Algal Research 65 (2022) 102733

Contents lists available at ScienceDirect

Algal Research

journal homepage: www.elsevier.com/locate/algal

Techno-economic modelling of high-value metabolites and secondary products from microalgae cultivated in closed photobioreactors with supplementary lighting

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ARTICLE INFO

Keywords:
Techno-economic modelling
Microalgae cultivation
Photobioreactors
High-value metabolites
Secondary compounds

ABSTRACT

The purpose of this study is to develop an initial computational model to evaluate the techno-economic viability of high-value and secondary resources from microalgae. The isolation of high-value metabolites is the driving product to improve the overall economics. This approach will allow marketing secondary compounds at more competitive rates for applications such as biofuel, biomaterials, food or animal feed supplements. In this assessment, we consider cultivations in flat-panel, airlift and tubular closed photobioreactor [PBR] systems to avoid possible contamination and limit environmental exposures. The facilities are also equipped with supplementary LED lightings and temperature control to improve productivity. Based on the methodology described in this work, we evaluate the techno-economic viability of the suggested systems. A probable productivity range is selected based on the logistic growth with a recovery rate between 60% and 80%. The sensitivity analysis shows that the ratio of high-value metabolites is the most crucial factor determining the economics. Microalgae prices and productivities gain more importance at higher ratios. The sensitivity analyses indicate a low-level impact of productivity and cultivation costs on high priced metabolites.

1. Introduction

Microalgae cultivation for biofuel or biochemical productions is the focus of many research activities in publications related to bioresources and biorefineries. Readers find numerous results in connection with microalgae culture, processing and utilisation. The current state of research presents outcomes connected to many different conditions and experimental design sets. Since not all the parameters are controllable, it is often difficult to derive unambiguous conclusions from many published data. The commercialisation of microalgae products relies strongly on the practicality and the economic viability studies covering cultivation methods, processing operations and utilisations. The innovations in biotechnology and biorefinery [1] enable the adaptation of multiproduct recovery from biomass. The marine and freshwater bioresources such as microalgae, cyanobacteria and diatoms metabolise various compounds with different commercial values. The best values achievable from the constituents and metabolites depend on the application of bioprospecting. The generation of various products with different commercial values is a promising way to make the cultivation and utilisation of microalgae commercially viable. For example, the extraction of high-value components such as carotenoids, omega3, proteins will be conducive to economically viable utilisation of the remaining bio-components as biofuel. However, many studies show that the cultivation of microalgae for the sole purpose of biofuel production is economically not appealing.

Microalgae are photosynthetic micro-organisms that produce many valuable components such as essential fatty acids, proteins, and polysaccharides. The food industry increasingly enriches its products with nutritional supplements for improved health. Therefore, microalgae can contribute significantly to improve the nutritional value of human food and animal feed. Concerning essential fatty acids, the intake of omega-3 has been associated with many health benefits [2]. Alpha-linolenic acid (ALA) is an essential omega-3 fatty acid found in plants such as chia seeds, linseed, canola, nuts, and olive leaves.

In contrast, seafood contains considerable amounts of Docosahexaenoic acid (DHA) and Eicosapentaenoic acid (EPA) [3]. Fish oil is

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https://doi.org/10.1016/j.algal.2022.102733
Received 25 October 2021; Received in revised form 7 February 2022; Accepted 29 April 2022
Available online 6 May 2022

considered the most significant source of dietary omega-3 [4–8]. The synthesis of DHA and EPA starts from microalgae. As part of the food chain, these fatty acids are transferred to zooplanktons and further to other marine life forms [9–11]. That is why microalgae are considered an essential source of polyunsaturated fatty acids (PUFA). In contrast to fish oil, microalgae have further advantages regarding oxidative stabilities [12].

Nannochloropsis oceanica [13], *Tetraselmis sp.* [14] and *Porphyridium cruentum* [15], and the marine diatom *Phaeodactylum tricornutum* [16] are among species, which contain a high proportion of EPA. *Crypthecodinium cohnii* [17], *Schizochytrium* [18] and *Thraustochytrium sp.* [19] are some DHA rich sources. The synthesis of Monogalactosyldiacylglycerols (MGDG) was the central investigation of a study by Junpeng et al. [20] using *Chlorella sorokiniana*, *Nannochloropsis oceanica*, and *Arthrospira platensis* at normal and nitrogen depleted conditions. MGDG is an essential source of polyunsaturated fatty acids (PUFA).

The growing conditions have a significant influence on the ratio of high-value components. For example, the increased seawater concentration seems to increase lipid productivity substantially [21]. Fernandez et al. [22] investigated the impact of irradiation on EPA production from *Phaeodactylum tricornutum.* Seto et al. [23] performed a similar study with *Chlorella minutissima* at different light intensities, temperatures and seawater additions. Derwenskus [24] and McClure [25] studied the production of EPA in different PBRs. They observed a maximum EPA content of 6% per microalgae dry weight in flat-panels for *Phaeodactylum tricornutum.* Pudney et al. [26], on the other hand, highlights an EPA accumulation of up to 35% in *Phaeodactylum tricornutum.*

Proteins represent the other essential functional group of microalgae. The availability of essential amino acids in microalgae is comparable with many animal products such as eggs or chicken meat [27]. Amino acid index of some species exceeds those from egg albumin. However, the digestibility coefficient and net protein utilisation are below animal products [28]. On the other hand, higher protein availability in some microalgae will lessen this discrepancy. *Tetraselmis Chuii*, *Nannochloropsis granulate*, *Spirulina platensis*, *Nannochloris bacillaris*, and the diatom *Phaeodactylum tricornutum* and the freshwater species *Chlorella vulgaris* and *Tetracystis sp.* are among the species, which contain all the essential amino acids [29]. The cultivation and the processing of microalgae has a noticeable influence on the availability of the end-product. Matos [27], for instance, addressed the importance of drying methods to obtain nutritive proteins from microalgae.

Concerning cultivation, nitrogen is one of the critical nutrients for protein synthesis [30]. Microalgal proteins can be used in isolated form or as whole biomass in human or animal food. For example, Sharawy et al. [31] investigated a partial replacement of proteins with *Tetraselmis suecica* for growing white-leg shrimps.

Microalgae are also the source of many different Carbohydrates, which are present in the form of Polysaccharides. They constitute a complex chain of straight or branched monosaccharides. Some examples are Glucose, fructose, Ribose, mannose, arabinose, Galactose, xylose, and the rare sugars Rhamnose. Polysaccharide types, structures and their quantity depend on the microalgae species and the environmental conditions they are cultured. Polysaccharides' structures are very complex and are not entirely understood. A case in point is the isolation of polysaccharides from *Tetraselmis*, which consists of 2-keto-sugar acids 3-deoxy-manno-2-octulosonic acid (KDO), 3-deoxy-5-*O*-methyl-manno-2-octulosonic acid (5OMeKdo), 3-deoxy-lyxo-2-heptulosaric acid (Dha), and further monomers [32,33]. Some investigated polysaccharides from microalgae are Spirulan, Alignate, Carrageenan, Beta-Glucan [34], Ulvan, laminarin, alginate and fucoidan. In addition, certain microalgae, particularly marine species, are surrounded by extracellular polysaccharides. *Porphyridium* and *Rhodella*, for example, contain sulphated heteropolysaccharides with anionic properties [35].

The extent and the potential availability of different polysaccharide structures and their benefits are not thoroughly investigated. Maybe that is why their commercial uses are still limited. However, they have a great commercial significance in different areas such as biopolymer, food, pharmaceutical, and cosmetic industries. Metabolites isolated from some microalgae species contain exopolysaccharides and polysaccharides with antibacterial, inflammatory and antifungal properties. *Tetraselmis* species, for example, give off water-soluble Polysaccharides with antifungal properties [36]. Algal polysaccharides can also be used in agriculture as bio-stimulants to enhance crop yield and increase the resistance of plants against environmental stress [37,38]. Thus, the isolated polysaccharides from microalgae have the potential of being profitable value-added products. The science of polysaccharide extraction from microalgae is not well documented in the public domain and requires more research. Some scattered information is available about polysaccharide isolation from macroalgae. The polysaccharide extraction process depends on the microalgae species and the polysaccharide types. Marcati et al. [39], as a case in point, discuss the extraction of polysaccharides from *Porphyridium cruentum*. The extraction of water-soluble polysaccharides from *Tetraselmis* species is discussed in a publication by Kashif et al. [36].

The extraction and isolation of bioactive compounds such as pigments, antioxidants and vitamins represent a more promising approach to commercially extent microalgae cultivations. Some isolated metabolites show anti-inflammatory, analgesic and anti-cancer properties. In addition, they include antiviral, anti-microbial and anti-fungal substances [40,41]. The medicinal application extends to antibiotics, blood pressure regulation agents, and the treatment of various cardiovascular diseases [42]. Microalgae, cyanobacteria and diatoms contain different valuable bioactive compounds and pigments. Primary groups are carotenoids, Phycobiliproteins, chlorophylls, and phenols.

The functional group of carotenoids include compounds such as astaxanthin, beta-carotene, violaxanthin, fucoxanthin, zeaxanthin, lycopene, Loroxanthin, and lutein. Carotenoids protect against oxidative stress and offer many other health benefits [43,44]. *Dunaliella salina* and *Haematococcus pluvialis* are the primary sources of beta-carotene and astaxanthin, respectively. Depending on the cultural conditions, the quantity of beta-carotene and astaxanthin from the above sources can be up to 10% for beta-carotene and 4% for astaxanthin based on microalgae dry weight [45,46]. Astaxanthin has a very high commercial value. In smaller quantities, astaxanthin is also synthesized in other species such as *Neochloris wimmeri*, *Tetraselmis suecica* and *Nannochloropsis sp.* [47,48]. An economic production, however, can still be viable through a systematic multiproduct approach.

Phycobiliproteins are water-soluble fluorescent pigments [49]. The classification includes phycocyanin, phycoerythrin, allophycocyanin groups exhibiting their own characteristic structure and chromophore absorption spectra [50,51]. Cyanobacteria and red algae are the primary sources for the isolation [52]. Their application covers areas such as fluorescence labelling of antibodies, DNA and protein detection [53,54]. They can also be used as colourants in the food and cosmetic industry [53,55,56]. Phycobiliproteins have antioxidative, hepatoprotective, and neuroprotective properties useful in the pharmaceutical industry [53,57,58]. Their uses in the treatments of several cancer types and tumours are documented in various publications [53,59–62].

The extraction of high-value compounds is the primary step towards the commercialisation of microalgae. Their successful cultivations require a balanced amount of nutrients, light and carbon dioxide at conditions favourable to related species. Case studies can help to establish systematic procedures to increase productivity and reduce costs. The applications of mathematical models, advanced multivariate statistics and artificial intelligence are conducive to investigating many cases within a limited timeframe. Juxtaposing experimental data with theoretical results will help to verify and isolate favourable cases.

This manuscript investigates the techno-economic viability of microalgae cultivation for high-value compound extraction along with the utilisation of the remaining biomass for low-cost applications such as bioenergy or biomaterials. We developed an initial methodology to

assess the techno-economic viability of microalgae cultivations for the utilisation in high-value products. Subsequently, sensitivity analyses were carried out to understand the effect of dominant parameter variations on the target price of microalgae and the available high-value compounds. The price range depends on the selected technology and the ratio of the high-value compound in the microalgae.

The current techno-economic data in the literature is predominantly confined to dry microalgae cultivation for biofuel production. Holtermann and Madlener evaluated the use of PBR for biofuel and hydrogen production [63]. Their study relates to the amount of energy captured in biofuel. The energy price is given here at around €150/MWh for a two-stage hydrogen production unit and €50/MWh for a one-stage configuration. The photosynthetic efficiencies considered in their study are between 1.8 and 5.6, higher than the range estimated in this study. In another study, Bennerjee and Ramaswamy estimated the cost of microalgae cultivated in a flat-panel PBR at around $4/kg in the US at similar solar irradiation selected in this manuscript [64]. Barlow, et al. investigated the algae price cultivated in rotating biofilm-reactor for biofuel and biorefinery. Their price for the base case scenario with a productivity of 12 $g{\cdot}m^{-2}{\cdot}day^{-1}$ is around $4/kg of dry ash-free microalgae [65]. According to their investigation, the microalgae price can be reduced to around $1.1/kg at high productivities around 30 $g{\cdot}m^{-2}{\cdot}day^{-1}$. These costs are considerably lower than the values we estimated in this study. The discrepancy is attributed to higher PBR fixed and operating costs compared to biofilms and higher post-harvesting operating costs. This study also considers additional costs for a PBR temperature control, LED lighting, post-harvesting process, and 20 to 40% biomass losses. A study carried out by the Sandia National Laboratories, and the National Renewable Energy Laboratories shows a significant microalgae cost difference for the production of beta-carotene and biodiesel [66]. Their assumptions are based on two different microalgae types: *Dunaliella* for beta-carotene extraction and *Nannochloropsis* for biofuel. The microalgae prices estimated in their study is around $94 for beta-carotene and $2/kg for the use as biofuel at 2 $g{\cdot}m^{-2}{\cdot}day^{-1}$ and 20 $g{\cdot}m^{-2}{\cdot}day^{-1}$ productivity in open-pond, respectively.

Based on the mass and energy balance principles, we modelled several case studies adapted to locations with a yearly Direct Normal Irradiation (DNI) of around 1800 kWh/m^2. Many areas around the world have similar DNI values [67]. For example, South Perth, Adelaide, and Sydney are some locations in Australia. In the Middle East, we have areas such as the coastal part of Qatar and the northern part of UAE. France, South Italy, Spain, and Portugal are some examples in Europe. We also find similar patterns around major cities in South America such as Santiago, Buenos Aires, many parts of Brazil. In the US, the west coast area around San Francisco and inland between Phoenix and Salt Lake City fall into this category. Many areas in Asia, such as north China and Mongolia, can be identified. In Africa, we can identify the area starting from the Middle West running through the centre of Africa to the east coast.

The case study includes temperature-controlled microalgae cultivations in closed photobioreactors [PBR] to avoid contaminations and limit environmental exposures. Here, we consider three types of technologies: flat-panel, airlift and tubular PBRs. At the selected condition, good productivities are reported for species such as *Tetraselmis*, *Picochlorium* and *Nannochloris* [68,69]. However, the model can be adapted to any species. To increase illumination time and counteract possible shadings, we also consider the option of additional LED lightings. Furthermore, observations show that the customisation of lighting regimes will impact the synthesis of certain compounds in microalgae. A case in point is the positive impact of prolonged high illuminations on carotenoid synthesis with a simultaneous reduction in chlorophyll [70–73].

2. Materials and methods

This work examines the techno-economic viability of microalgal biomass as a source of high-value metabolites and the utilisation of remaining biomass for low-cost applications such as biofuel or biomaterials. Several models are developed here to analyse the techno-economic feasibility of microalgae cultivation for the production of high-value products. Closed photobioreactor (PBR) systems are a good match for this task. They protect the harvest against possible cross contaminations and reduce exposures to environmental conditions such as sandstorms [74–76]. We consider three closed cultivation methods in this work. These are flat-panel, airlift and tubular PBRs. Fig. 1 shows the model used in this case study for the techno-economic analysis of producing high-value compounds (HVC) and secondary compounds (SC) for low-cost applications. The model covers various operating parameters adapted to the selected photobioreactors. The following model is scaled to a one-hectare installation for a better understanding. The system, however, can be scaled up or down to any commercial size thanks to the modular nature of photobioreactors. Furthermore, the illuminated surface area of the bioreactor can be increased using additional LED lights for better productivity.

Our previous studies indicate *Tetraselmis*, *Picochlorium* and *Nannochloris* to be suitable species isolated and successfully cultivated in the regions with an average yearly Direct Normal Irradiation (DNI) of 1800 kWh/m^2. The specific productivity depends significantly on the growing conditions and the selected species. Numerous literature sources address these correlations. The values range from values less than 10 $g{\cdot}m^{-2}{\cdot}day^{-1}$ [77–79] to values above 40 $g{\cdot}m^{-2}{\cdot}day^{-1}$ [80,81]. Other sources report values between 10 and 40 $g{\cdot}m^{-2}{\cdot}day^{-1}$ [82–88]. We have already experienced average productivity of 20 $g{\cdot}m^{-2}{\cdot}day^{-1}$ in open ponds at conditions prevalent in South Perth, Australia. This productivity is within the range of values given in a number of literature sources for locations with a similar irradiance [66,89]. The above values are indicative, showing few examples of favourable productivities. This study used a mathematical model to determine the range of average annual productivities.

To model microalgae productivity for this case study, we used logistic growth to simulate a large number of cases corresponding to maximum cell densities between one and six kg/m^3 and specific growth rates between 0.2 and a maximum theoretical value of two. Fig. 2a shows the cell density curve of different specific growth rates as a function of days. Here, we used an initial starting culture of 70 mg/l, a maximum cell density of 3 g/l and a recovery efficiency of 70% based on a sample size taken on day 4. The best annual productivities were determined based on the number of days required to achieve the highest cumulative yield. Fig. 2b represents the overall results of areal microalgae production according to the Gaussian probability density function at optimised harvesting times. We expect daily yields between 20 and 40 $g{\cdot}m^{-2}{\cdot}day^{-1}$ based on the above assumptions, excluding losses. Fig. 2c shows the probability of areal productivities as a function of maximum microalgae concentrations (MC). Considering Photosynthetic Photon Flux Density (PPFD) ranging from 50 to 1000 $\mu mol\ s^{-1}\ m^{-2}$ and a specific yield between 0.5 and 1.5 g cell dry weight (CDW) per mol of photons, we modelled different scenarios corresponding with a light period ranging from 8 h to 20 h per day. Fig. 2d shows the results modelled according to the above conditions.

The general productivity of cultivations can be estimated according to Eq. (1) [90]. It indicates the productivity at time X_t at time t considering a cell concentration doubling time of t_d and an initial cell concentration X_0.

$$X_t = X_0.e^{\frac{ln2}{t_d}.t} \tag{1}$$

The area productivity in the literature is diverse, ranging from small values to high productivities of over 60 $g{\cdot}m^{-2}{\cdot}day^{-1}$. Considering Eq. (2) derived from [91], we should be able to achieve specific productivity

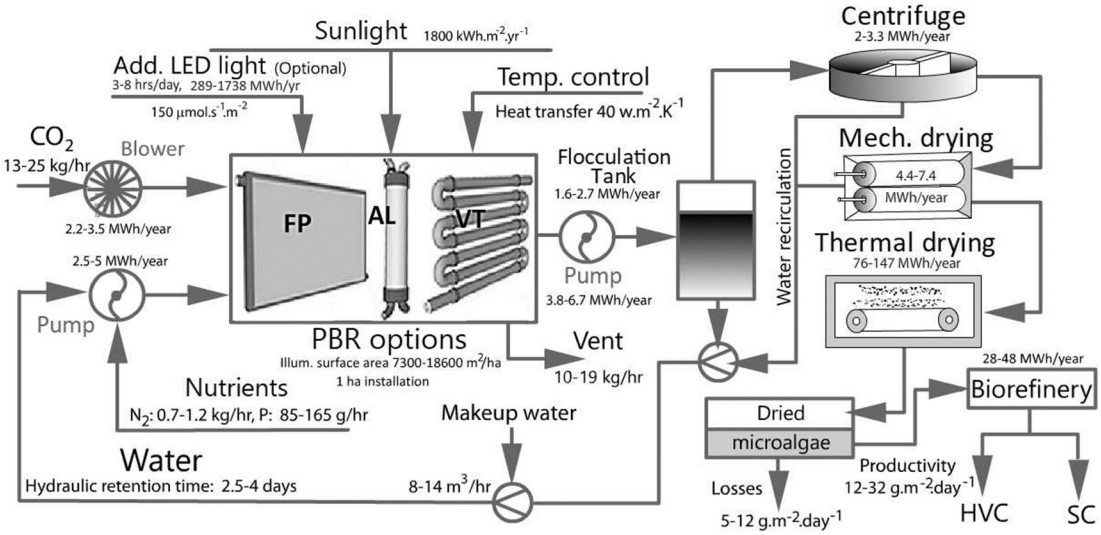
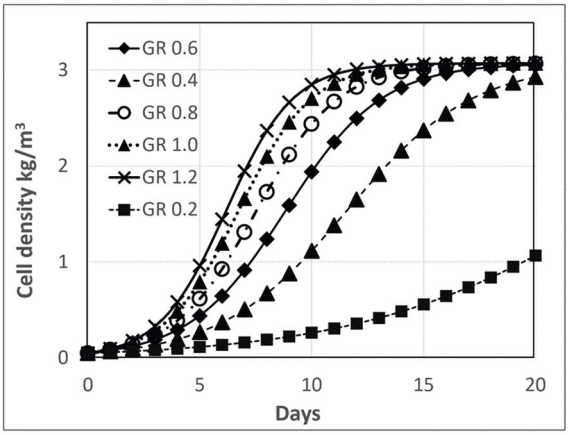
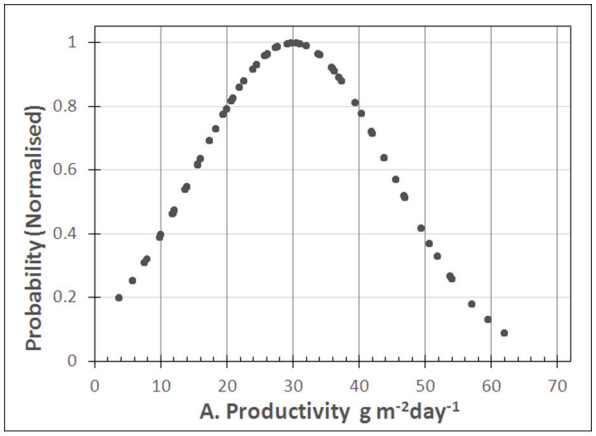


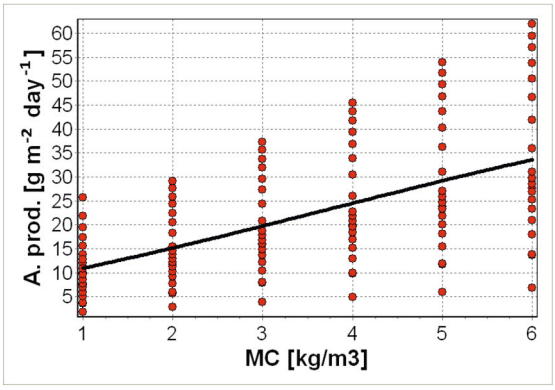
Fig. 1. Individual PBR modules considered in this study for the production of high-value (HVC) and secondary compounds (SC).



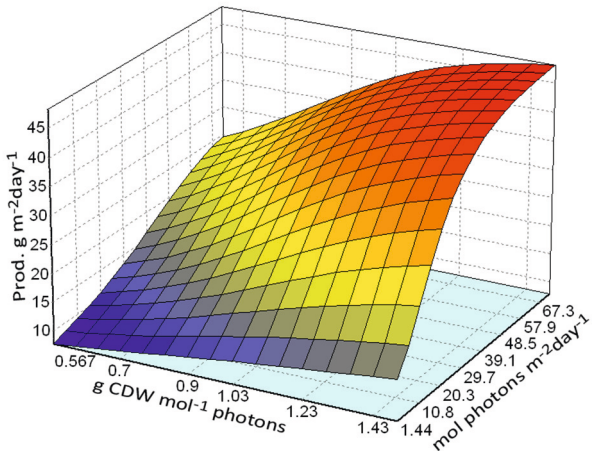
a. Days to achieve maximum cell density



b. Gaussian Probability density of areal productivities



c. Areal productivities at different microalgae concentrations.



d. Productivity at different solar iradiances and as a function of light specific yield

Fig. 2. Productivity assessment based on a number of case studies.

(Y_{area}) of up to 35 g·m^{-2}·day^{-1} in areas with an average yearly DNI of around 1800 kwh/m^2 [67] at a photosynthetic efficiency (η_{photo}) of up to 5%. The calorific value of microalgae ($CV_{microalgae}$) is given at around 25 MJ/kg for the dry biomass [92]. According to the equation, higher productivity is concurrent with lower calorific values. Since lipids have higher calorific values, in general, we can assume that microalgae high in lipids will have lower productivities. A case in point is the nitrogen starvation of *Tetraselmis sp.*, which induces higher lipids in microalgae cells and increases the content of omega-3 [14]. Simultaneously, however, the culture growth will be inhibited [14]. The interactions are, however, more complex. There are many discrepancies found in the literature. Although nitrogen starvation increases lipid formation in many species, other species, such as *Tetraselmis suecica* and *Dunaliela sp.*, seem to respond differently [93]. Bounnit et al. [76] report higher lipid formation for nitrogen-limited and depleted *Nannochloris atomus* cultures. Nitrogen and sulphate starvation also improves the productivity, solubility and polysaccharides' compositions in *Porphyridium sp.* [94–97]. Polysaccharide formation seems to be mainly driven by CO_2 [98].

$$Y_{area} = \frac{\eta_{photo}.DNI}{CV_{microalgae}} \tag{2}$$

The relation between the area and volumetric productivity (Y_{area} and Y_{vol}) can be derived through the surface-to-volume ratio as a quotient of the illuminated PBR area A_i, divided by PBR volume V. Accordingly, Eq. (3) predicts the volumetric productivity. The conversion can also be made through further derivations using the diameter of tubular (d) or the thickness of flat-panel (δ) PBRs. Parameter i represents the ratio of the illuminated surface to the overall PBR area. The highest value is 0.5 for unidirectional illumination. On the other hand, the Bidirectional lighting system has a maximum value of 1, indicating the use of natural and artificial light.

$$Y_{vol} = \frac{Y_{area}.A_i}{V} = \frac{4.Y_{area}.i}{d} = \frac{2.Y_{area}.i}{\delta} \tag{3}$$

2.1. PBR size and productivity estimation

We have developed several algorithms to estimate the dimension of PBRs for the production of different quantities of microalgae for the production of high-value products. The main variables to be estimated are the total illuminated area, the volume of PBR and the land's size, which PBR occupies. Logically, productivity depends on the illuminated surface area. That is why we are using this reference point. However, we can easily convert the reference point to a land-based area because all the cases in this study are scaled to one-hectare land. The other main reason to use illuminated surface area is that we are also considering additional LED lighting. Therefore, it is more practical for the techno-economic assessment to use illuminated surface area instead of land area. Eq. (4) highlights the total illuminated area calculation for airlift PBR systems ($A_{AL\text{-}total}$). Here, we consider the size of each module with diameter d_{AL} and height h_{col}. Other variables are the number of columns in each module (N_t), the number of modules in each row (N_m), the number of rows (N_r), and the ratio of illuminated surface to the overall PBR area (i). Eq. (5) helps to estimate the total volume of the airlift PBR. Eq. (6) approximates the required land area for PBR. Here, s_m stands for the average distance between the PBR modules in each row, and s_r is the average distance between the rows. The specific productivity can be increased by minimising s_r to a degree where the illuminated surface area is not affected. The use of LED lights can be conducive to minimising s_r. Eq. (8) does not include the land area for any service facilities or microalgae processing plants.

$$A_{AL-total} = d_{AL}.\pi.h_{col}.i.N_t.N_m.N_r \tag{4}$$

$$V_{AL-total} = 0.25.N_t.N_m.N_r.d_{AL}^2.\pi.h_{col} \tag{5}$$

$$A_{land-AL} = [(d_{AL}{*}N_t) + (N_t - 1).s_m].[(d_{AL}{*}N_r) + (N_r - 1).s_r] \tag{6}$$

Eq. (7) estimates the total illuminated surface area of flat-panel PBR farms, where h_m is the height of each module and w_m is the width. N_m denotes the number of modules in each row, and N_r stands for the number of rows. Variable i represents the percentage of the illuminated surface area. Unidirectional lighting has a top value of 0.5, and bidirectional lighting has a maximum value of 1. The overall volume of PBR is calculated according to Eq. (8). Variable δ represents the thickness of the system. Eq. (9) shows the land area required for the installation of flat-panel PBR. Variables s_m and s_r represent the average spacings between modules in each row and the number of rows, respectively.

$$A_{FP-total} = 2.h_m.w_m.N_m.N_r.i \tag{7}$$

$$V_{FP-total} = h_m.w_m.\delta.N_m.N_r \tag{8}$$

$$A_{Land-Fp} = [(w_m.N_m) + (N_m - 1).s_m].[(\delta.N_r) + (N_r - 1).s_r] \tag{9}$$

The tubular PBR module considered for the modelling consists of horizontally staked tubes standing vertically. U-bent couplings connect the PBR tubes. Eq. (10) is used to estimate the total illuminated area of the tubular PBR ($A_{TB\text{-}total}$), where d_t stands for the tube diameter and l_t for the length of the module. The module numbers in each row and the row number are given by N_m and N_r, respectively. N_t denotes the number of tubes positioned in each level in a module. This variable can be calculated according to Eq. (11), where s_g is the distance of the first tube from the ground, s_t is the distance between tubes, and h_m stands for the height of the module. The loop factor (m) suggested in this modelling describes the geometry of the u-coupling. We use a value of one, which means up and downward connections of tubes to maximise i, which is the ratio of the illuminated area. Values above two describe loop connections, which indicates that the pipe loops continue behind the illuminated surface. In other words, there are two pipes in each level positioned above each other. There is a strong relation between m and i. If we consider two pipes in each level of a module in loop connections, interrelated shadings can occur between the tubes affecting the illuminated areas. As a further derivation of the total tubular PBR area, Eq. (12) estimates the total tubular PBR volume. The land requirement for tubular PBR ($A_{land\text{-}TB}$) can be calculated by Eq. (13). The variable s_m and the number of rows s_r summarise the average distance between each module in a row. The equation below can also be adapted to calculate tubular PBR installations with horizontal tube arrangements.

$$A_{TB-Total} = d_t.\pi.l_t.i.m.N_m.N_r.N_t \tag{10}$$

$$N_t = \frac{h_m - s_g + s_t}{d_t + s_t} \tag{11}$$

$$V_{TB-Total} = 0.25.d_t^2.\pi.l_t.i.m.N_m.N_r.N_t \tag{12}$$

$$A_{land-TB} = [(d_t{*}N_r{*}m) + (N_r - 1).s_r].[(l_t{*}N_m) + (N_m - 1).s_m] \tag{13}$$

Eq. (14) defines the productivity of PBRs ($Y_{PBR\text{-}total}$). Here, we can write the equation as functions of the areal (y_A) or volumetric yields (y_V) applied to the total area ($A_{PBR\text{-}total}$) or volume ($V_{PBR\text{-}total}$) of PBRs. We can also express the equation in terms of the surface to volume ratio (SV) as the quotient of y_V over y_A. Productivity losses can occur due to many reasons such as oxygen inhabitation, high concentrations, lack of nutrients, climatic conditions, harvesting issues, and PBR outages due to maintenance or any other technical issues. The average percentage of the possible losses is represented by factor w in the equation.

$$\begin{aligned} Y_{PBR-total} &= A_{PBR-total}.y_A.(1-w) = V_{PBR-total}.y_V.(1-w) \\ &= V_{PBR-total}.SV.y_A.(1-w) \end{aligned} \tag{14}$$

2.2. PBR and harvesting cost estimation

The costing method for the proposed technology is not a clear-cut science and depends on many factors. The capital requirement for establishing PBR cultivations strongly varies, depending on materials, system configurations, and country of origin. The literature shows a wide range of specific costs for PBR [99–103]. Flat-panel PBR cultivation systems are the least costly option, whereas tubular PBRs are the most expensive alternatives with typically higher yields. However, the latter seems to require more maintenance, which may affect the overall productivity in the long run. The use of materials has a significant impact on economics. Tubular PBR cultivation systems made of glass put forward by Schott [104] indicate a total system cost ranging from $400 m^{-2} to over $900 m^{-2}. On the other hand, PBR modules made of acrylic-based tubes are purchasable for less than $200 m^{-2} [105]. The specific cost needs to be below $150 m^{-2} to make PBR economically more viable [68,101,106]. The total installed costs of closed cultivation systems can be more than three times the cost of PBR [82] if we consider additional process equipment units, installations, engineering and supervision, land, insurances, and taxes.

Additional process equipment pieces are an essential part of functional PBR systems. Different options are available to estimate the additional expenses of individual units integrated into the overall system. Suppliers are a good source of information. There is also a large amount of information available online. Moreover, mathematical models and software packages such as Aspen plus and Chemcad provide process equipment cost information. In this case study, we used the models published by Sinnott and Towler [107] and Matches [108] to estimate the costs of buffer tanks, pumps for water recirculation, nutrient supply, and compressors for carbon dioxide injection into the culture. We increase the overall capital requirement by over 140% of the initial PBR costs by adding the installation costs. Th Installation costs include piping and fitting, electrical installations, and a field laboratory. Here, we also include the costs of engineering and supervision, taxes and insurance.

Further expenses must be added to the PBR costs for harvesting and post-harvesting facilities. These include facilities for increasing microalgae concentrations, dewatering and drying. Here, we opted for flocculation tanks, centrifuge separation units, direct contact rotary drums followed by thermal drying in an atmospheric tray dryer. The cost estimated in this study is based on the models in the literature [107,108].

As described earlier, the capital requirement for establishing microalgae cultivation and harvesting based on photobioreactors depend strongly on many factors such as material selection, system configurations, and installation costs. Therefore, this study's costing estimated and used is a generic assessment, which I used as an average value for wider cost variations as part of a sensitivity analysis. Accordingly, we assessed the impact of different fixed and variable costs on the cost of dried microalgae.

To sum up, the overall cost factors mentioned above, Eq. (15) summarises the total cost (TC) calculation for establishing PBRs. The cost of the bioreactors is calculated based on the illuminated surface area (A) and the specific photobioreactor costs (S_{PBR}) in $/$m^{-2}$. The system integration cost (SI_{PBR}) includes pumps, pipes and fittings, electrical equipment, control and field laboratory. It also includes installation costs such as labour, supervision and engineering expenses. The costs for post-harvesting processes are calculated based on the yield (Y), the specific cost of process equipment (SC_P) and their specific installation expenses (SI_p).

$$TC = A(S_{PBR} + SI_{PBR}) + Y(SC_P + SI_P) + TC_{LED} + TC_{Cooling} + C_{Ind} + C_{Misc} + C_{Cont} \quad (15)$$

The post-harvesting process considered in this work comprises microalgae dewatering and drying. We will discuss the total cost of lighting (TC_{LED}) and cooling ($TC_{Cooling}$) in the following sections. The indirect cost (C_{Ind}) is allocated to capital expenditures indirectly linked to the cultivation site. Land, service facilities, power generation, and carbon dioxide provision are a few examples. C_{Misc} represents all further costs in the project. The contingencies (C_{Cont}) cover any unexpected charges. This number is usually higher for new and one-of-the-kind project types. In this work, we consider an average value of 24% of the total capital cost for contingencies. All the costs relate to specific values in $ per tonnes of dry microalgae [109,110] adjusted to 2020 price levels [111].

2.3. LED light requirements

There are three lightings options considered for the proposed cultivation facilities. These are: a. natural light b. supplementary unidirectional and c. bidirectional lighting using Light-emitting diodes (LED). The provision of uni- and bi-directional supplementary lighting will be conducive to reduce mutual shading and increase light availability to the culture. Based on photon flux density [112], we calculated the theoretical power requirement for operating light-emitting diodes for artificial light integration into PBRs. The minimum power requirement (P_{min}) for LED lighting can be estimated according to Eq. (16). Here, $PPFD$ is the photosynthetic photon flux density [μmol m^{-2} s^{-1}], h is Planck's constant and c is the speed of light. Parameter A stands for illuminated surface area, N_A is the Avogadro constant, and λ corresponds to the selected light wavelength. The real power requirement (P_{real} in kW) depends on the efficiency (η) or photon efficacy (ε) of the LED light, as shown by Eq. (17) [113]. The relation between the efficiency of LED lights and the photon efficacy is described by Eq. (18). In this work, we estimated the total cost of LED lighting (TC_{LED}) based on its power requirements. Eq. (19) shows the estimation of the total LED lighting costs using a specific investment of SC_{LED} in $\$\cdot kW^{-1}$, and an installation factor (I) as a percentage of LED costs. Eq. (20) predicts the annual cost of LED operation, where t_{PBR} is the total system lifetime in years, $t_{LED\text{-}Repl}$ is the average LED lifetime in years, and $I_{LED\text{-}Repl}$ is a percentage of the LED cost for miscellaneous replacement expenses, including labour. SP_{LED} stands for the specific power requirement in Watt m^{-2} (W m^{-2}), $t_{AO\text{-}LED}$ is the number of hours of LED operation in a year and, C_{Elect} is the cost of electricity in $.kWh^{1}.

$$P_{min} = \frac{PPFD.\ N_A.h.c.A}{\lambda} \quad (16)$$

$$P_{real} = \frac{P_{min}}{\eta} = \frac{PPFD.A}{\varepsilon} \quad (17)$$

$$\eta = \frac{\varepsilon.N_A.h.c}{\lambda} \quad (18)$$

$$TC_{LED} = P_{real}.SC_{LED}.(1+I) \quad (19)$$

$$AC_{OP} = \left[\left(\frac{P_{real}.SC_{LED}}{t_{LED-Repl}}\right).\left(1+I_{LED-Repl}\right)\right] + \left(SP_{LED}.A.t_{AO-LED}.C_{Elect}\right) \quad (20)$$

Table 1
Techno-economic assumptions for supplementary LED light.

PPFD	150	μmol s^{-1} m^{-2}
λ	650	nm
ε	100	lm W^{-1}
SC_{LED}	500	$\$\cdot kW^{-1}$
I	80	%
$t_{LED\text{-}Repl}$	5	years
Total system lifetime (t_{PBR})	20	years
$I_{LED\text{-}Repl}$	10	%
$t_{AO\text{-}LED}$	2000–3000	h $year^{-1}$
C_{Elect}	0 to 0.25	$ kWh^{-1}
HRT	2	days

Table 1 summarises the assumed values of variables used in Eqs. (16) to (20) within this project. The selected photosynthetic photon flux density corresponds to the industrial standard to cultivate common crops [114–116] as supplementary lighting. At an efficacy of 100 lm/W (lm W^{-1}), the selected wavelength emits red light. This number is relatively low. However, it is safe to use this conservative value considering other possible inefficiencies within the system. Higher numbers are achievable nowadays, and the efficacy of future LED light is still improving [117]. Red and far-red photons are well absorbable by plants, and red LED lights show good photon efficacies [113].

2.4. Estimation of cooling and cooling costs

The absorption of solar energy can cause the build-up of a considerable amount of heat within PBRs during the daytime. Excessive heat is a significant cause of culture losses. Particularly distinctive is the build-up of heat in PBR is in tropic and subtopic areas. Based on the specific heat transfer of water, Eq. (21) determines the thermal energy absorbed in a one-hectare PBR system. Here, T stands for water temperature, A_{iPBR} illuminated surface area of PBR, t is the time, m is the mass of medium, and C_p is the specific heat capacity of water. The approximation does not include the thermal conductivity of the tubes and the cooling effect given to the surrounding environment. The maximum heat absorbed through solar radiation by PBR (E_{max}) in kWh is given by Eq. (22). System designers need to extend the thermal cooling models presented here to address any particular PBR designs. Here, however, we would like to know the maximum cooling energy required and the associated cost.

$$\frac{dT}{dt} = \frac{I.A_{iPBR}}{C_p.m} \tag{21}$$

$$\frac{dE_{max}}{dt} = I.A_{iPBR} \tag{22}$$

Considering a solar irradiance of 1800 kWh/m^2, the amount of thermal energy that needs to be removed from one-hectare cultivation in airlift, flat-panel and tubular PBRs amounts to over 14 GJ, 15 GJ and 17 GJ per hour, respectively. There is also the possibility of low-grade heat recovery from these sources. A theoretical maximum power output of 469. 5 and 1072 kW is available from one-hectare airlift, flat-panel and tubular PBRs based on the Carnot cycle. However, the waste heat is rejected in this assessment and is not considered towards any low-grade thermal utilisation.

There are different ways of controlling the temperatures within bioreactors. The use of infrared reflecting thin films [118,119], the integration of external or internal heat exchangers, evaporative cooling, installation of chillers and installations in a greenhouse or a sheltered area are few examples. This study estimated the costs for infrared reflecting thin films, a greenhouse, plate and frame external heat exchangers, cooling tower, and internal glass tubes for internal cooling. Concerning the latter, we assume a glass tube price between $5 and $10 per meter [120,121]. The overall cost includes the expenditures for pumping cooling water through the pipes and 80% installation cost. We use I. Newton and J.BJ. Fourier equation to approximate the thermal energy flow, which leads to cooling. Infrared-rejecting or reflecting thin films can partially limit the solar radiations at a particular wavelength range. This method is applicable in conjunction with additional measures to avoid heat build-up in the reactors. The minimum bulk cost for IR rejecting films is given at around $2.5 m^{-2} [118,119]. Considering the postage, labour and installation costs, however, we assume a total cost of $12 m^{-2} in this study. A further possibility is the installation of PBRs in greenhouses. The cost of a greenhouse is given at around $22 m^{-2} [122]. Here, we also include 70% installation cost and the use of IR reflecting films.

This study also considers the cost of integrating external heat exchangers. Shell-and-tube heat exchangers add significantly to the overall costs. The integration of a plate-and-frame heat exchangers is a less expensive option. However, the circulation of the cultivation media through the heat exchangers (dark phase) can reduce the overall yield. The costing of plate-and-frame was carried out according to the model by Sinnott and Towler [107] and updated to 2020 costs [111]. The costing also includes pumps and 80% installation expenses. The pumps circulate cooling water and PBR medium through the heat exchanger.

Considering the above cooling options, the economic and sensitivity assessment in this work includes the mean, minimum and maximum cost of cooling in the overall cost estimation.

2.5. Operating cost estimation

Concerning the operating costs, we considered six different recurring expenses. These are labour, energy, maintenance, nutrients, administration, and overheads. Labour is regarded as one of the most significant outlays. Considering the fact that operating costs are not clear-cut values and can vary from case to case, we assume a value equal to a percentage of the capital cost for these operations. Previous experiences show that annual labour costs are around 10% of capital investments. The value is significantly higher when productivities are low. Maintenance costs comprise spare parts, repairs, cleaning and everyday problem-solving activities. In this work, we consider periodic replacement of some parts such as pumps, illuminated surface areas and LED lights. Concerning the latter, we consider new fittings every five years. The replacement of the illuminated surface area depends on the choice of materials. Usually, durable materials such as glass reduce operating costs but require higher initial capital costs. As a rule of thumb, the annual maintenance cost amounts to a value of around 5% of the total capital investments. A value of around 3% of the total capital investment is assigned for covering the annual costs of administration, overheads and consumables. The cost of fertilisers and nutrients amounts to about 1% of the initial capital investment.

A further crucial operating cost is energy. The total energy cost for cultivating and harvesting a given amount of microalgae in dry tonnes (m) can be estimated using the specific energy consumption (SEC) in kWh per dry tonnes of microalgae along with the specific cost of energy (SCE) in $/kWh. Eq. (23) shows this methodology. The parameter N signifies the number of equipment established for cultivating and harvesting microalgae. The energy requirement for cultivation comprises pump operations for recirculation along with carbon dioxide and nutrients additions. Harvesting and drying processes include the energy for flocculation, extraction by centrifuges, mechanical, and thermal drying. Therefore, we require more than 1300 kWh per dry tonne of biomass energy, from which 640 kWh is electricity for cultivation and harvesting. The rest goes towards thermal drying.

$$O_E = \sum_{k=1}^{N} SEC_k.m.SCE_k \tag{23}$$

Fig. 3 presents the energy requirement per kg of solid microalgae at different concentrations. As shown in the diagram, the operating cost of drying depends strongly on microalgae solid concentration. The highest energy use is associated with thermal convection drying. The calculation is based on the heat of vaporisation at temperatures between 303 and 373 K at vapour pressures between 4.25 and 101 kPa. This is the minimum amount of thermal energy required to evaporate the water from microalgae. In practice, more thermal energy is required due to heat losses and intracellular moistures. This requirement is reflected in the diagram and calculated based on the published data from Shelef et al. [123]. Fig. 3 also include the energy requirement for spray, microwave and fluid bed drying. The models represented in the figure below are based on the published data showing the energy requirement at different solid concentrations [124–126].

As indicated above, effective dewatering is essential prior to drying. In this work, we used a flocculation tank and mechanical dewatering to

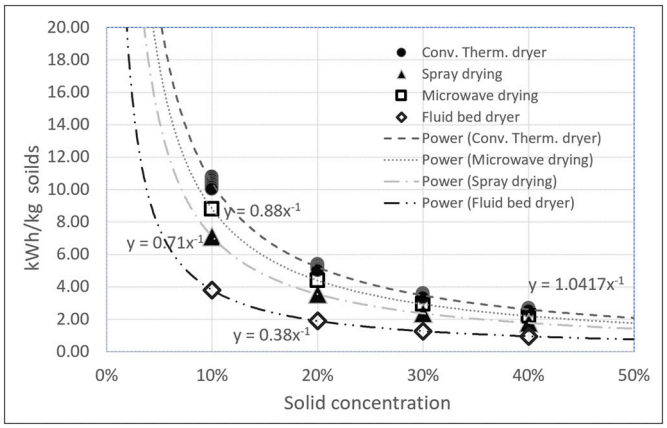


Fig. 3. Energy requirement for microalgae drying as a function of solid concentrations.

increase the solid concentration to 30%. Here, we assume 0.4 MJ/kg of dry algae for dewatering. We apply 1.2 kWh/kg of dry cell dry weight to dry microalgae to 5% final moisture. To reduce energy consumption, the final product can be kept at a higher moisture content.

To cover the variations in operating costs, we will carry out a sensitivity analysis disclosing the impact of low to high operating costs on the price of the high-value compounds. The results can be used to adapt the economics to new situations. The price of the secondary compound is set to a constant value of $0.5/kg.

3. Results and discussions

This section summarises the main results of the techno-economic viability study of integrated PBRs for the production of high-value compounds and secondary compounds for use in applications such as biofuel, biochemicals as supplementary feedstock in animal feed. In our economic assessment, we assume a discounted cash flow rate of 4% and a system lifetime of 20 years.

The system configuration comprises several relatively small and manageable PBR modules, which can be organised in different positions in a one-hectare land area. Regarding the flat-panel PBR, modules are 2 m wide, up to 2 m high and have a thickness of 0.1 m. The spacing between modules is selected at around 0.1 m for every meter within a row. For example, for every 20-meter array, there will be 2 m gap for servicing. The distance between each row is around 2 m.

The airlift PBR modules consist of two-meter-high columns with a diameter of 0.2 m. These are organised in many rows, which consist of many columns occupying a one-hectare area. We selected an average spacing of 0.2 between columns. The distances between rows are around 2.3 m. The tubular PBR modules are made of 15 tubes stacked up to 3 m high. The tubes are 3 m long and have a diameter of 0.1 m. The tubes are connected through u-couplings within each module. The average distance between rows is selected at around 2.3 m. The average distance between the modules in each row is around 0.35 m.

Based on the above assumptions, we can calculate the land requirements, illuminated PBR surface area and the total PBR volume according to the equations described in the previous section. The overall yield will be estimated based on specific productivities. Considering the results shown in Fig. 2, we assume three maximum values: 20, 30and 40 g of dry microalgae per m^2 per day (g m^{-2} d^{-1}) and consider between 20% and 40% productivity losses (w). Due to various reasons, not all biomass can be recovered. Since it is not always possible to maintain the optimal growing environment, the impact of lower productivities can also be examined through the extrapolation of data.

The economics of high-value compounds depends strongly on their availability in the selected microalgae genus. To understand the effect of this variation on the economic viability of microalgae cultivations, we consider high-value compound ratios between 0.1% and 30%. Higher values can be extrapolated from the results. In general, the entire dried microalgae can also be marketed as high-value compounds for further use in products such as fishmeal, animal feed or omega-3 supplement.

Due to the larger surface area, higher productivities can be achieved using tubular PBR systems. Furthermore, supplementary lighting is conducive to increasing productivity and triggering the synthesis of specific metabolites. Therefore, we also use 3 h of unidirectional and 8 h of bidirectional artificial LED lightings per day. This work suggests an irradiance of 150 μmol s^{-1} m^{-2} photons at 650 nm light spectrum. The main technical characteristics of the investigated cases are given in Table 2.

Fig. 4 shows PBR microalgae cultivation, harvesting and drying capital requirement variations for a high-value compound extraction. The figure also includes the cost variations for additional LED lighting and temperature control used in this study. The total cost also includes a 25% contingency. The acquisitions of photobioreactors and their installations constitute the highest cost portion. The installation contains all the necessary equipment. Included are: pumps, pipes, fittings, electrical automation, control systems, labour, engineering, and supervision. The remaining expenses are allocated to indirect costs. The capital requirement for the cultivation using only normal daylights doesn't include the LED light costs. The harvesting cost of cases with bidirectional illumination is higher due to a higher overall yield. The cost for temperature control is mainly dependent on the solar radiation. We assume a negligible amount of heat transfer from the LED light. That is why we assume the same temperature control expenditure for uni and bi-directional LED lighting. All the costs given here are indicative and refer to the cultivation of one hectare. Smaller units tend to require higher specific investments, whereas the larger units can be more cost-effective according to the economies of scale.

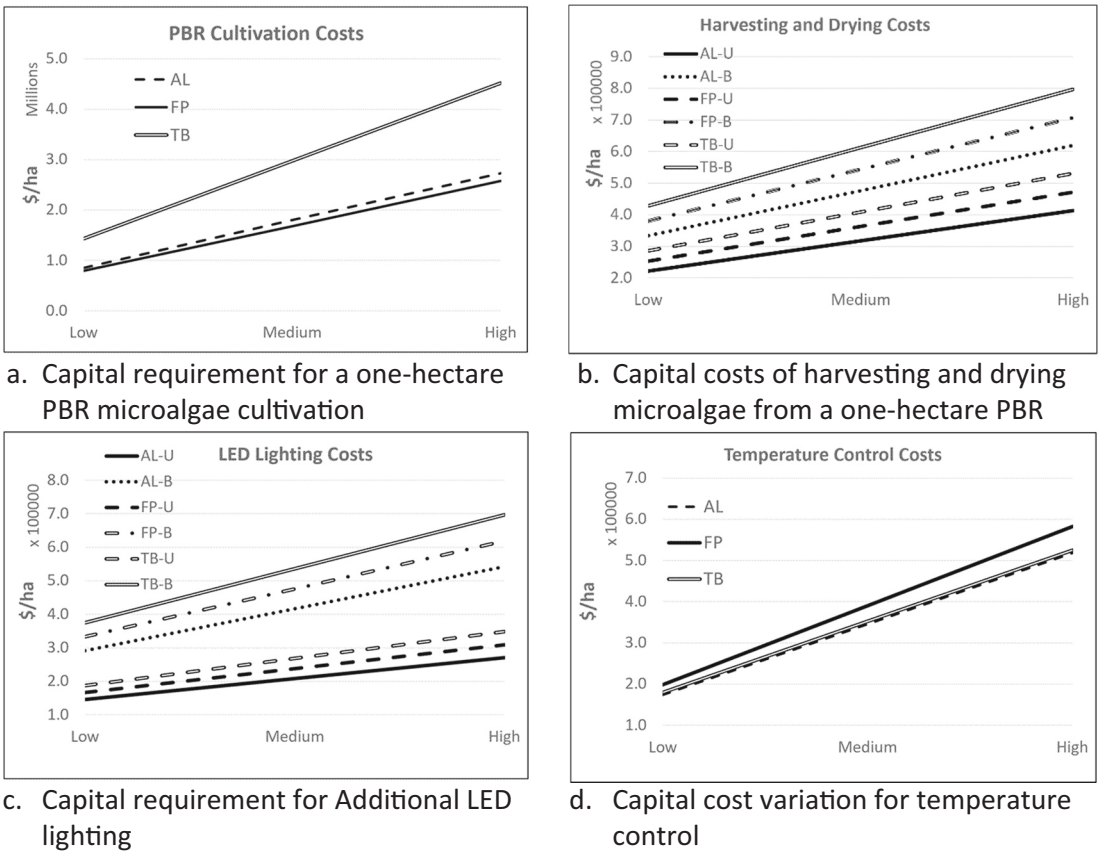
Table 3 shows the specific operating costs of suggested microalgae cultivation in closed PBR's for high-value and secondary compound isolation. The operating costs can vary from case to case. The table provides the minimum and the maximum operating costs in relation to a one-hectare cultivation per year. The medium value corresponds to the expected annual cost per hectare. Favourable economic conditions, such as low-priced or even free electricity, water and carbon dioxide and cost-effective labour, can improve the operating costs. In contrast, the operating costs can increase significantly if the resources have to be provided at high costs.

Discounted cash flow analyses have been devised to evaluate the economic profitability of microalgal cultivations in the suggested systems by setting the expected annual revenues against the operating costs. The expected annual revenues are described as a product of microalgae yields and the breakeven microalgae prices (BEMP). BEMP estimation is based on the net present value analyses using a discounted cash flow rate of 4% and a project life of 20 years. We need to achieve a

Table 2
Main performance characteristics of the investigated case studies within a one hectare land.

Technology	Surface area [m^2]	Volume [m^3]	LED power [kW]	Prod. [$g{\cdot}m^{-2}{\cdot}day^{-1}$]
FP NL	8280	828	0	15–31
FP Unid.	8280	828	264	16–32
FP Bid.	16,560	828	529	12–24
AL NL	7253	725	0	15–31
AL Unid.	7253	725	232	16–32
AL Bid.	14,507	725	463	12–24
T. NL	9326	466	0	15–31
T. Unid.	9326	466	268	16–32
T. Bid.	18,652	466	536	12–24

FP: Flat-panel, AL: Airlift, T: Tubular PBRs, NL: Natural light, Unid.: Uni-direction, Bid.: Bi-direction.



a. Capital requirement for a one-hectare PBR microalgae cultivation

b. Capital costs of harvesting and drying microalgae from a one-hectare PBR

c. Capital requirement for Additional LED lighting

d. Capital cost variation for temperature control

Fig. 4. Capital requirement variations for microalgae cultivation, harvesting and drying including additional LED lighting and temperature control tailored to a one-hectare PBR microalgae cultivation (FP: Flat planel, AL: Airlift, TB: Tubular PBRs, U: uni-directional and B: Bi-directional LED lighting).

Table 3
PBR operating costs.

	Low OP cost $ ha^{-1}	Medium OP cost $ ha^{-1}	High Op cost $ ha^{-1}
Airlift NL	152,929	218,470	284,011
Airlift unidir.	195,749	279,641	363,534
Airlift Bidir	394,391	563,416	732,440
Flat-panel NL	182,217	260,310	338,403
Flat-panel unidir.	231,098	330,140	429,182
Flat-panel bidir.	450,239	643,199	836,158
VTB NL	248,998	355,712	462,425
VTB unidir.	304,053	434,361	564,669
VTB bidir.	505,895	722,707	939,519

net present value of zero to obtain a return on our initial investment. Negative numbers indicate a net loss, which means that the earnings gained throughout the project are less than the initial investments. On the other hand, positive net present values show that the earnings exceed the initial capital investment.

Since the economic assessments are not a clear-cut science, sensitivity analyses were carried out to show the impact of dominant parameters on the economic results. Based on the modelled cases, we evaluate the impact of capital costs on the microalgae price (Fig. 5a). The cost variations of airlift, flat-panel and tubular PBRs illuminated with natural daylight, uni- and bi-directional supplementary lighting as described previously in Table 1 are set against the breakeven microalgae prices in Fig. 5b. Although the economics of tubular PBRs are less favourable, this technology can be a good alternative depending on the application areas requiring compact settings and high yields. Flat-panel PBRs found to have the best economic performance. The utilisation of LED lights can further improve economics. The impact of operating cost variations on the breakeven microalgae price is shown in Fig. 5c.

Fig. 5d demonstrates the impact of productivity on the breakeven microalgae. The correlation here is non-linear. The figure shows that the impact on the breakeven microalgae prices at lower productivities is more significant. This analysis includes a production loss of 20% for unidirectional and 40% for bi-directional cultivations. Cultivation losses can occur for many reasons; high microalgae concentrations, losses during the harvesting, seasonal variations, prolonged maintenance works, high oxygen inhibition, and reduced photosynthetic efficiencies are a few examples. The losses are more distinctive for bidirectional lighting because of higher cell concentrations. Lower productivities can significantly increase the breakeven microalgae prices. The overall variations given in the calculations can help to extrapolate the impact of multiple variables and allows flexibility to consider various changes.

The availability of high-value compounds in microalgae is the main parameter determining the economics. Other variables such as productivity, microalgae costs and capital investments are secondary and become more significant when the whole microalgae is utilised, or a high ratio of a particular compound is isolated. Fig. 6a shows the significance of the HVC ratio on economics. The productivity of microalgae seems to have comparatively unremarkable impacts on the minimum HVC price at low productivity ratios. This characteristic, however, becomes more noticeable at higher HVC ratios. Fig. 6b demonstrates the effect of the breakeven microalgae selling price on HVC prices at different HVC availability in microalgae. The effects of microalgae costs on the minimum HVC price at low and high availability ratios in microalgae are presented in Fig. 6c and d, respectively. Considering fatty acids as examples, we see that *Nannochloropsis salina*, *Scenedesmus obliquus*, *Botryococcus braunii*, and *Tetraselmis suecica* contains between

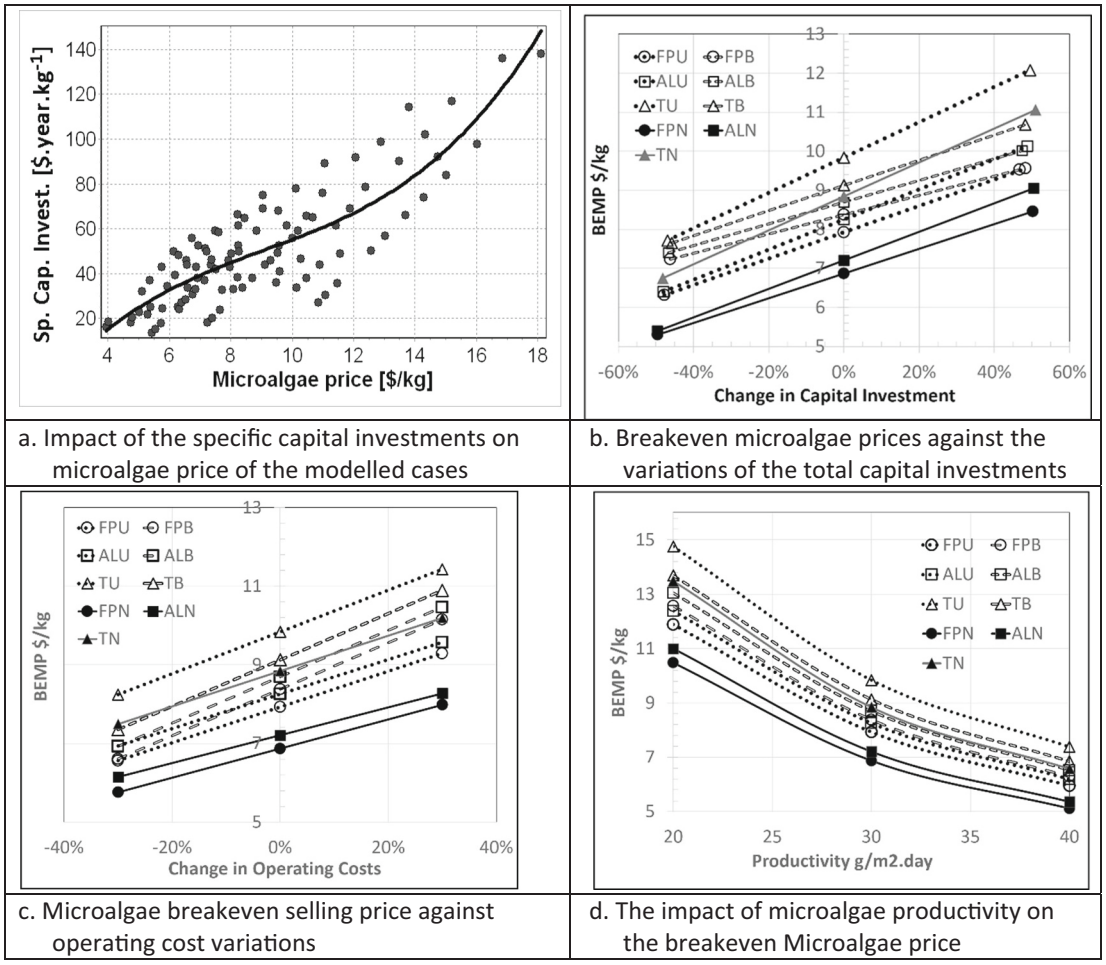
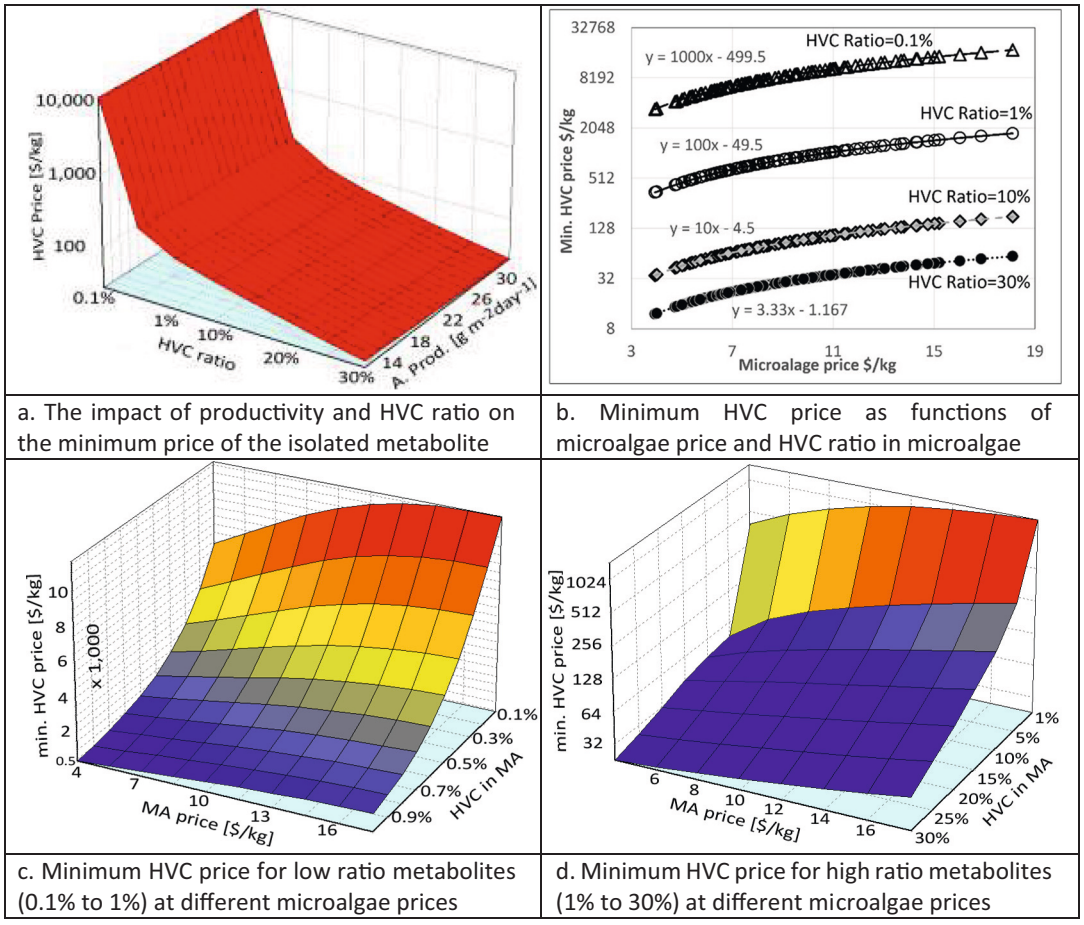


Fig. 5. Economic sensitivity analysis for flat-panel PBR with natural day light (FPN), unidirectional (FPU) and bidirectional supplementary lighting (FPB), airlift PBR with natural day light (ALN), unidirectional (ALU) and bidirectional supplementary lighting (ALB) as well as tubular PBR with natural day light (TN), unidirectional (TU) and bidirectional supplementary lighting (TB).

20 and 40% total lipids per dry weight of microalgae [29,127,128]. The extracted bio-oil from these sources will be around $35 per litre as a high-value product, including 20% extraction costs at a microalgae price of $10 kg and a bio-oil density of 0.92 kg/l [129]. The extracted bio-oil will be a good source of omega-3 [130–132]. The leftovers from the process can be marketed as secondary compounds at a lower cost. In this work, we consider a price of $500/t dry weight. The secondary compounds still contain valuable metabolites. In the case of *Scenedesmus obliquus*, as an example, the protein-rich leftovers can be used as fishmeal or animal feed [133]. With regard to *Tetraselmis suecica*, the leftovers still contain around 53% carbohydrates and 21% proteins and around 6% lipids. Moreover, *Tetraselmis suecica* is a good source of β-Glucan [128]. There will be around 20% β-glucans in the leftover. In connection with gluten-free bread, Nune et al. [134] examined the utilisation of *Tetraselmis Chuii*, which contains bioactive compounds. The use of microalgae leftovers in food products is an appealing option. The extractions of carotenoids as high-value compounds are another example. *Haematococcus pluvialis*, *Dunaliella salina* and *Scenedesmus almeriensis* are some good candidates here [42,135,136]. The former contains up to 7% carotenoids. This fraction includes up to 43% Astaxanthin as a high-value compound with a high market price [46,136–138]. Again, the remaining biomass is available for other purposes at a low cost.

The interrelationship of all the parameters is demonstrated in Fig. 7 using principal component (PC) analysis. The graph shows PC1, PC2 and PC3 projected into two dimensions. A rotation of the graph around its axis simulates a three-dimensional movement of vectors on a two-dimensional plane. This graphical animation is conducive to explaining around 85% of the variability of the modelled cases. The variabilities explained by principal components are usually shown in a scree plot. A static two-dimensional plot of PC1 and PC2, in this case, describes 71% of the variability in the modelled data. All the cases are represented as dots and all the parameters as vectors in the graph. The cases can be divided into different clusters showing specific cases. The relation between parameters can be interpreted by examining the angle between the vectors. Small angles are positively related, whereas larger angles approaching 180 degrees indicate negative correlations. According to the graph, microalgae (MA) price, specific investment (*Sp.* Invest.) and operating costs (*Sp.* OC) have a positive correlation with high-value compound (HVC) prices. Irradiance and the illuminated surface area also impact the price due to supplementary LED lighting and the transparent material used to capture the light. Since we are using only $500/t for microalgae leftovers as a secondary compound, the impact on the HVC price is negligible. The yield and photosynthetic efficiencies are closely related. Their impact on HVC is moderate due to a higher cost to improve productivity. HVC price and HVC ratio are negatively correlated. That is why it is vital to select the correct type of microalgae and the cultivation process to optimise the ratio of the target compound in the microalgae. Finally, the amount of carbon dioxide fixated by microalgae cultivation is strongly affected by artificial lighting. Indeed, more carbon dioxide is emitted by cultivations with 8 h daily bi-directional lighting with electricity based on Natural gas. As an



a. The impact of productivity and HVC ratio on the minimum price of the isolated metabolite

b. Minimum HVC price as functions of microalgae price and HVC ratio in microalgae

c. Minimum HVC price for low ratio metabolites (0.1% to 1%) at different microalgae prices

d. Minimum HVC price for high ratio metabolites (1% to 30%) at different microalgae prices

Fig. 6. Sensitivity analysis of HVC prices.

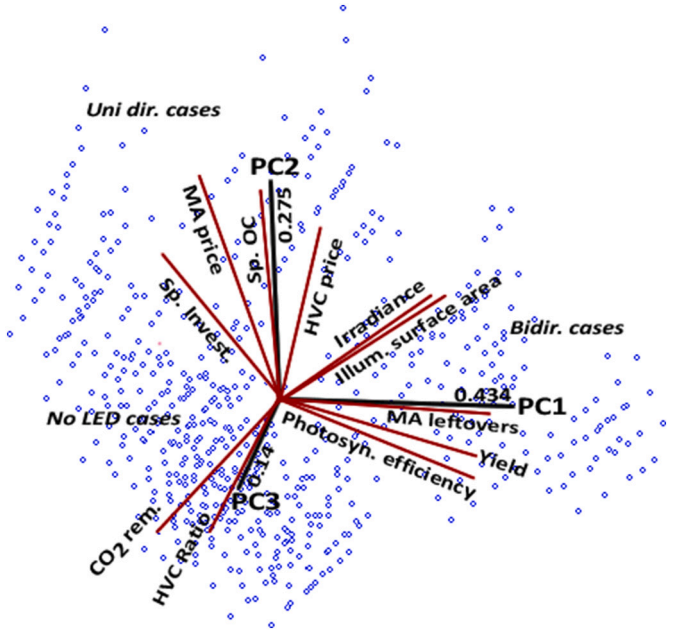


Fig. 7. Principal component analysis showing the interrelation between main parameters.

alternative option, the utilisation of renewable energy will add substantially to the costs. Regarding 3 h of artificial lighting per day, only cases with good productivities will be carbon negative.

4. Conclusion

A preliminary methodology has been developed in this study to evaluate the techno-economic viability of isolating high-value and secondary compounds from microalgae. Here we developed models to determine the technical setups, capital requirements and operating costs of three types of closed photobioreactors [PBR]: flat-panel, airlift and tubular systems. The latter provides relatively high overall productivities at higher costs and complexity. Flat-panel demonstrates the best overall economic performance. However, the system is carbon positive for almost all the cases with artificial light operated 3 h or more per day due to relatively high surface area and moderate productivity. Airlift PBRs are, in comparison, easier to operate and clean. The analysis also includes fixed and variable costs of artificial light, temperature control, harvesting, and drying. The impacts of the main parameters on the techno-economic performance of high-value compounds were analysed using sensitivity analysis. The results show that the ratios of high-value metabolites in the microalgae are the dominant parameter determining the economics. The minimum prices of isolated metabolites are extremely high at ratios below 1%. The impact of other parameters such as productivity and the breakeven microalgae selling price becomes more significant at higher ratios. The price of the secondary compounds is fixed to $500 per dry tonne. This approach allows the competitive use of this resource for applications such as biofuel, biomaterials or any other bioproducts. The effect of productivity, microalgae price.

CRediT authorship contribution statement

Sina Rezvani: Methodology, Formal analysis, Investigation, Writing

- Original Draft, Visualization. **Imen Saadaoui:** Validation, Resources, Data Curation, Writing - Review & Editing, Funding acquisition. **Hareb Al Jabri:** Conceptualization, Resources and Review & Editing. **Navid R. Moheimani:** Conceptualization, Resources, Writing - Review & Editing, Supervision, Project administration.

Funding

This publication was made possible by the QNRF-MME grant # [MME01-0924-190063] from the Qatar National Research Fund (a member of Qatar Foundation) and the Ministry of Municipality and Environment, Qatar. The findings herein reflect the work, and are solely the responsability of the authors.

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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