the BBI-JU MAGNIFICENT Project (ID: 745754).

2. Methods

This study focused on developing a techno-economic assessment of the whole process of microalgae production and subsequent harvesting and drying stages to obtain a final biomass product. The process established is thoroughly described in this section (*Description of the* process). The tool for analysis was built with Microsoft Excel® spreadsheet application, in which the inputs are introduced (see *General inputs*), and results are automatically obtained through built-in calculations, allowing the study of different scenarios. A detailed description of the model calculation methodology can be found in the Supplementary material.

2.1. Description of the process

The scheme simulated in this study is a process developed with the BBI-JU project MAGNIFICENT, based on Necton S.A.'s commercial facilities (South Portugal), but is not a representation of Necton's processes and production cost. Some modifications were made to adapt the original process to a more industrialised scale, explained throughout this section.

The process was divided into five stages, as shown in Supplementary Fig. 1: 1) Inoculation, 2) Pre-treatment of seawater, 3) Microalgae cultivation, 4) Harvesting, and 5) Drying. Each process stage is controlled and monitored simultaneously, with real-time data obtained with the *SCADA* system.

2.1.1. Inoculation

A facility section dedicated to microalgae inoculation was considered (10% of the total culture volume). In this case, closed flat-panel PBRs were considered. These are described in more detail in the section on Cultivation systems (General inputs). Three different microalgae strains; *Phaeodactylum tricornutum* (PHT), *Tisochrysis lutea* (TISO), and *Nannochloropsis oceanica* (NAS), were grown in these systems, depending on the strategy to be followed.

2.1.2. Pre-treatment

The pre-treatment starts with the pumping of the water from the Ria Formosa (Portugal) to the settlement tanks, with a maximum hydraulic retention time (HRT) of 72 h (experimental data obtained within MAGNIFICENT Project). Each tank incorporated a level probe. From this point, the water was pumped to the filtering unit using ultrafiltration (UF) membrane technology (0.03 μm). It was then disinfected with ultraviolet (UV) lamps, providing a dose of approximately 44.6 MJ/cm^2 (Atlántica-agua http://www.atlantica-agua.com). Finally, the water was nutrient-enriched in a mixing tank (HRT = 30 s) (Benvenuti et al., 2017). The culture medium used was NutriBloom ® Plus, the commercial medium developed in-house by Necton, added at a concentration of 2 mL/L of culture. The carbon source used was commercial CO_2, injected into the PBRs on demand using a pH-control system. The Necton facility commonly operates using a semi-continuous cultivation approach, but a continuous regime was adopted for this study, as it is the most productive regime. The daily dilution rates were 7.17 ± 2.37% for PHT, 8.83 ± 2.68% for TISO and 9.90 ± 0.64% for NAS, according to experimental data.

2.1.3. Microalgae cultivation

Vertically stacked tubular PBRs were considered for cultivation (15 m^3), using pumps to circulate the culture through the tubes. ABS polymer beads were used at a concentration of 1.8 kg of beads per cubic meter of culture (NAS and PHT) and 7 kg per cubic meter in the case of TISO to avoid biofouling. In addition, to ensure that the culture did not exceed the maximum temperature set point of 27 °C (PHT), 35 °C (TISO) and 35 °C (NAS), water sprinklers along the top of the PBRs, were used. After passing through the photosynthetic stage, cultures were degassed inside a tank by a cascade approach preventing O_2 accumulation.

Once the culture leaves the PBRs, it passes through a mesh vessel (HRT = 7.5 min) where the anti-fouling beads are retained. This tank is equipped with a probe that measures the water level. The culture then moves on to the next stage, harvesting.

2.1.4. Harvesting

As a harvesting method, centrifugation was used to obtain microalgae paste. In addition, this study also simulates an alternative scenario with a different harvesting process, UF through membranes.

2.1.5. Drying

Two drying alternatives were analysed. The first is freeze-drying the paste from the centrifuge, obtaining a product with 1.5% moisture. The second option is spray drying the concentrate from UF, in which a final product (powder format) with 5% moisture content is obtained.

2.2. General inputs

2.2.1. Microalgae strains

The production of three species of microalgae was studied: NAS, TISO and PHT. We considered two possible strategies for their cultivation based on experimental data. The first strategy aimed to exclusively cultivate NAS whole year-round, as this species has proven suitability to grow under all weather conditions found in Algarve. The second strategy pursued the alternate cultivation of TISO (from June to November) and PHT (from December to May). TISO requires higher temperatures to grow (12–35 °C), while PHT benefits from colder weather (5–27 °C). This alternation allows an almost uninterrupted production, otherwise unachievable for these strains. Experimental data on TISO and PHT strains are reported in the study by Pereira et al. (Pereira et al., 2021).

2.2.2. Location

The projections were simulated in the south of Portugal, specifically Olhão (37°01′40″N 7°50′20″W). It is located within the "Ria Formosa" Natural Park, an area that extends along the leeward shore of the Algarve. Area-specific data were collected for inputs to this model: climatic conditions (irradiance and temperature) (Source: EnergyPlus database), electricity, freshwater and, treating wastewater costs, as well as the salary and the contribution of employees (Supplementary Table 3).

2.2.3. Scale

Two production scales were studied: 1 and 10 ha to determine the impact of economies of scale on the final cost of biomass. The extrapolation of the purchase cost for equipment from Supplementary Table 6 to other non-specified capacities was based on the scale factor rules (Eq. (1)) (Sinnott and Towler, 2013).

$$Cost\ B = Cost\ A \bullet \left(\frac{Size\ B}{Size\ A}\right)^{n} \tag{1}$$

where:

Cost B represents the purchase cost of the equipment to be scaled, with a *Size B* capacity.

Cost A represents the cost of the *Size A* reference equipment A.

Finally, *n* is the corresponding scaling factor for each piece of equipment, collected in Supplementary Table 6.

2.2.4. Cultivation systems

The simulation has been carried out for cultivation in vertically stacked tubular PBRs. Each PBR includes 80 polymethyl methacrylate (PMMA) tubes with 63 mm outer diameter and 7 mm wall thickness. These are attached to a stainless-steel structure, with 14 fences per PBR. Each PBR is 48.5 m long, with a height of 1.7 m. The vertical distance between the tubes is 200 mm. The culture circulates (0.45 m/s) through one circulation pump per PBR. The system has a degasser (5 m^3) to eliminate the excess oxygen, located in the extreme where pumping for culture circulation is performed.

Each module (PBR + gaps + degasser) corresponds to a total ground area of 400 m^2 and a volume of 38 L per m^2 of ground area. These PBRs are the same as in the study by Pereira et al. (Pereira et al., 2021), except for the total area. Pereira et al. (Norsker et al., 2011) considered an area of 340 m^2. For our industrial approach, a slightly greater distance between module of reactors was preferred.

Although inside the tubes there are anti-fouling beads, which restricts biofouling, cleaning is required four times a year, with hydrochloric acid (0.001 *v*/v), caustic soda (0.0003 v/v) and sodium hypochlorite (0.001 v/v). In addition, for each PBR, there is an O_2, pH and temperature probes.

The inoculum production is carried out in flat panel type reactors. These panels are transparent plastic bags (LDPE) supported by a stainless-steel structure. Each flat panel (1 m^3) is 10 m long, 1 m high, and 0.1 m wide. The distance between row of 0.51 m. The bags are replaced every two weeks (except for NAS, for which this is done weekly). The flat panels have an aeration system at the bottom (tubes of aeration) to homogenise and degas the culture. Air blowers supply the airflow at a rate of 0.65 *v*/v/min (experimental data). A probe in each flat panel monitors the O_2 and temperature conditions of the culture.

2.2.5. Harvesting technologies

The model has integrated two options of technologies for harvesting: centrifugation and UF. The centrifugation process separates the microalgae from the water by driving force and can concentrate the biomass to 22% DW for TISO, 24% DW for PHT, and 32% DW for NAS, with a harvesting efficiency between 90 and 95% (experimental data). UF concentrates the biomass at 5.21% DW (experimental data), with an efficiency of 99% (Fasaei et al., 2018). The biomass not recovered in the harvesting units is considered lost. UF membranes also require cleaning with hydrochloric acid at 33% and sodium hypochlorite at 13%. Each filtration cycle filters 20 m^3, consuming 1.3 L of HCl and 0.9 L of NaClO.

2.2.6. Drying technologies

The dehydration of the biomass can be carried out in two ways, spray-drying, or freeze-drying. The selected method depends on the harvesting process. When the centrifuge is used, then the dehydration is performed by freeze-drying, as this process requires a higher percentage of solids. When the filtration membranes are chosen as harvesting technology, spray drying is then used to remove water.

The spray dryer removes 95% of the water in the final product (experimental data). This process is based on a temperature increase which allows the incoming air to dry and atomise the concentrated microalgae culture. The temperature reached is 240 °C, with the average inlet air being 17.73 ± 4.77 °C. In this stage, to heat the air for atomised biomass drying, gas natural was used, with an 80% efficiency from steam generation by gas heating (Fasaei et al., 2018).

The freeze-drying process works by freezing the material and then reducing the surrounding pressure to allow the water frozen in the material to sublimate directly from the solid phase to the gaseous phase without passing through the liquid state. It removes 98.50% of the water in the microalgae paste, and this process lasts for 24 h.

3. Result & discussion

The results of the techno-economic analysis of this study are presented in the following sections. Seven projections were simulated (Table 1), grouped into 4 cases. The aim is to determine each simulation's costs and identify the strengths and weaknesses to achieve an industrialised and economically feasible process.

In the first case, the same process was simulated as in the experimental facilities (MAGNIFICENT Project), with the objective to study two operation strategies (1a-alternating two species of microalgae and 1b-cultivation of a single strain of microalgae). The second case focuses on biomass processing, comparing the two harvesting technologies (2a-centrifugation and 2b-UF membranes). The drying process is also compared, using two alternatives, 2c-spray dryer, and 1b-freeze dryer. Once the most beneficial process from a cost standpoint is chosen, it is compared in case 3 at 1 ha (1b) and 10 ha (3a) scales. Finally, one more case, case 4, was proposed to see the influence of the culture medium source (4a use of fertilisers or 1b use of commercial nutrient solution).

Case 1. Culture strategy – Single specie vs species alternation

Two scenarios were evaluated to compare different operating strategies. Firstly, alternation of microalgae strains (case 1a); production of PHT during the coldest months (from December to May) in combination with

Table 1
Summary of projected cases.

Case	Microalgae strain	Upstream	Downstream	Source of nutrients	Scale
1	**Culture strategy – single specie vs species alternation**				
1a	TISO + PHT	PBR + centrifugation	Freeze dryer	Commercial	1 ha
1b	NAS	PBR + centrifugation	Freeze dryer	Commercial	1 ha
2	**Processing**				
2a	NAS	PBR + centrifugation	–	Commercial	1 ha
2b	NAS	PBR + UF	–	Commercial	1 ha
2c	NAS	PBR + UF	Spray dyer	Commercial	1 ha
1b	NAS	PBR + centrifugation	Freeze dryer	Commercial	1 ha
3	**Scale**				
3a	NAS	UF	Spray dyer	Commercial	10 ha
2c	NAS	UF	Spray dyer	Commercial	1 ha
4	**Culture medium**				
4a	NAS	UF	Spray dyer	Fertilisers	10 ha
3a	NAS	UF	Spray dyer	Commercial	10 ha

production of TISO during the hottest months (from June to November). This strategy pursues year-round production using two strains with limited productive seasons (Pereira et al., 2021). And secondly, cultivation of a single microalgae strain (case 1b); exclusive production of NAS throughout the year. Both scenarios follow the process proposed in this study (Supplementary Fig. 1).

For the first strategy (species alternation culture strategy: TISO + PHT), our projections determine an annual productivity of 12.94 t/ha/y with a biomass cost of 105.19 €/kg DW (dry biomass). This scenario requires an investment cost of 7.72 M€ for the 1-ha facility. The total cost is 1.36 M €/y, and 41% of this cost belongs to CAPEX. The equipment with the most significant influence on CAPEX is the PBR, representing 71.18% of the total MEC (Fig. 1) and 29.50% of the cost of biomass. OPEX represents the remaining 59% of the total cost, with labour (23.06% of OPEX) presenting the main contribution to operational costs (Fig. 1). The energy (electricity and natural gas) required per kilogram of biomass is 131.30 kWh.

Different results are obtained for the second strategy (single microalgae: NAS). In this case, the estimated productivity case is 27.61 t/ha/y (twice than in case 1a) at the cost of 53.32 €/kg DW (49% lower than in case 1a). The increase in production is due to the high value of photosynthetic efficiency (PE) of NAS (1.02%), which is derived from the experimental results, compared to PHT (0.81%) and TISO (0.38%), that species-specific PE is used during the cultivation season. This increase in production for NAS implies a rise in the cost of investment (6.50%) and the annual cost (8.18%), as larger equipment is needed to pump and process more water and biomass flows. However, as shown, the higher productivity compensates for this and biomass cost decreases.

The equipment with the most significant impact on capital costs are still the PBRs (66.83% of the total MEC, Fig. 2) and representing 27.219% of the cost of biomass, with a percentage similar to the previous one (Fig. 1).

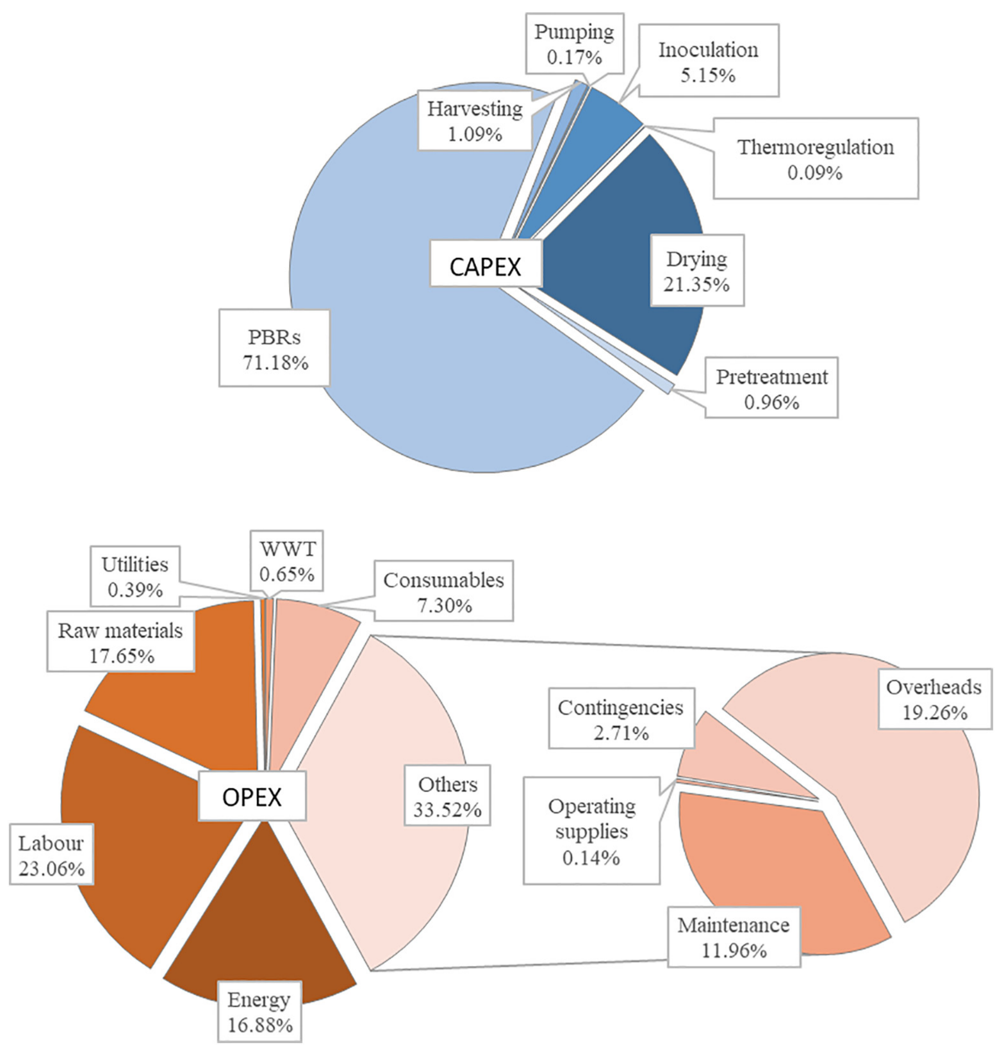

Fig. 1. Equipment and operational cost contribution for case 1a (TISO + PHT).

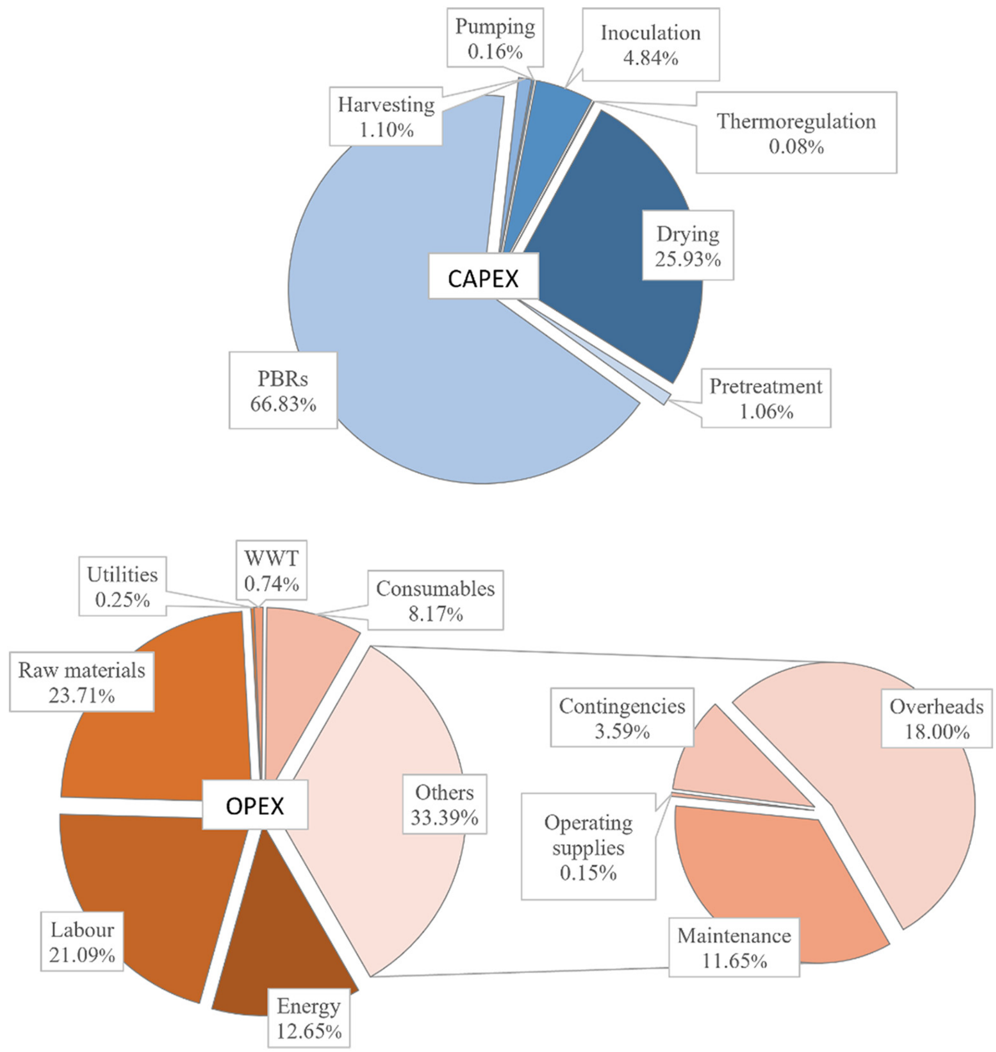

Fig. 2. Equipment and operational cost contribution for case 1b (NAS).

However, while labour was the most influential factor in operational costs for the previous case 1a, raw materials gain importance and prevail in case 1b with NAS production (23.71% total OPEX, Fig. 2). This is due to higher productivity, and therefore more nutrients and chemicals are needed to clean the PBRs.

The consumption per kilogram for NAS (50.82 kWh/kg DW) is 2.58 times lower than for TISO + PHT, mainly because of the higher production. This value is higher than in the work of Tredici et al., (5.96 kWh/kg (Tredici et al., 2016)) in which a similar process is proposed, with the difference that the equipment does not work 24 h a day as in this study.

Comparing the biomass costs with other authors (both for case 1a and case 1b), the costs of this study are high. For example, Ruiz et al. estimated a production and harvesting cost for a 1 ha installation in southern Spain of 28.40 €/kg (Ruiz et al., 2016), however the productivities used were 2 to 4 times higher.

Case 2. Processing – harvesting and drying

The strategy of culturing NAS all year round (case 1b) has shown better production and costs results; therefore, the following projections considered this microalga strain and strategy exclusively.

This section presents the cost analysis to produce different final product formats: firstly, a paste obtained by centrifugation (case 2a); secondly, a concentrated culture using UF membranes (case 2b); and finally, a microalgae powder obtained by spray-drying (case 2c) or freeze-drying (case 1b). Simulation 1b has been previously made in case 1 and is used in case 2 for comparison.

For the first scenario (case 2a), a paste is obtained by centrifugation (32% DW), producing 27.61 t/y of biomass. The estimated cost for this scenario is 44.46 €/kg DW (Fig. 3). However, the use of UF membranes (case 2b) yields 30.01 t/y at the cost of 41.28 €/kg DW (Fig. 3). UF membranes imply less biomass lost in the process, resulting in higher final production, about 8.7% higher. In terms of final cost, the centrifugation process results in biomass cost 7.7% higher than that obtained with UF. The main reasons for this are the loss of biomass during the centrifugation process and slightly higher energy consumption (28.53 kWh/kg DW biomass) than UF (25.83 kWh/kg DW biomass). There are other interesting harvesting alternatives that could contribute to cost reduction. Such as gravity settling, flocculation, electro-flocculation, auto-flocculation or flotation, which involve low equipment and operational costs (Barros et al., 2015).

To obtain a powder product using the UF membrane harvesting method, the concentrated culture is dried using a spray dryer (case 2c), resulting in an estimated cost of 49.57 €/kg DW (Fig. 3). The UF membrane harvesting, and spray-drying processes represent 2.74% and 20.08% increase in the cost of biomass, respectively. When the paste is freeze-dried after the centrifugation process, it results in a final cost of 53.32 €/kg DW (Fig. 3). The centrifugal harvesting process represents an increase of 10.65% in the cost of biomass. Furthermore, freeze-drying represents an increase of 19.93% in the cost of biomass. Although the freeze-drying process

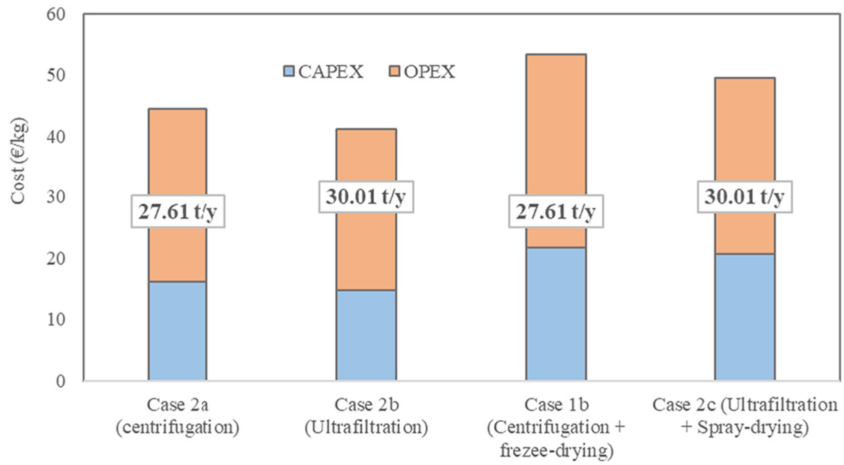

Fig. 3. Production capacity and cost for the different formats of final products (1 ha).

is considered more expensive than spray drying according to the literature (Milledge and Heaven, 2013) (Molina Grima et al., 2003) (Ansari et al., 2018), in this study both processes imply an increase in cost of 20%. However, the spray drying process consumes more energy (36.45 kWh/kg DW) than freeze-drying (22.29 kWh/kg DW). Biomass losses in centrifugation were the reason for the higher biomass cost in case 1b (centrifugation + freeze-drying). An alternative to these two drying methods could be sun drying with potentially lower cost and energy consumption (Kim, 2015). However, exclusively the original existing processes of the commercial installation of Necton S.A. are applied.

Case 3. Production scale – 1 ha vs 10 *ha*

In order to evaluate the production scale effect, the scale of the production facility was increased from 1 to 10 ha. Similar processes and conditions

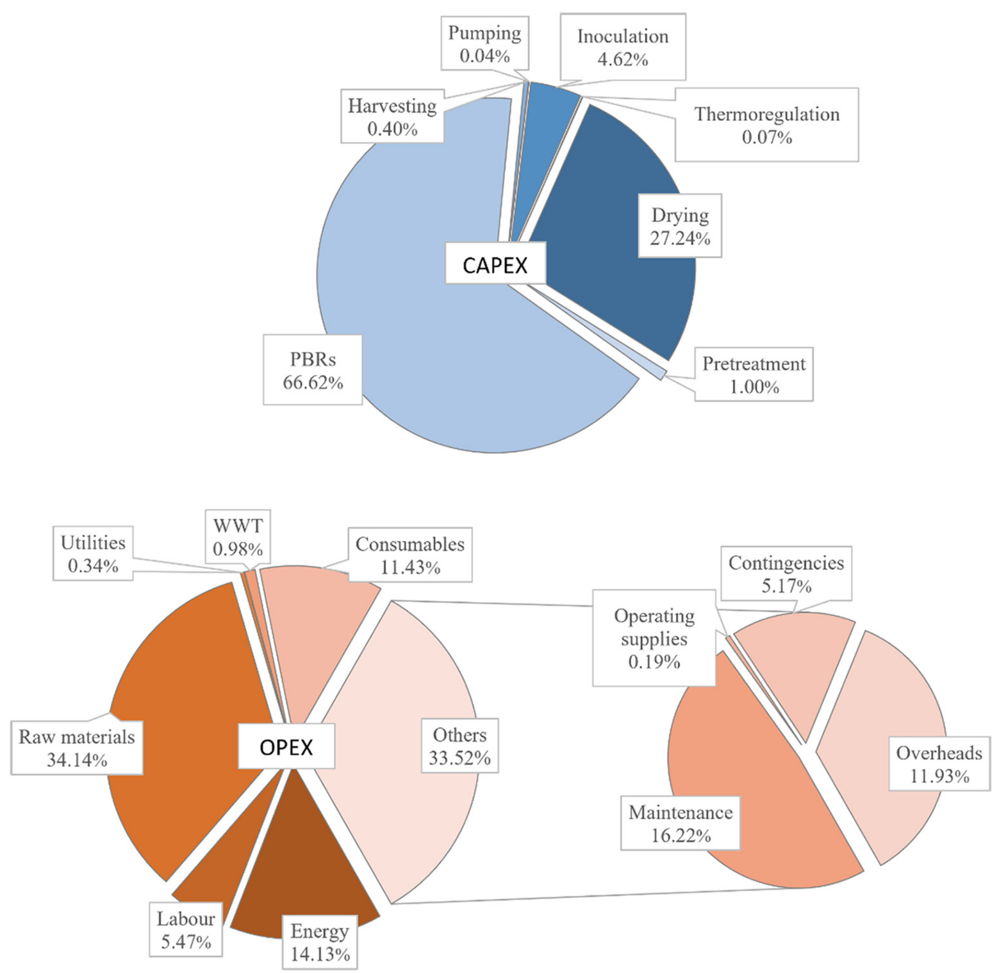

Fig. 4. Equipment and operational cost contribution for case 3a (10 ha).

simulated in case 2c were selected for 10 ha, considering only the production of NAS, and processing using UF and spray-drying.

The result of this projection (case 3a) shows a production of 300 t/y, ten times greater than the homologous case on 1 ha (case 2c). The biomass cost is reduced, from the scale effect, by 18.01% (40.65 €/kg DW).

Among this total cost, 19.83 €/kg DW corresponds to CAPEX. The most important contributor to the investment (81.61 M€) is the PBR, with 66.62% of the total MEC (Fig. 4) and 32.50% of the cost of biomass. As for operational expenses, 20.83 €/kg DW of the total biomass cost correspond to OPEX. Maintenance and raw materials (culture medium for microalgae) are the most significant expenses, with 16.22 and 34.14%, respectively, of the total OPEX (Fig. 4). This scenario presents an energy consumption of 62.71 kWh/kg DW biomass, similar to 1 ha, as the increase of scale implies replicating modules in most cases (62.28 kWh/kg DW of biomass).

Case 4. Culture medium - commercial nutrient solution vs fertiliser

Additionally, the last projection for 10 ha of production (case 4a) has been included to evaluate the identified effect of raw materials. In all previous cases (case 3a), a commercial culture medium (NutriBloom ® Plus) was used to enrich seawater as a source of nutrients for microalgae growth. However, at an industrial scale usually, bulk fertilisers are used; in this case (case 4a), urea and triple superphosphate were considered such as the study by Schipper et al. (Schipper et al., 2021). The use of these macronutrients would be a good strategy exclusively as long as micronutrients essential for the growth of the microalgae (i.e. metals) were naturally present in seawater (Millero et al., 2008). Studies have even used seawater (due to its ion concentration) to replace part of the freshwater and nutrients in the culture media, opening a way to reduce the costs of medium preparation (Jung et al., 2015). Furthermore, according to the study of Meyer (Meyer, 2012), the low concentrations of these minor nutrients represent less than 5% of the total cost. As a result, in case of 4a, the cost of biomass is reduced by 10.92% (36.21 €/kg DW) compared to case 3a (40.65 €/kg DW). As in the previous cases, the element with the most significant weight in the CAPEX (54.76% of the total cost) is the PBR (66.62% of the MEC) and represents 36.49% of the biomass cost. As for OPEX (45.24% of the total cost), maintenance (20.62% of OPEX) is estimated to be the main contributor to the operating costs.

Under this scenario, raw materials reduce their weight, going from 34.14% (case 3a) to 19.88% of OPEX (case 4a). The difference is significant in terms of OPEX: commercial culture solution accounts for 19.60% of raw

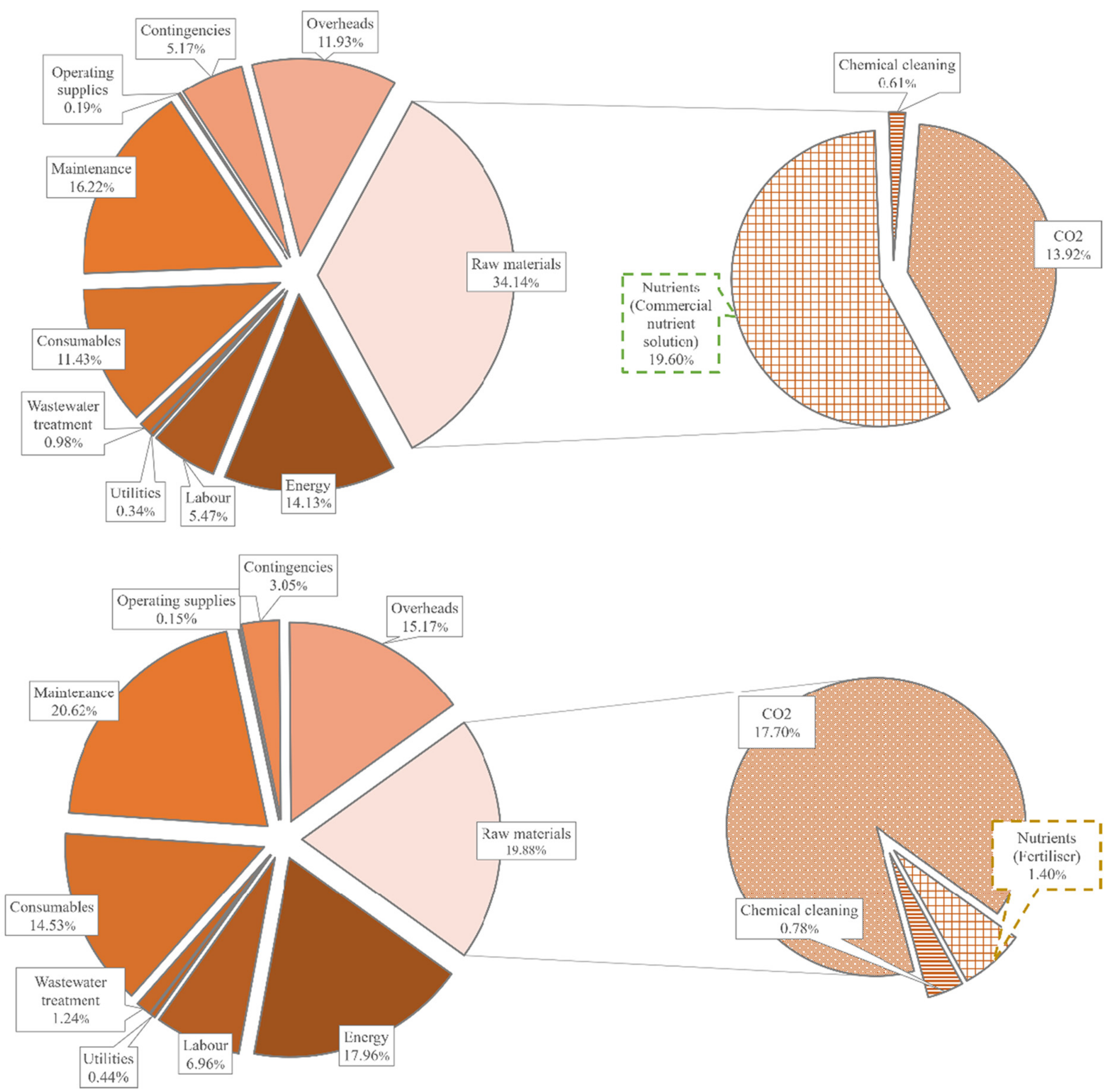

Fig. 5. Figure above: Operational cost contribution for case 3a (10 ha). Figure below: Operational cost contribution for case 4a (fertilisers).

materials (Fig. 5), but if fertilisers are used (Fig. 5), they account for only 1.40% of raw materials.

3.1. Commercialisation

Currently, two business cases for the exploitation of microalgae are identified; bulk products or commodities (chemicals, food and feed); and specialities markets (high-value products) for food additives, cosmetics, and nutraceuticals (Ruiz et al., 2016) (MALGAS, 2014).

Commercialisation is mainly dedicated to the speciality market, as it is a lower volume, high-cost niche where microalgae can be competitive. However, the most important product from microalgae biotechnology in terms of production quantity and economic value remains the microalgae biomass itself (Pulz and Gross, 2004). In the food market (including human health and wellbeing), microalgae biomass is mainly sold in powder or compressed forms (Pulz and Gross, 2004). Moreover, the animal feed market is booming, both in aquaculture and livestock farming (Pulz and Gross, 2004). Even so, there is no risk of market saturation by new products from microalgae. When comparing the size of the different markets for which microalgae are intended, for example, the biofuel market requires huge productions, in the order of 10^7 t/y, the food market about 10^4 t/y, the agricultural market 10^5 t/year and the animal feed market 10^6 t/y, far away from the global capacity of microalgae biomass (10^4 t/y) (Acién et al., 2012b). Therefore, in commodities, a risk of market saturation is not expected, mainly due to volume and possible legislation constraints. In the short term, improved production systems, especially the development of new technologies, and the improvement of highly productive strains, are expected to greatly increase the production capacity and the range of applications to which microalgae can contribute to the near future (Fernández et al., 2021) (Enzing et al., 2014) (Araújo, 2019).

Fig. 6 shows typical market price ranges for different applications of microalgae biomass. The dashed line shows the production cost for case 4a, showing a price within the range for natural food, functional foods, additives, aquaculture, and agricultural applications. It is also worthy considering the selling price of each species, as in terms of income, some scenarios may be more beneficial than others. Supplementary Table 8 shows the market selling prices for the species studied in this study. The selling prices of each species (as frozen paste) must be multiplied by the annual production for TISO + PHT (case 1a) or NAS (case 1b) to analyse the potential income from our scenarios. Despite the higher NAS production, 2.13 times more than TISO + PHT, the income is higher for the two alternating microalgae strains (see Table 2) because they can be presently sold at a higher price. The prices collected in Supplementary Table 8 are for frozen paste; however, this study does not consider the freezing process. In any case, the estimation is made on the income and not on profit, in which all costs should be considered.

Table 2
Income estimates based on the selling prices of each species (centrifugation + 1 ha).

Microalgae specie	Production (t/y DW)	Estimated income (M€/y)
NAS	27.61 (Case 1b)	1.304
TISO + PHT	12.94 (Case 1a)	1.125

3.2. Short-term improvements of the microalgae production process

Microalgae can contribute substantially to the bioeconomy. However, due to a still low production capacity and relatively high production costs, the current commercial applications are limited. In the short term, both technical and economic improvements are expected to support the expansion of the sector. In this section, four large factors have been studied (productivity, CAPEX, OPEX, and scale), to assess its effect to achieve a potentially competitive cost of biomass.

- The productivity, and therefore the improvement of PE, has been recognised by many studies as the most important factor in reducing costs (Schipper et al., 2021; Norsker et al., 2011; Ruiz et al., 2016). If PE doubled from 1.02 to 2.04% (a realistic value as the maximum achieved has been 8–10% total light (Melis, 2009)), the biomass costs would decrease to 23.78 €/kg DW (34.43%).
- In all the cases simulated in this study, PBRs are the most important element in capital costs, representing 66.62–90.29% of CAPEX. If the cost of PBR was roughly halved from 1 M€/ha (cost in our study) to 0.51 M €/ha (Norsker et al., 2011), a biomass cost of 20.87 €/kg DW could be achieved (12.24% reduction).
- Concerning the operational cost, the raw materials are the most influential elements in most of the simulated cases. They range from 17.65–34.14% of OPEX. The use of waste streams to supply nutrients to the microalgae is one of the alternatives to lower costs (Gouveia et al., 2016). However, it may limit the final applications of biomass. If the cost of nutrients (N and P) and CO_2 were zero, assuming that the source of these compounds are waste streams of water and gases,

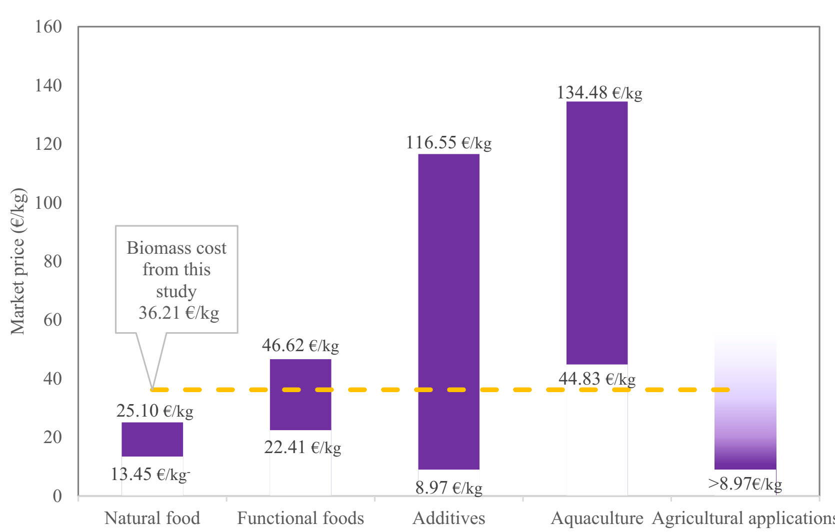

Fig. 6. Typical range of market prices for different applications of microalgae biomass (adapted from [1]. Prices updated to 2021). The dashed line indicates the production cost benchmark of case 4a of this study. [1] *MALGAS, "Guía: Oportunidades de negocio alrededor de las microalgas," AST Ingeniería S.L. AST Ingeniería S.L., Asturias (España), p. 86, 2014.*

the cost of biomass could be 17.26 €/kg DW (17.30% reduction).
- Finally, an enlargement of the scale to 100 ha would lead to an increase in annual production and a decrease in costs. A biomass cost reduction of 31.75% from 10 to 100 ha is considered, similarly to a previous study from Schipper et al. (Schipper et al., 2021). A cost of 11.77 €/kg DW would be reached.

The result of simultaneously applying all these combinations to the last simulated case (case 4a), would result in a reduction of the biomass cost by 67.50% (11.77 €/kg).

4. Conclusions

The techno-economic analysis has helped identify bottlenecks, the most appropriate flow charts, and scales for the market objective. In our case, production in vertically stacked tubular PBR combined with UF and spray-drying was selected as the most promising strategy. However, the biochemical analysis of the freeze- vs. spray-dried biomass was not conducted and considered in the present study, which might impact the final biomass value. An industrial facility (10 ha) located in Portugal could produce 300.10 t per year of *Nannochloropsis* at the cost of 36.21 €/kg DW, potentially competitive in some niche markets.

PBR cost was the element with the most significant weight in the investment in the seven scenarios, varying between 67 and 90% of the total equipment cost, representing approximately 27 to 36% of the final biomass cost. When establishing a production strategy (NAS all year round or TISO + PHT in alternation), the parameter that mainly controls the final cost is the PE. Therefore, NAS, with a higher PE (1.02%) as demonstrated by empirical data, achieves lower biomass costs. Despite having a lower selling price than TISO and PHT, a higher income was estimated due to the high annual production. The UF + spray dryer strategy involves lower costs (7.03% reduction of biomass cost) than centrifuge + freeze dryer. In the NAS culture scenario, a rise from 1 to 10 ha represents an 17.99% reduction in the final cost of biomass. This reduction is mainly related to the cost of personnel per area that decreases with the scale (with a contribution in the OPEX reduced from 21.25 to 5.47%). The commercial culture medium accounts for 19.60% of the operating costs; in case fertilisers were used, it would only account for 1.40% of the total operating costs. With the use of fertilisers instead of the commercial culture medium, the final cost of biomass would be reduced by 10.92%.

To contribute to the expansion of the microalgae market, a multidisciplinary approach is needed, combining different factors. Simultaneously increasing PE, reducing the cost of PBR, using both liquid and gaseous waste streams and scaling up to 100 ha could reduce the cost by a further 67.50%.

CRediT authorship contribution statement

Bárbara Vázquez-Romero: Conceptualization, Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **José Antonio Perales:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **Hugo Pereira:** Validation, Investigation. **Maria Barbosa:** Conceptualization, Writing – review & editing, Resources, Funding acquisition, Project administration. **Jesús Ruiz:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Acién, F.G., Fernández, J.M., Magán, J.J., Molina, E., 2012. Production cost of a real microalgae production plant and strategies to reduce it. Biotechnol. Adv. 30, 1344–1353. https://doi.org/10.1016/J.BIOTECHADV.2012.02.005.

Acién, F.G., Fernández-Sevilla, J.M., Molina-Grima, E., 2012. Contribución de las microalgas al desarrollo de la bioeconomía. Mediterráneo Econ. 309–332.

Ansari, F.A., Gupta, S.K., Nasr, M., Rawat, I., Bux, F., 2018. Evaluation of various cell drying and disruption techniques for sustainable metabolite extractions from microalgae grown in wastewater: a multivariate approach. J. Clean. Prod. 182, 634–643. https://doi.org/10.1016/j.jclepro.2018.02.098.

Araújo, R., 2019. Report on the community of practice workshop: algae production in Europe: status, challenges and future developments, Brussels. https://ec.europa.eu/jrc.

Araújo, R., Vázquez Calderón, F., Sánchez López, J., Azevedo, I.C., Bruhn, A., Fluch, S., Garcia Tasende, M., Ghaderiardakani, F., Ilmjärv, T., Laurans, M., Mac Monagail, M., Mangini, S., Peteiro, C., Rebours, C., Stefansson, T., Ullmann, J., 2021. Current status of the algae production industry in Europe: an emerging sector of the blue bioeconomy. Front. Mar. Sci. 7, 1–24. https://doi.org/10.3389/fmars.2020.626389.

Barros, A.I., Gonçalves, A.L., Simões, M., Pires, J.C.M., 2015. Harvesting techniques applied to microalgae: a review. Renew. Sust. Energ. Rev. 41, 1489–1500. https://doi.org/10.1016/j.rser.2014.09.037.

Benvenuti, G., Ruiz, J., Lamers, P.P., Bosma, R., Wijffels, R.H., Barbosa, M.J., 2017. Towards microalgal triglycerides in the commodity markets. Biotechnol. Biofuels https://doi.org/10.1186/s13068-017-0873-2.

Dasan, Y.K., Lam, M.K., Yusup, S., Lim, J.W., Lee, K.T., 2019. Life cycle evaluation of microalgae biofuels production: effect of cultivation system on energy, carbon emission and cost balance analysis. Sci. Total Environ. 688, 112–128. https://doi.org/10.1016/J.SCITOTENV.2019.06.181.

Enzing, C., Ploeg, M., Barbosa, M., Sijtsma, L., 2014. Microalgae-based products for the food and feed sector: an outlook for Europe. JRC Sci. Policy Rep., 19–37 https://doi.org/10.2791/3339.

European Commission, 2012. Innovating for sustainable growth: a bioeconomy for Europe. Ind. Biotechnol, pp. 57–61 https://doi.org/10.1089/ind.2012.1508.

European Commission, 2018. A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy, Society and the Environment. https://doi.org/10.2777/478385.

Fasaei, F., Bitter, J.H., Slegers, P.M., van Boxtel, A.J.B., 2018. Techno-economic evaluation of microalgae harvesting and dewatering systems. Algal Res. 31, 347–362. https://doi.org/10.1016/j.algal.2017.11.038.

Fernández, F.G.A., Reis, A., Wijffels, R.H., Barbosa, M., Verdelho, V., Llamas, B., 2021. The role of microalgae in the bioeconomy. Nat. Biotechnol. 61, 99–107. https://doi.org/10.1016/j.nbt.2020.11.011.

Gouveia, L., Graça, S., Sousa, C., Ambrosano, L., Ribeiro, B., Botrel, E.P., Neto, P.C., Ferreira, A.F., Silva, C.M., 2016. Microalgae biomass production using wastewater: treatment and costs. Scale-up considerations. Algal Res. 16, 167–176. https://doi.org/10.1016/j.algal.2016.03.010.

Jung, J.Y., Lee, H., Shin, W.S., Sung, M.G., Kwon, J.H., Yang, J.W., 2015. Utilization of seawater for cost-effective cultivation and harvesting of Scenedesmus obliquus. Bioprocess Biosyst. Eng. 38, 449–455. https://doi.org/10.1007/s00449-014-1284-4.

Kim, S.K., 2015. Handbook of Marine Microalgae: Biotechnology Advances, Handb. Mar. Microalgae Biotechnol. Adv, pp. 1–585 https://doi.org/10.1016/C2013-0-19117-9.

MALGAS, 2014. Guía: Oportunidades de negocio alrededor de las microalgas. AST Ing. S.L, p. 86.

Melis, A., 2009. Solar energy conversion efficiencies in photosynthesis: minimizing the chlorophyll antennae to maximize efficiency. Plant Sci. 177, 272–280. https://doi.org/10.1016/J.PLANTSCI.2009.06.005.

Meyer, M., 2012. Economic analysis of energy and matter generation from microalgae-An environmental LCC model for hydrogen and biogas production from Chlamydomonas reinhardtii, Institutionen för energi och teknik. SLU, Uppsala, Sweden. http://stud.epsilon.slu.se.

Milledge, J.J., Heaven, S., 2013. A review of the harvesting of micro-algae for biofuel production. Rev. Environ. Sci. Biotechnol. 12, 165–178. https://doi.org/10.1007/s11157-012-9301-z.

Millero, F.J., Feistel, R., Wright, D.G., McDougall, T.J., 2008. The composition of standard seawater and the definition of the reference-composition salinity scale. Deep-Sea Res. I Oceanogr. Res. Pap. 55, 50–72. https://doi.org/10.1016/j.dsr.2007.10.001.

Molina Grima, E., Belarbi, E.H., Acién Fernández, F.G., Robles Medina, A., Chisti, Y., 2003. Recovery of microalgal biomass and metabolites: process options and economics. Biotechnol. Adv. 20, 491–515. https://doi.org/10.1016/S0734-9750(02)00050-2.

Norsker, N.H., Barbosa, M.J., Vermuë, M.H., Wijffels, R.H., 2011. Microalgal production - a close look at the economics. Biotechnol. Adv. 29, 24–27. https://doi.org/10.1016/j.biotechadv.2010.08.005.

Oostlander, P.C., van Houcke, J., Wijffels, R.H., Barbosa, M.J., 2020. Microalgae production cost in aquaculture hatcheries. Aquaculture 525, 735310. https://doi.org/10.1016/j.aquaculture.2020.735310.

Pereira, H., Sá, M., Maia, I., Rodrigues, A., Teles, I., Wijffels, R.H., Navalho, J., Barbosa, M., 2021. Fucoxanthin production from tisochrysis lutea and Phaeodactylum tricornutum at industrial scale. Algal Res. 56, 102322. https://doi.org/10.1016/j.algal.2021.102322.

Pulz, O., Gross, W., 2004. Valuable products from biotechnology of microalgae. Appl. Microbiol. Biotechnol. 65, 635–648. https://doi.org/10.1007/s00253-004-1647-x.

Ruiz, J., Olivieri, G., De Vree, J., Bosma, R., Willems, P., Reith, J.H., Eppink, M.H.M., Kleinegris, D.M.M., Wijffels, R.H., Barbosa, M.J., 2016. Towards industrial products from microalgae. Energy Environ. Sci. 9, 3036–3043. https://doi.org/10.1039/c6ee01493c.

Russell, C., Rodriguez, C., Yaseen, M., 2022. High-value biochemical products & applications of freshwater eukaryotic microalgae. Sci. Total Environ. 809, 151111. https://doi.org/10.1016/J.SCITOTENV.2021.151111.

Schipper, K., Al-Jabri, H.M.S.J., Wijffels, R.H., Barbosa, M.J., 2021. Techno-economics of algae production in the arabian peninsula. Bioresour. Technol. 331, 125043. https://doi.org/10.1016/j.biortech.2021.125043.

Sinnott, R.K., Towler, G., 2013. Chemical Engineering Design. 2nd ed. Elsevier Ltd.

Tredici, M.R., Rodolfi, L., Biondi, N., Bassi, N., Sampietro, G., 2016. Techno-economic analysis of microalgal biomass production in a 1-ha Green Wall panel (GWP®) plant. Algal Res. 19, 253–263. https://doi.org/10.1016/j.algal.2016.09.005.

UN General Assembly, 2015. Transforming our World: The 2030 Agenda for Sus-tainable Development - Resolution A/RES/70/1 Adopted by the General Assemblyon 25 September 2015. https://doi.org/10.1891/9780826190123.ap02.