Received: 25 February 2020 | Revised: 18 June 2020 | Accepted: 20 June 2020

DOI: 10.1002/er.5768

RESEARCH ARTICLE

INTERNATIONAL JOURNAL OF ENERGY RESEARCH WILEY

Improving the economic feasibility of biodiesel production from microalgal biomass via high-value products coproduction

Fariha Khanum[1] | **Adewale Giwa**[2,3] | **Mutasim Nour**[1] | **Sulaiman Al-Zuhair**[4] | **Hanifa Taher**[2,3]

[1]School of Engineering and Physical Sciences, Heriot Watt University, Dubai, UAE

[2]Department of Chemical Engineering, Khalifa University of Science and Technology, Abu Dhabi, UAE

[3]Research and Innovation Center on CO_2 and H_2 (RICH), Khalifa University of Science and Technology, Abu Dhabi, UAE

[4]Department of Chemical and Petroleum Engineering, UAE University, Al Ain, UAE

Correspondence
Hanifa Taher, Department of Chemical Engineering, Khalifa University of Science and Technology, P.O. Box 127788, Abu Dhabi, UAE.
Email: hanifa.alblooshi@ku.ac.ae

Summary

Microalgal biodiesel has emerged as a promising fuel source, but has still not been adopted commercially. One of the several inherent challenges is its high production cost, which mandates the need to develop an integrated process to produce other valuable coproducts economically. This article combines life cycle assessment and preliminary life cycle cost assessment of a proposed biorefinery, in which a high value product, β-carotene, is coproduced from microalgae with biodiesel. The GaBi 6 environmental management software was employed to investigate the environmental impact associated with the production life cycle. The mass flow rates and the energy consumed in all stages of biodiesel and β-carotene coproduction for the functional unit of 1 kg of biodiesel were assessed. When the coproduction of β-carotene was not taken into consideration, the total energy input for a functional unit of 1.0 kg biodiesel/m^2/y and the net energy ratio, that is, energy returned on energy invested were estimated to be 128.1 GWh/y and 0.27, respectively. The life cycle cost analysis showed that although the total production cost associated with coproduction of β-carotene from *Dunaliella salina* was higher than that of the sole production of biodiesel, it generates a hiked revenue of up to $37 million/y. Over the system lifetime of 10 years, the sole production of biodiesel showed a loss of US$345 million per functional unit, whereas the coproduction of β-carotene achieved a net profit of US$120.7 million per functional unit. This work clearly showed that the coproduction of β-carotene with biodiesel from *D. salina* overcomes the cost-ineffectiveness resulting from the production of biodiesel alone.

KEYWORDS

biodiesel, coproduction, *Dunaliella salina*, life cycle assessment, technoeconomic analysis, β-carotene

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2020 The Authors. *International Journal of Energy Research* published by John Wiley & Sons Ltd

1 | INTRODUCTION

Fossil fuel dependent countries are beginning to develop renewable fuel alternatives to conserve their oil and gas reserves, sustain their economic growth, and explore alternative energy sources to mitigate the environmental impacts of fossil fuel-based energy production. The United Arab Emirates (UAE), is ranked as one of the countries displaying highest energy consumption per capita,[1] despite being an oil/gas producing economy. In November 2019, new hydrocarbon reserves estimated at 7 billion barrels of crude oil and 58 trillion standard cubic feet of conventional gas were discovered, indicating a finite supply of nonrenewable fuels.[2] Consequently, the country has acknowledged the need for enhancing its renewable energy resources with minimum ecological impacts. As a substitute to fossil fuels, biofuels are very promising, owing to their versatility, reliability, and minimal environmental strain.[3] At the end of 2018, the Energy Information Administration (EIA) reported that the United States and Brazil, the leading biofuel producers of the world, collectively contributed to 87% of the biofuel production.[4] The two most predominant commercially produced biofuels are bioethanol and biodiesel.[4,5]

The conventional production of biodiesel from agriculture crops has not been regarded as an entirely sustainable approach in the long run, owing to their adverse possible effects of deforestation, depletion of biodiversity, and a possible competition with food resources or land devoted for agriculture.[6] Biodiesel production has been investigated from oils extracted from different sources, such as Jatropha, neem, castor bean, hemp, and karanja. Unconventional sources, such as food wastes, poultry fat, used cooking oil, and microalgae, have been considered.[7-15] Besides biodiesel, microalgae have been investigated for the production of other biofuels, such as bioethanol, biohydrogen, and biosyngas.[16,17] Many dedicated research studies have been focusing worldwide on microalgae-based biodiesel production to fully exploit their benefits over that produced from conventional first and second-generation oil-rich feedstock.[18,19] They are distinguished from oil crops by their unique capacity to produce more lipids, demonstrating yields of 1800 to 2000 gal/acre/y, compared with only 50, 130, and 650 gal/acre/y for soybeans, rapeseed, and palm oil, respectively.[20,21] The driving factor for increased lipid accumulation is physical and chemical manipulations of the cultivation medium.[22,23] Most importantly, microalgae can thrive on freshwater, saltwater, and brackish water, and their cultivation does not require fertile lands, that could otherwise be dedicated to production of food resources.[24] Additionally, some strains of marine microalgae can grow in extreme conditions of high temperatures and sunlight and have the potential to produce a variety of intermediate metabolites that possess nutritional, cosmetic and pharmaceutical applications.[25] Another benefit of using microalgae in the production of biodiesel is their capability to fix inorganic CO_2 by converting it into productive biomass, thus serving as indispensable carbon sequestering agents.[26]

Although the concept of microalgal biodiesel was proposed several decades ago, its commercialization has not yet been fully achieved due to net energy constraints of the process, that is, the energy inputs to the microalgal conversion processes for biodiesel surpass the energy contained in the biodiesel.[27,28] For the process to be economically viable, it was shown that the appropriate culture and harvesting methods with the most suitable lipid extraction method should be carefully selected.[6] Very few studies have analyzed the coproduction of microalgal biodiesel with a high valuable product, which is expected to enhance the return on the energy invested.

The microalgae strain of interest needs to meet three chief requirements, namely, (a) proliferates under the environmental conditions of the geographical area under consideration (b) contains a significant quantity of lipids (c) accumulate a considerable amount of the valuable coproduct. Therefore, a marine microalga, *Dunaliella salina* (*D. salina*, thereafter) was selected, which is a green alga that can grow in saline environments, high ambient temperatures, and abundant light intensity,[16] making it suitable for cultivation in the desert climate of the UAE. *D. salina* has the capacity to thrive in outdoor conditions and is being grown in very large (>200 ha in area), shallow unmixed ponds.[29] *D. salina* strain is currently being commercially cultivated in Hutt and Whyhalla lagoons in Australia for bulk β-carotene production.[21] It has a relatively high lipids content in the range of 35%[30]; also, under stress conditions, it can accumulate significant amounts of valuable substances, such as vitamins, proteins, and pigments,[31] including β-carotene.[32] The stress factor, here, is the homeostasis disruption by salinity, leading to cell metabolism alterations during homeostasis acclimation and restoration.[33] Therefore, the commercial-scale cultivation of *D. salina* is an option to reduce the contamination risk because highly selective cultivations can be achieved.[34] β-carotene is a high-value nutraceutical, which is useful for human immune enrichment, as a source of provitamin and antioxidant, and as an agent for food coloring.[35,36] *D salina* has been widely studied, and is one of the richest sources of natural β-carotene with accumulation rates of up to 14%, when the optimum conditions for caretogenesis are provided.[37] Moreover, the cell wall of *D. salina* is not rigid, making β-carotene extraction easier compared with other strains that contain rigid cell walls.[38] Thus, *D. salina* strain is suitable for commercial exploitation in countries with arid environmental conditions, including the UAE.

Regardless of the selective advantages of using microalgae as feedstock for biodiesel production as outlined above, the economic feasibility having a process solely for the biodiesel production may not be apparent. For the process to be commercially scalable and offset the high input energy costs in biofuel production,[26] either coupling the microalgal biomass cultivation with wastewater treatment or coproducing biodiesel with another high-value product is essential.[39,40] To address this concern, the coproduction of β-carotene with biodiesel production from *D. salina* is suggested in this work, which could offer an added source of income and enhance the economic feasibility of the overall process.

An integrated environmental life cycle assessment (LCA) and life cycle cost (LCC) study was carried out to establish the economic benefits and environmental impacts of the coproduction process, compared with the single-product option. LCA helps to enumerate the impacts of the materials consumed and emissions released, and are critical for constructive evaluation of the entire coproduction process. It is also crucial to estimate the energy returned on energy invested in the process. An LCCA (life cycle cost assessment) is a potential tool used to identify the economic weightage of different variables involved in a production process and to optimize the design of the system in a cost effective way. Hence, it was used in this work taking into consideration all expenses involved in setting up the system, its operating and maintenance costs and the ultimate end-of-life costs. Detailed examination of the influence of β-carotene coproduction on the overall production cost can hence be provided. Previous studies conducted on coproduction systems of a high value product with a biofuel were focused only on comparing and optimizing various approaches and technologies for the synthesis and extraction, without probing in detail about the environment footprint and economic viability. As far as the authors know, and as given in Table 1, this is the first LCA and LCCA of the coproduction of β-carotene with biodiesel from microalgae. It is the first work in which both technoeconomic and LCAs were carried out for such a process. A basic sensitivity analysis was also carried out to explore the interdependence between different significant input variables on the production system and how their modification could alter the energy balance and the process economic cost.[41] The findings of this study are beneficial for life cycle planning purposes, especially in countries that aim to expand their energy resources through lucrative biodiesel production systems from microalgae.

2 | METHODOLOGY

2.1 | System boundaries

The scope of the system includes the cultivation of *D. salina* and its conversion into biodiesel and β-carotene. The conceptual boundaries include: (a) the cultivation of *D. salina* in an open pond; (b) harvesting of the cultivated *D. salina*; (c) dewatering (drying) of the harvested biomass; (d) solvent extraction of β-carotene from a portion of the dry biomass; (e) solvent extraction of lipids from the remaining portion of the dry biomass; and (f) transesterification of extracted lipids to biodiesel. Figure 1 shows the unit processes. The functional unit was 1 kg of

TABLE 1 Examples of previous studies on coproduction of value products with biodiesel from microalgae

Coproduct	Microalgae strain	Technical assessment	LCA of coproduction	Economic assessment	References
Astaxanthin	*Coelastrum* sp. HA-1	Estimation of optimum yields of biomass, lipid, and astaxanthin	Not done	Not done	101
Nutraceuticals, anaerobic digester feed, animal feed	Several strains	Not done	Oil production cost comparison	Not done	102
Lutein, astaxanthin	*Neochloris oleoabundans*	Estimation of optimum yields of lipids and the coproducts	Not done	Not done	103
β-carotene and zeaxanthin	*Chlorella saccharophila*	Estimation of optimum yields of lipids and the coproducts	Not done	Not done	104
Lutein	*Dunaliella tertiolecta*	Estimation of biomass, lipids, and coproduct productivity	Not done	Not done	105
Lutein, β-carotene	*Ettlia* sp. YC001	Estimation of the maximum productivity of biomass, lipids, and coproduct	Not done	Not done	106

Abbreviation: LCA, life cycle assessment.

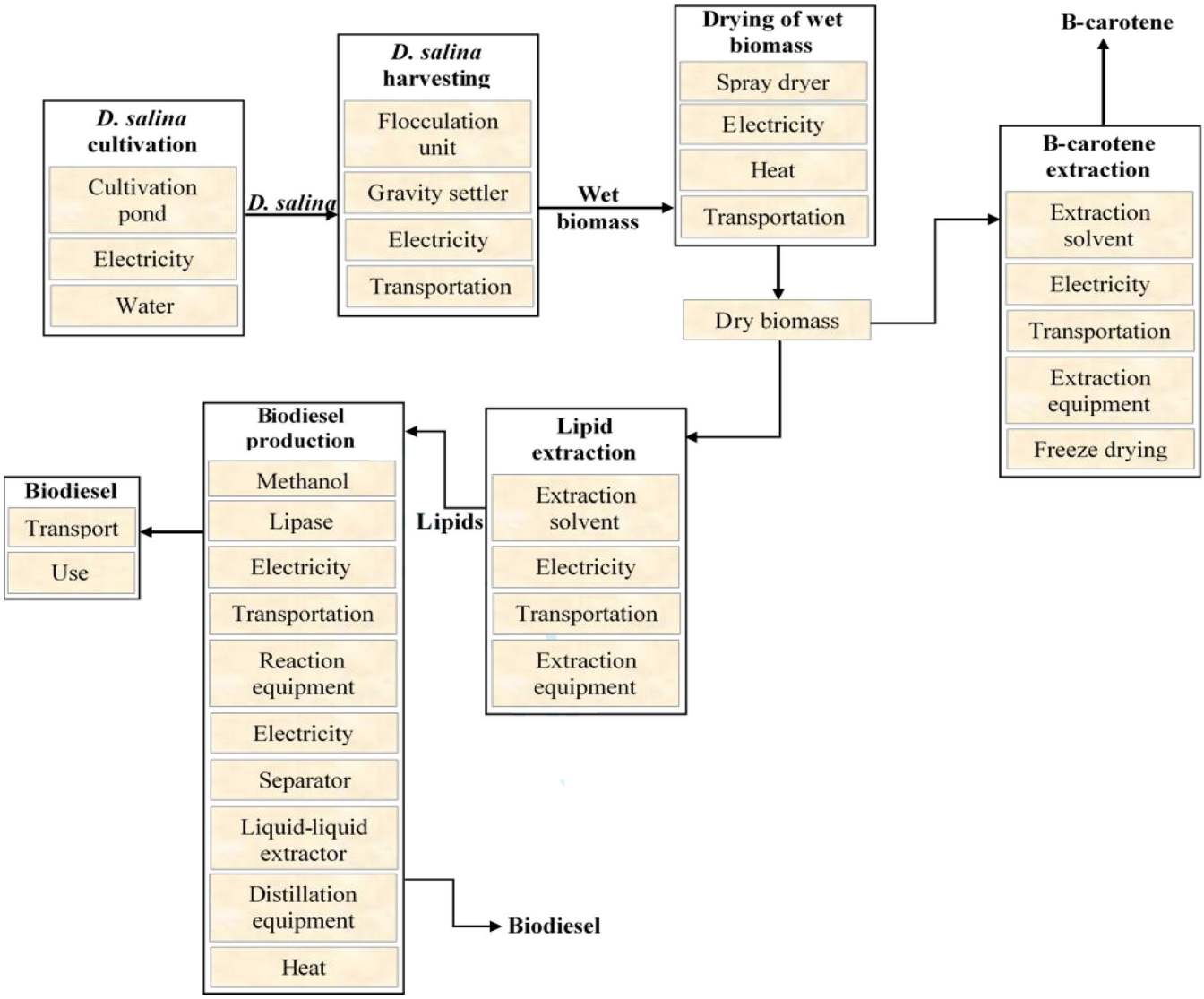


FIGURE 1 Conceptual boundaries employed for the life cycle assessment of β-carotene and biodiesel production from *Dunaliella salina* [Colour figure can be viewed at wileyonlinelibrary.com]

biodiesel/m^2 of microalgal cultivation area per year. The energy balance was estimated as the net energy ratio (NER), that is, the ratio of the total energy produced (energy content of biodiesel produced) to the total energy consumed by the process. The environmental impacts of the production train are assessed based on the recommendations of the International Reference Life Cycle Data System (ILCD; Ekvall et al).[42]

2.2 | Model optimization

An open pond system was considered as the model for the large-scale cultivation of *D. salina* because it is comparatively cheaper and easier to maintain when large nonagricultural lands are available.[16] It was shown that *D. salina* survive well in open extreme environments. Therefore, its cultivation in open pond systems preferable over closed photobioreactor systems, which may not be economical due to their higher operating cost and energy requirements and other operational restraints.[43] In addition, it was verified that *Dunaliella* growth could be achieved along the seashore or close to salt lagoons areas and salt producing industries.[44-46] The strain was therefore selected, as its cultivation requirements are in line with the climatic and geographical conditions of the UAE. Besides the abundant sunlight throughout the year, the UAE has large salt flats (natural subkhas), mainly in the emirate of Abu Dhabi. A virtual model for the photoautotrophic cultivation of *D. salina* in coastal salt lagoons located in Abu

Dhabi was therefore developed. The open pond system would be able to receive the required water from the sea using channels to further reduce the production cost. The surface area of the pond was fixed at 333 ha, with a cultivation depth of 30 cm (essential for light penetration). The cultivation was considered to be carried out under atmospheric CO_2 with a fixed rate of 1.83 kg CO_2/kg of algal biomass.[26] Optimal cultivation conditions of *D. salina*, such as temperature, salinity, pH, and nutrients requirements, which formed the basis of this study, were obtained from published studies. *D. salina* has a wide salt, temperature and pH tolerance levels, which ranged between 3% and 31% NaCl, 20°C to 40°C and up to pH 11, respectively. For the highest productivity though, the optimum salinity range was reported to be in the range 20% to 25% NaCl and optimum pH was 8.[26,44-48] Based on assessment and analysis of alternative technologies, the optimized process chain adopted in this study consisted of: (a) cultivation in open ponds, (b) harvesting by flocculation complemented by gravity sedimentation, (c) dewatering of algal biomass by spray drying, (d) lipid and β-carotene extractions, and (e) enzymatic transesterification. The mixing in the open pond was achieved naturally by wind convection currents, which is less expensive than raceways that require paddle wheels to circulate the culture.[49,50] In such a biological system that is open to various external factors, it is challenging to estimate the exact degrees of freedom. The biomass productivities can vary based on unexpected environmental conditions and contamination could occur which would affect lipid productivity and thereby process conversion efficiency. Nevertheless, and in order to introduce a degree of optimization in our specified model, a sensitivity analysis was conducted to get a general information on how some fluctuations in the values of selected parameters used in the energy balance and LCCs analysis may affect the final economics.

2.3 | Technologies used in the system

The average daily and annual sunshine durations in Abu Dhabi were documented to be 9.6 and 3568 hours, respectively.[51] The dependence of *D. salina* productivity, P_{algae}, on solar irradiance is described by Equation (1).[52]

$$P_{algae} = I_o\left(\frac{PE}{100}\right), \quad (1)$$

In Equation (1), PE is photosynthetic percentage efficiency (%) and I_o is solar irradiance at ground level. The solar radiance (I_o) was taken as 6.036 kWh/m^2 d, which was obtained from the climatic data of UAE.[51,53] The photosynthetic percentage efficiency of *D. salina* was taken as 2.5%. The medium for the growth of *D. salina* and conditions for the accumulation of β-carotene in *D. salina* cells were the same as those considered in the work of Tafreshi and Shariati.[54] Under high salinity of 31% NaCl, an ambient temperature of up to 40°C, and nitrogen starvation with Modified Johnson's medium, Tafreshi and Shariati[54] reported β-carotene accumulation in *D. salina* cell chloroplast of up to 12%. The total water demand for *D. salina* cultivation per unit area, Q_w, was estimated to be 8.7 m^3/m^2 y using Equation (2).[52]

$$Q_w = \frac{(1-R)\times T\times d}{HRT} + Q_e. \quad (2)$$

In Equation (2), T is the number of operational days in a year (300 days), d is the depth of the pond (0.3 m), HRT is the hydraulic retention time (14 days), Q_e is the water loss due to evaporation, and R is the recirculation ratio of wet microalgae. No recirculation was considered in this study, and the value of R was considered to be zero. HRT values ranging from 11 to 18 days have been proposed previously for algae cultivation. The operational days in a year have been set as 300, taking into consideration a 65-day unoperational margin. This means that 2 growth cycles per month and 20 cycles per year were considered in this study. The average evaporation water loss, Q_e in Abu Dhabi has been reported to be a significant value of 2.28 m^3/m^{2}y on account of the prevailing dry weather.[55]

After cultivation, the harvesting of *D. salina* is usually a challenge due to its unicellular nature. Therefore, the harvesting of *D. salina* was considered to be achieved by induced flocculation, followed by gravity settling. The technical specifications of the flocculation unit were: specific energy requirement of 0.458 kWh/kg[56] and flocculation efficiency of 90%.[57] The flocculation efficiency was the percentage of the microalgae cells in the diluted suspension that was collected in the harvested paste. The harvested biomass was considered to be dewatered using the spray drying method. For the purpose of calculations, An APV spray dryer with a power consumption of 40 kWh, overall thermal efficiency of 76%, and specific energy requirement of 0.1 kWh/kg was considered.[58] The dried biomass was split into one portion for the lipid extraction and the other portion for β-carotene extraction.

Lipids were extracted from a portion of the dried biomass using *n*-hexane. Lipid productivity was estimated from P_{algae} and *D. salina* oil density, as shown in Equation (3).

$$P_L = \frac{P_{algae}\times L\%}{ED\times OD} + Q_e. \quad (3)$$

In Equation (3), $P_L$is the lipid productivity or volume of lipids-produced per unit area; ED is the energy density

of *D. salina*, computed from the weighted average of the lower heating values of lipids, carbohydrates, and proteins in *D. salina* (24.7 MJ/kg); *L*% and OD are the percentage of the weight of the lipids (25%) and density (864 g/L) in *D. salina*, respectively.[59] Biodiesel was considered to be produced from the extracted lipids by enzymatic transesterification. By using lipase, the need for free fatty acids (FFA) reduction unit was eliminated, as unlike alkaline catalysts, the enzyme is insensitive toward the FFA content in the feed.[22] The biodiesel production conversion was assumed to be 88% of the extracted lipids, in accordance with the data from the literature, that is, biodiesel yields up to 88% to 92.5% have been reported in previous studies on the transesterification of microalgal oil. [60,61]

The process for β-carotene extraction depends on the market specifications of the desired product.[62] The most efficient form of extraction involves the use of organic solvents, such as *n*-hexane, acetone, ethanol.[20] However, if a completely natural end product is required, hot jojoba oil or vegetable oil are used for extraction.[63] Jojoba oil, for example, possesses high liquid wax penetration rates, which give it a higher processing capacity. The portion deployed for β-carotene production was considered to contain a conservative β-carotene proportion of 12% of dry biomass.[64] Extraction of β-carotene from dry cells was considered to be achieved using *n*-hexane (96% conc.) and hot jojoba oil, according to Emeish.[63] Freeze-drying was considered to be applied in order to remove residual solvents from the extracted β-carotene, according to previous studies on β-carotene extraction from *D. salina*.[64,65] β-carotene was considered to be recovered at a freeze-drying temperature of −85°C, the vacuum pressure of 32 Pa, and for a period of 4 hours. The energy consumption of the freeze dryer was 2 kWh/kg.[66] Freeze-drying has emerged as a steady and effective bioseparation procedure that helps to maintain the stability of heat-sensitive substances, such as vitamins, proteins, and pigments. Unlike other drying techniques, sublimation by freeze-drying ensures minimized structural damage to both the extracted product and the left-over biomass.

Electricity requirements include electricity for pumping into and out of the open pond, harvesting, dewatering, β-carotene extraction, lipid extraction, and transesterification. Water pumping power requirements were estimated from the water flow velocity in and out of the pond (Equation (4)), which was operated by pumps with an overall efficiency of 85%.

$$\text{Required pumping power} = (v \times h \times g)/\varepsilon. \quad (4)$$

In Equation (4), v is the flow velocity. v, is 12 ft/s, that is, the maximum flow velocity that can be delivered by an ANSI schedule 40 pipe considered in this study, with a nominal pipe size of 4 in. h is the height at which the pump is located, namely, the static head, which is the vertical distance between the pump and the pond. h is 10 ft. g is gravitational acceleration (9.8 m/s^2), and ε is overall efficiency (0.85). Electricity data for additional process equipment were obtained from the Eco-Invent database of Gabi 6 environmental management software and the power ratings of the equipment.

2.4 | Environmental impact assessment

The sequential steps involved in performing an LCA study define the goal and scope of the model, the evaluation of the inventory required, assessment of the impacts and ultimately, and the correct interpretation of the results. An environmental impact assessment of the process has been carried out using the Gabi 6 environmental management software. Environmental impacts were quantified in terms of five impact categories, namely, global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), ozone depletion potential (ODP), and photochemical ozone formation potential (PCOP). These impact categories result from the material and energy balances and emissions from the system. They were quantified based on in-built characterization factors in the Gabi software, that is, in terms of analytical measures, inorganic emissions, organic emissions, radioactive emissions, other emissions, heavy metal discharge, and discharge of particulates from the process, according to ISO14046.[67]

GWP impact category was indexed to CO_{2eq} into seawater, which is a representative indicator that assesses the emissions of CO_2, greenhouse gases, such as CO, CH_4, N_2O, chlorofluorocarbons (CFCs), and other molecules that exhibit the propensity to absorb the infrared radiation reflected from the lithosphere. The contributions of other greenhouse gases to GWP were expressed relative to the effect of CO_2. The CO_{2eq} was estimated using an in-built numerical indicator for each stage or unit process, known as characterization or equivalence factor, which was developed by the Joint Research Center of the European Commission (JRC; Sala et al). These characterization factors are the values provided in the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change.

The value of the EP was expressed in terms of kg $PO_4^{-3}{}_{eq}$. Other nutrient enriching components, such as NO_3^- and NH_4^+, were referenced to $PO_4^{-3}{}_{eq}$ using in-built equivalence factors. The other three impact categories, namely AP, ODP, and PCOP, were expressed in terms of in-built equivalence factors for acidification, ozone depletion, and photochemical ozone formation, respectively, that is, these impact categories were estimated as SO_{2eq}, CFC_{eq}, and C_2H_{4eq}, respectively.

The relative importance of the impacts of the stages on the overall impact of the process was evaluated by weighting the impact of each stage, computed from the product of the stage's impact potential and a weighting factor. The weighting factors for all stages were taken as 1.12, 1.2, 1.3, 4.4, and 1.0 for GWP, EP, AP, ODP, and PCOP, respectively, according to sociopolitical targets.[68,69]

2.5 | LCCA and sensitivity analysis

The economic assessments found in the existing literature[70-72] were not comprehensive and considered only the costs of the microalgal oil conversion process to biodiesel. Hence, a fundamental LCCA was performed, which is extremely useful in presenting a clear insight on how several cost variables may contribute to the total costs of a production system. It also emphasizes the functional areas of the entire process that require improvements to increase the overall efficiency, thereby affecting the process economics.[73] In all previously conducted economic assessments, the associated capital, transportation, and energy requirements of the unit processes were mostly ignored. In this study, these important factors were incorporated in the cost estimations, which involved two chief components: capital and operating costs.

The production life was fixed as 10 years while making the following calculations. To calculate the total LCC of the system, all costs involved were classified into several key categories and was estimated using Equation (5)[74,75]:

$$\mathrm{LCC} = C_\mathrm{i} + C_\mathrm{o} + C_\mathrm{m} + C_\mathrm{e} + C_\mathrm{d} + C_\mathrm{r}, \quad (5)$$

where, C_i is capital cost involved in setting up the system, C_o is the total operating cost, C_m is maintenance cost, C_e is energy cost, C_d is cost due to production downtime, resulting from microbial contamination or sudden expected shutdown of the equipment, and C_r is residual cost due to the disposal of the system after its estimated production life. The capital cost was estimated from the sum of the costs of civil and mechanical works for open pond construction, laboratory supplies and building, and office and process equipment. Total operational cost was estimated from the costs of upstream material, transportation, maintenance and labor, and electricity for water filling, make-up water, *D. salina* harvesting, dewatering, lipid extraction, and transesterification. Maintenance cost, including regular servicing of the equipment, cleaning of the pond, and so forth, was considered to be 10% of the fixed capital cost. Energy cost, including the cost of electricity required for dewatering, harvesting, lipid extraction, transesterification, office equipment, and so forth, was calculated using the electricity fee of Abu Dhabi Distribution Company, which is ¢4/kWh. The downtime costs were not considered in this study, because it was covered in the operational days of the year, which was taken to be 300 days. As previously mentioned, unoperational margin of 65 days/y was taken to account for any loss of production. The residual cost due to the disposal of the system after its estimated production life is an integral value to be considered while computing the total LCCs. To predict the disposal value, the salvage or the residual value was taken to be 10% of operating cost.

A local sensitivity analysis was carried out using the one-at-a-time approach, which consider the variation of a single variable from the base case to observe its sole effect on the output variables. The energy produced to energy consumed was not a suitable reference to be used, because β-carotene does not possess a functional calorific value. Three design parameters and one market force were identified to observe the effect of increasing their value on the overall energy requirements and the projected revenue of the system. The three considered design parameters were (a) spray drying thermal efficiency (from 76% to 85%), (b) β-carotene accumulation in *D. salina* (from 12% to 14%, which is the maximum reported content) and (c) transesterification efficiency (from 88% to 92%, which is the highest reported conversion), and the market force was selling price of β-carotene (from 200 to 300 $/kg).

For the purpose of conservative revenue assessment, two cases were defined: the first one considered biodiesel and β-carotene coproduction, whereas the second considered biodiesel production only. The second case assumed that all the dried biomass was converted into lipids and, then, to biodiesel. The revenues are computed from the selling prices of biodiesel and β-carotene. The revenue from the commercial production of β-carotene was estimated from the unit price of US$200/kg β-carotene, which is approximately the production price without any profit margins. However, the unit price of β-carotene in the global market, as documented by earlier studies,[76] is found to between US $300 and US$700/kg. For biodiesel to compete favorably as an alternative to petroleum diesel in the energy market, its selling price was taken to be the same as that of petroleum diesel, which is US$0.7/L in UAE. The net present values (NPVs) of the annual profits were estimated by discounting the annual costs and revenues (computed for the future), with the current discount rate of 2% adopted in the UAE.[77]

The payback period (PBP) of the coproduction process was also computed. The PBP was the amount of time it would take to recover the cost of investment, that is, the length of time it would take the investment to reach the break-even point. PBP estimation is important because it is one of the economic appraisal techniques that provides

information about the temporal profitability of a production process. For the coproduction process, the cost of investment was calculated as the NPV of the cost of production over the process lifetime. PBP was then estimated as the ratio between the cost of investment and net cash flow per annum (Equation (6)).

$$\mathrm{PBP} = \frac{\text{Cost of investment}}{\text{Net cash flow per annum}} = \frac{\text{NPV (cost)}}{\text{NPV (profit) per annum}} \quad (6)$$

The annual net cash flow was computed as the NPV of profit per annum.

3 | RESULTS AND DISCUSSION

3.1 | Material and energy balances

The essential features used in commercial cultivation of *D salina*, with the intended purpose of β-carotene accumulation in large-scale open system, are the high salinity and adequate sunlight to stimulate maximum caretogenesis, as adopted in our model.[78] Thus, with suitable conditions and optimum nutrients, microalgae proliferate rapidly, owing to their high multiplication rates, and biomass doubling in 24 hours.[79] The material output from the cultivation stage is wet *D. salina*. The areal productivity of *D. salina* biomass from the open pond was determined to be 21 g/m^2 d using Equation (1). The productivity of *D. salina* per cultivation area for each growth cycle and for the entire year was estimated by multiplying P_{algae} by 14 and 300 days, respectively. The total biomass productivity for the entire cultivation area was also estimated by multiplying the areal productivity by the total cultivation area. Biomass cell density was estimated to be 0.98 g/L. Q_w was estimated with Equation (2) to be 6.42 m^3/m^2 y when water loss due to evaporation was neglected. This value was higher than the rate of 2.28 m^3/m^2 y predicted previously for arid regions.[52] This component of total water requirement is vital considering the extremely dry environment of UAE and can impact the total process environmental footprint. Q_w increased to 8.7 $m^3/m^2/y$ when considering the water loss due to evaporation.

The material output from the harvesting stage is wet *D. salina*, while the material outputs from the dewatering, lipid extraction, transesterification, and β-carotene stages are dry *D. salina* biomass, lipids, biodiesel, and β-carotene, respectively. Using the Gabi 6 software, the flow rates of *D. salina* outputs from the harvesting and dewatering stages were found to be 19 and 15 g/m^2 d, respectively. The mass flow rate of extracted lipids was estimated to be 4 g/m^2 d or a P_L value of 4.6 cm^3/m^2 d, as obtained from Equation (3). The mass flow rates of biodiesel and β-carotene produced from the process were estimated using the Gabi 6 software as 3.3 and 0.2 g/m^2 d, respectively. This areal productivity of biodiesel was equivalent to the functional unit employed in this study. The areal mass flow rates of all streams were converted to mass flow rates per cycle, per year, and total mass flow rates over the entire cultivation area using HRT, T, and A_s, respectively, as conversion factors (Table 2).

The energy requirements for each stage were also estimated. Equation (4) was used to calculate the energy consumed by the pumps running the open pond, which was estimated to be 1.28 MWh/y. Using the Gabi 6, the total energy requirement for the open pond cultivation, including electricity consumption for make-up water, was estimated as 2.4 MWh/y. The energy requirements for the harvesting, dewatering, and lipid extraction stages were estimated as 101.8, 22.2, and 0.100 GWh/y, respectively. Transesterification and β-carotene extraction consume 0.025 and 4 GWh/y, respectively, according to the functional unit employed in this study. The functional mass (ie, 1 kg of biodiesel) and 0.07 kg of β-carotene coproduct were found to be produced from 6.3 kg of *D. salina*. The energy consumed and mass flow rates across all stages are shown in Figure 2.

As shown in Figure 2, the harvesting stage was the highest energy intensive stage. The energy requirement of the harvesting stage outweighed the sum of the energy

TABLE 2 Flow rates of material outputs from the process stages

Stage	Material	Flow rates of material outputs			
		g/m^2 d	g/m^2 cycle	$kg/m^2/y$	t/y
Cultivation	Wet *D. salina*	21	294	6.3	20 998
Harvesting	Wet *D. salina*	19	266	5.7	18 998
Dewatering	Dry *D. salina*	15	210	4.5	14 999
Lipid extraction	Lipids	4	56	1.2	4000
Transesterification	Biodiesel	3.3	47	1	3333
β-carotene extraction	β-carotene	0.23	3.3	0.07	233

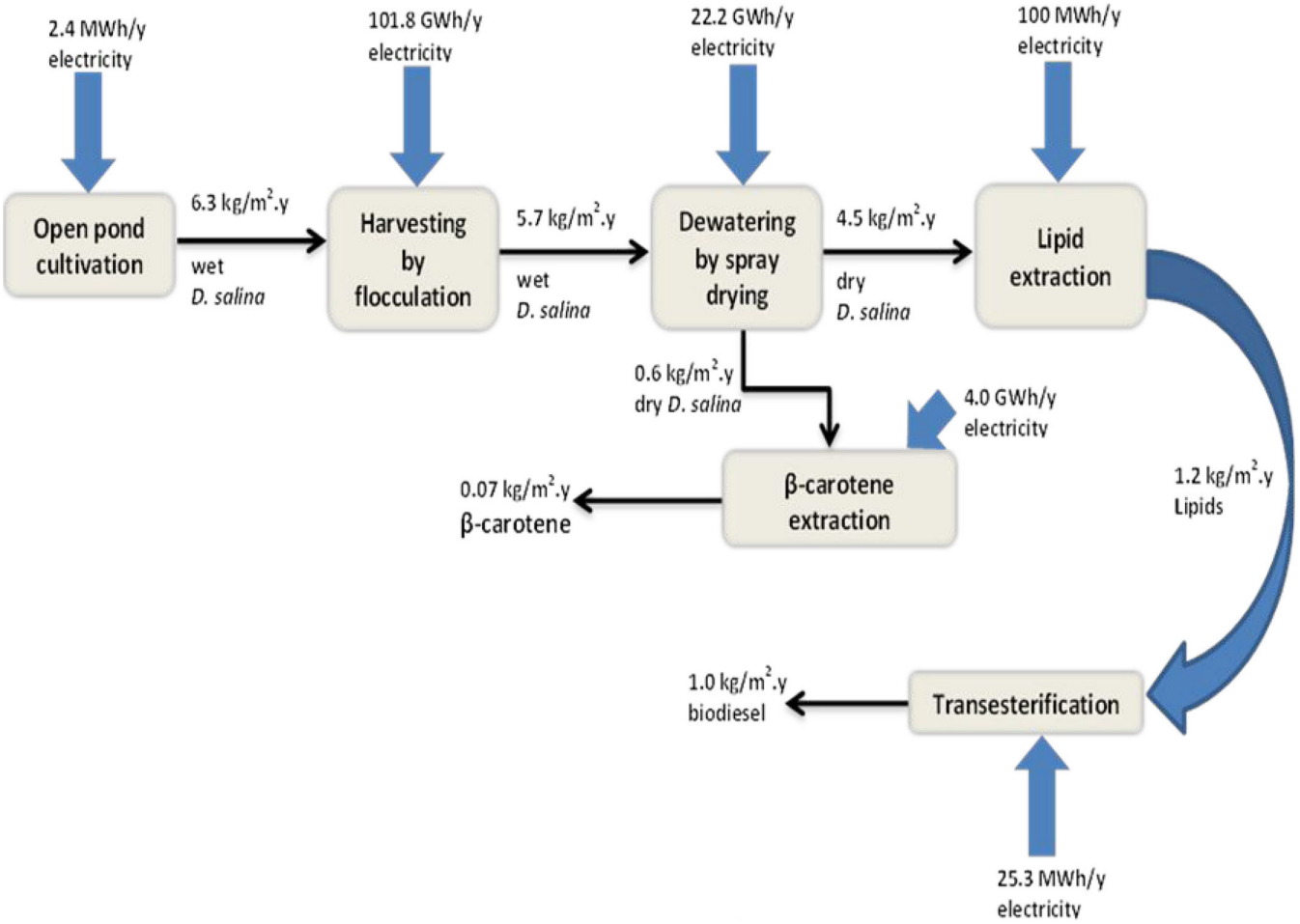


FIGURE 2 Estimated energy and mass flow rates of material inputs and outputs across all stages [Colour figure can be viewed at wileyonlinelibrary.com]

requirements of all other stages and accounted for 79% of the total energy requirement. This finding was in concordance with previous studies on *D. salina* harvesting that also reported that more energy was consumed in the harvesting stage relative to other stage, although a previous study has concluded that algal harvesting contributed to only 30% of the total production costs.[38,72,79,80] High harvesting energy can be attributed to the unicellular nature of *D. salina*. In this study, harvesting was a two-stage process, consisting of flocculation followed by gravity settling. Flocculation was opted for as a preliminary step to aggregate the cells for the second gravity sedimentation step.[81] It is highly imperative that preliminary flocculation results in a dense algal mixture to further increase the efficiency of gravity sedimentation process.[82] The specific energy requirement of the flocculation unit was a bit high (0.458 kWh/kg), which might be responsible for its significant contribution to the overall energy requirement. For effective light penetration in open ponds, the pond depth has to be limited and the culture cannot be over dense, which directly influence the cost of harvesting.[83-85] The energy consumption of the other stages decreases in the following order: dewatering, β-carotene extraction, lipid extraction, and transesterification. Dewatering by spray drying has been selected because it has been branded as an appropriate choice when the recovered algal biomass is of high value and its end use is for human consumption.[86] Other factors to be considered when selecting the drying technique is the production scale, and the preferred quality of the product, dictated by its end user applications.[87] While considering the lipids as a feedstock for biodiesel production, its fatty acid profile has to be carefully evaluated, as it can affect the properties and stability of the produced biodiesel.[88] Gas chromatography analysis of fatty acid profile of *D. salina* lipid showed that the highest fatty acid constituent was the unsaturated linolenic acid (C18:2) accounting for 30.26%, followed by linoleic acid (C18:2) at 13.24%. The highest saturated fatty acids constituent was palmitic acid (C16:0) at 18.2%.[89]

The total amount of energy required for the production of the functional unit was estimated to be 128.1 GWh/y. One of the products, namely biodiesel

produced in the transesterification stage, was only considered in the final bioenergy-produced determination, as the other product β-carotene is not an energy source. The lipid accumulation rate was taken as 25% of the recovered dry biomass from earlier documented studies.[90] It was estimated from the lower calorific value of biodiesel, that is, 37.5 MJ/kg,[91] which is equivalent to 9.1 kWh/L or 10.4 kWh/kg of biodiesel. The annual production of biodiesel from the functional unit would be 3333 t. The annual total energy output from the process was computed from the annual biodiesel production and lower calorific value of biodiesel. The annual total energy output was found to be 35 GWh/y, which was much lower than the total energy input of 128.1 GWh/y. The NER of the life cycle was estimated to be 0.27 only, namely, as calculated from the ratio of the total energy output to total energy input. Therefore, from an energy perspective taking into account all the components that can be quantified, the energy economics of this system was unfavorable, which was mainly due to the energy-intensive units used in the process, mainly harvesting, dewatering, and extraction.

NER values lower than 1.0 have also been reported in several previous studies on biofuel production from microalgae. For example, Monari et al,[92] examined the energy balance of biodiesel production from *Nannochloropsis* sp. cultivated at industrial scale in photobioreactors in Denmark. Different technologies were considered in the cultivation stage (freshwater vs wastewater), harvesting stage (flocculation vs centrifugation), and oil extraction stage (drying + hexane extraction vs supercritical CO_2 extraction). For every MJ of biodiesel produced, the energy requirements for the fresh water cultivation, wastewater cultivation, flocculation, centrifugation, drying, hexane extraction, and supercritical CO_2 extraction stages were estimated to be 2.8 MJ (as electrical energy), 2.8 MJ (as electrical energy), 0.18 MJ (as electrical energy), 0.4 MJ (as electrical energy), 1.12 MJ (as thermal energy), 0.04 MJ (as electrical energy) + 0.1 MJ (as thermal energy), 0.65 MJ (as electrical energy), and 0.02 MJ (as electrical energy), respectively. All combinations lead to NER values lower than 1.0. The life cycle impacts of combining different techniques of algae cultivation (raceway vs wastewater effluent cultivation) with different fuel conversion processes (whole cell pyrolysis vs oil extraction and hydrotreatment) have been compared by Handler et al.[93] Three scenarios were studied, namely, wastewater effluent cultivation/pyrolysis, raceway cultivation/oil extraction, and raceway cultivation/pyrolysis. Algal cultivation in wastewater effluent involved the use of primary effluent containing sizable nutrients from a wastewater treatment plant while raceway cultivation involved the 2cultivation of single-strain halotolerant algae (*Nannochloropsis* sp.) in a high input/high yield fashion (after nutrient removal). In all scenarios, hydroprocessing was considered for the cleaning of the liquid fuel product to ensure a final product of high quality. The raceway cultivation technique combined with oil extraction and pyrolysis resulted in NER values of 0.7 and 0.3, respectively, when dissolved air flotation was employed for dewatering. On the other hand, the combination of wastewater effluent cultivation with pyrolysis significantly reduced the NER due to energy credit allocation to the biological nutrient removal, which was not required in this scenario. In another study, pyrolysis was compared with hydrothermal liquefaction.[94] The two conversion processes were considered for the conversion of *Scenedesmus dimorphus*, which was cultivated with laboratory-grade macronutrients. NER values of 0.8 and 0.44 were obtained for the hydrothermal liquefaction and pyrolysis processes, respectively.

This suggests that, although the modeled process of biodiesel and β-carotene coproduction is technically viable, measurable energy requirements outweigh the renewable energy content of the biodiesel produced. Consequently, the environmental impact and cost-profit assessments were further carried out to evaluate the sustainability of the process better.

3.2 | Environmental impact assessment

The contributions of the process stages to GWP per 100 years are shown in Figure 3. The emissions contributing to global warming are CO_2, CH_4, N_2O, CFCs (11, 12, 113, 114, 115), HFCs (HFC-125, -134a, -152a), CCl_4, CCl_3CH_3, and CO. The energy-intensive units, namely, dewatering, harvesting, and β-carotene extraction contribute significantly to global warming, relative to other stages. Most of the GWP impacts for each stage were due to organic/inorganic emissions and particulates. These emissions were directly related to energy consumption and disposal of the materials of the flocculation unit, spray dryer, and freeze dryer at the end of the lifecycle. The impact of particle discharge to the sea, contributed by β-carotene extraction, was significantly higher than those of the other stages. This might be due to the presence of colloidal biomass particles in the sublimed phase that moves directly to the vapor phase during freeze-drying. As per the functional unit employed in this study, the total GWP was estimated to be 128.3 kg CO_{2eq}/y. As shown in Figure 3, the contributions of the cultivation, harvesting, dewatering, lipid extraction, β-carotene extraction, and transesterification stages to the total energy input per functional unit are 2.4 MWh, 101.8 GWh, 22.2 GWh, 100 MWh, 4 GWh, and 25.3 MWh, respectively. Therefore, as for the "particles to seawater" emission only, the impact

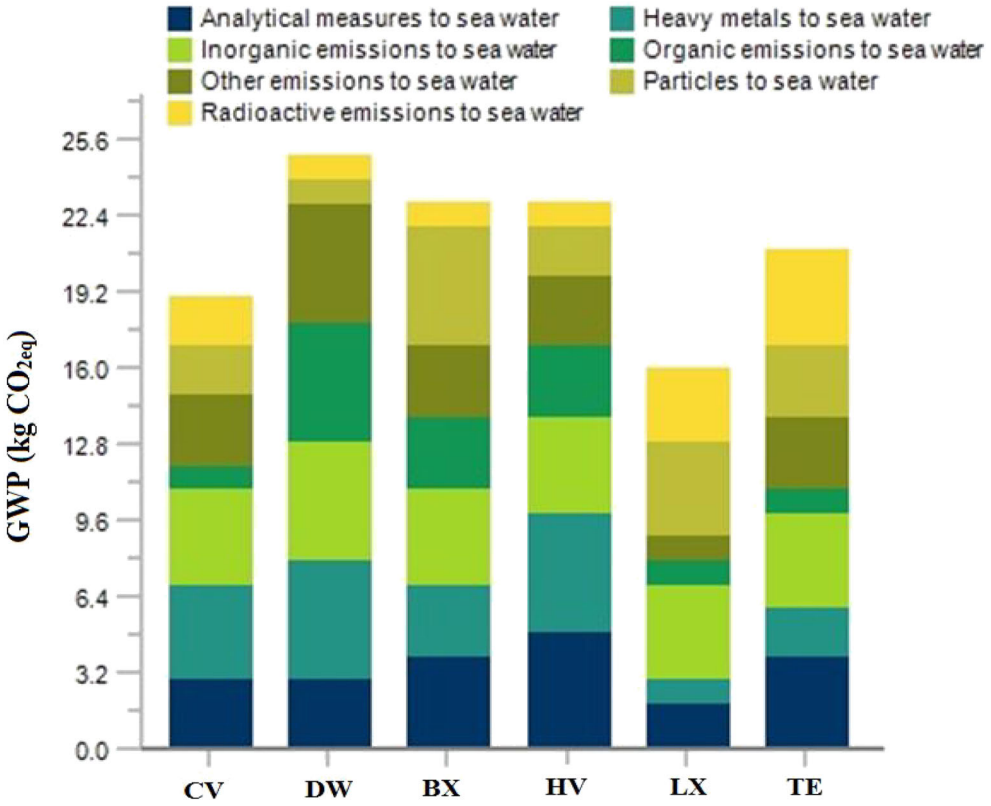


FIGURE 3 Global warming potential (GWP) contributions of the open pond cultivation (CV), dewatering (DW), β-carotene extraction (BX) units, harvesting (HV), lipid extraction (LX), and transesterification (TE) stages [Colour figure can be viewed at wileyonlinelibrary.com]

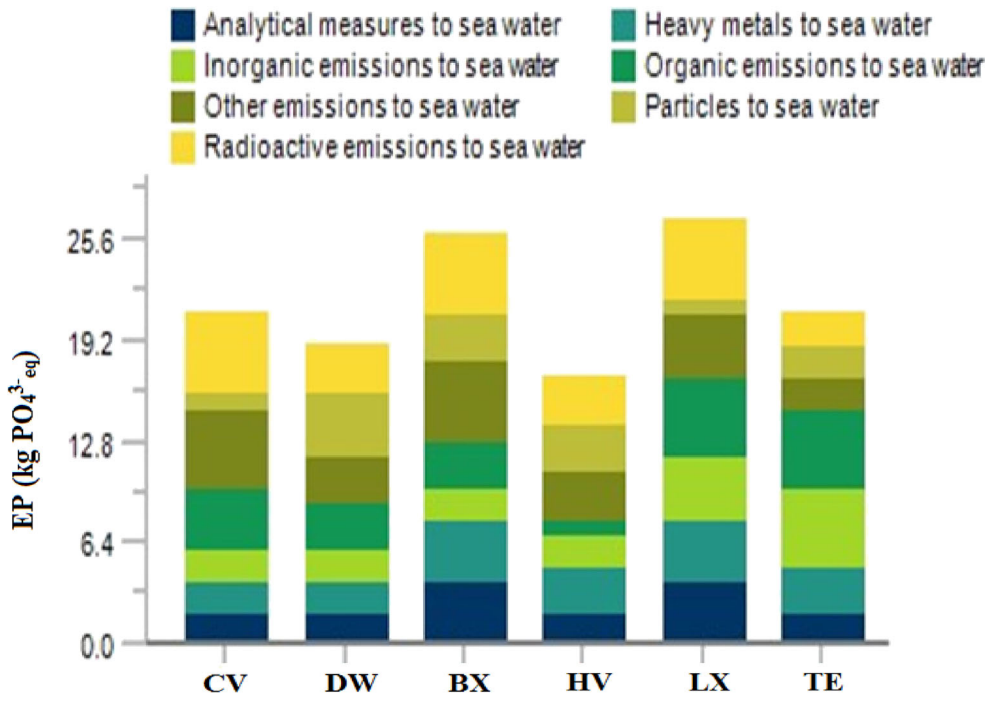


FIGURE 4 Eutrophication potential (EP) contributions of the open pond cultivation (CV), dewatering (DW), β-carotene extraction (BX), harvesting (HV), lipid extraction (LX), and transesterification (TE) per functional unit of biodiesel [Colour figure can be viewed at wileyonlinelibrary.com]

of β-carotene extraction is significantly higher than the impact of any other stage. However, in terms of the overall GWP, the dewatering stage has the highest overall GWP due to the higher energy consumption and emissions from the dewatering stage.

Normalizing the total GWP of the process with the global normalization reference of 8700 kg CO_{2eq}/capita y, a normalized impact potential of 15 mPt per functional unit was obtained. The normalization reference is the approximate (subjective) effect contributed by one person

(1 Pt) to global warming, that is, the CO_{2eq} derived from the contribution of an average person.[59]

The eutrophication impact of the process was evaluated in terms of EP, as shown in Figure 4. The total EP was estimated to be 129 kg $PO_4^{-3}{}_{eq}$ (42 kg P_{eq}) per functional unit. Some research studies have verified that the cultivation of microalgae can lower the EP of the marine environment by the uptake of nitrogen and carbon from water[25] and it is the process technological steps that contribute to this category. In alignment, we discovered that the lipid and β-carotene extraction stages contributed most significantly to the overall EP due to the seawater nutrient enrichment that would arise when the sludge from the extraction processes was disposed in seawater. Seawater is the predominant source of freshwater in the geographical area considered in this study. After extraction, the sludge consists of carbohydrate and protein (major components) along with some amounts of water and cellulose.[17] Thus, the residue affects the quality of seawater that is in turn used for freshwater production. The EP of the process was normalized against a global normalization reference of 0.73 kg P_{eq}/capita.[94] The normalized EP was estimated to be 58 Pt, indicating that the tendency of the process to cause eutrophication was high. This could be reduced by reusing the sludge or residue from the extraction stages and minimizing the exposure of the sludge to the marine ecosystem. Figure 5 shows the other impacts, namely AP, ODP, and PCOP,

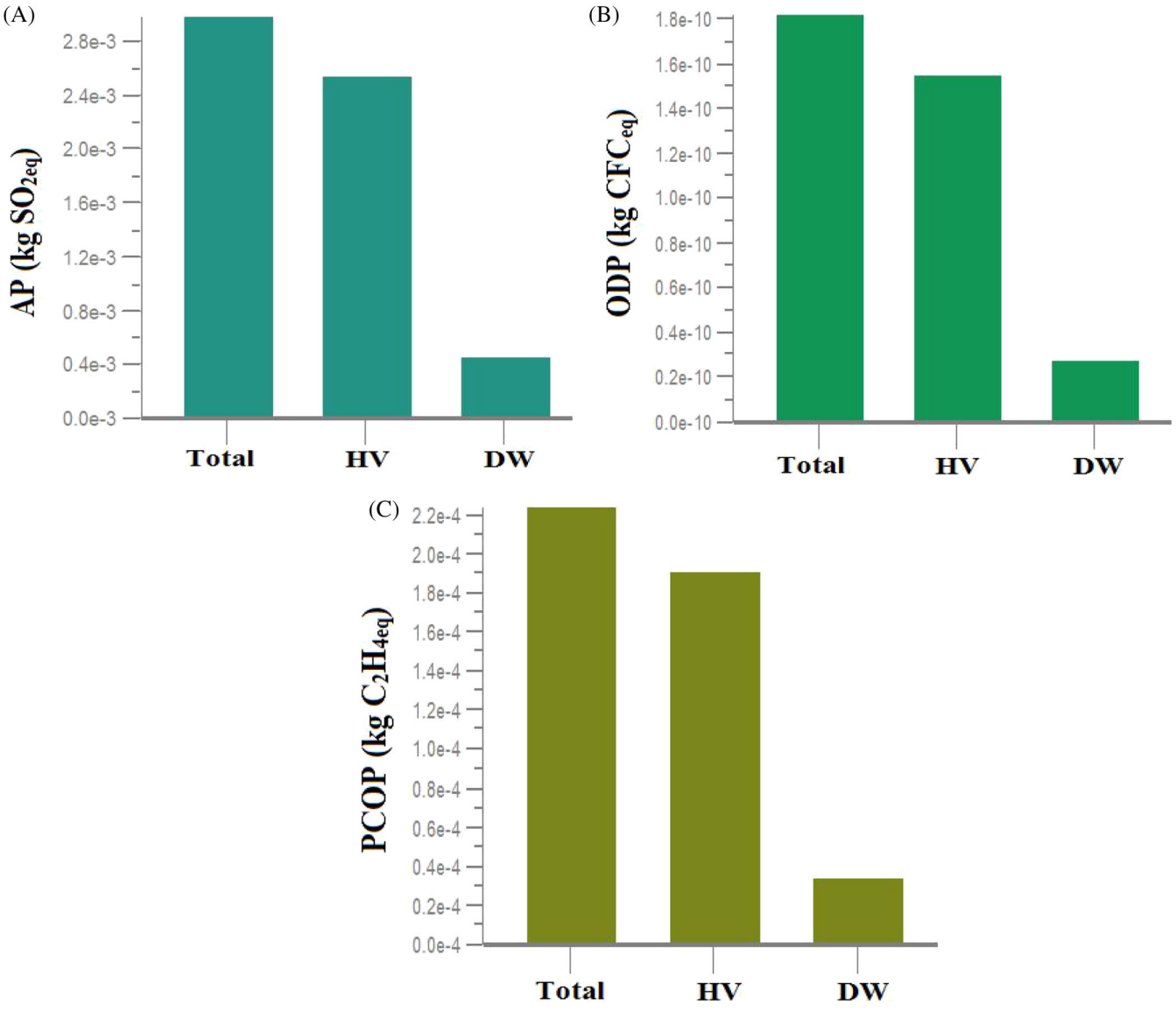


FIGURE 5 Total and sectorial A, acidification potential (AP); B, ozone depletion potential (ODP); and C, photochemical ozone formation potential (PCOP) of the harvesting (HV) and dewatering (DW) stages per functional unit of biodiesel [Colour figure can be viewed at wileyonlinelibrary.com]

of harvesting and dewatering stages and their total values.

The effects of AP were contributed by substances that discharge H^+ ions to the environment (such as SO_2, SO_3, and NO_x), leading to the acidification of water bodies and forest dieback. These gases are emitted from fossil fuel combustion during electricity production. Likewise, stratospheric ozone layer depletion was mainly caused by halogenated gases, CH_4 and N_2O. Photochemical ozone was formed from gaseous emissions (NO_x, CO, and so forth) and volatile organic compounds, such as ethene that release peroxy radicals under the influence of sunlight. Unlike the stratospheric ozone, photochemical ozone is formed in the troposphere, making it hazardous to human health.[95,96] The high contributions of harvesting and dewatering stages to AP, ODP, and PCOP is directly related to the fossil emissions resulting from the electricity requirements of these stages. Therefore, the two stages shown in Figure 5 exhibit the largest share of the total energy consumption, resulting in the highest AP, ODP, and PCOP impacts. The AP, ODP, and PCOP impacts estimated for the entire system per functional unit were 3 g SO_{2eq}, 0.18 μg CFC_{eq}, and 0.22 g C_2H_{4eq}, respectively. The harvesting stage alone was responsible for 89%, 88%, and 84% of the impact potentials due to acidification, ozone depletion, and photochemical ozone formation, respectively. Using global normalized references of 59 kg SO_{2eq}/capita y, 0.103 kg CFC_{eq}/capita y, and 22 kg C_2H_{4eq}/capita y,[58] the estimated normalized potentials were 50 μPt, 1.7 nPt, and 10 μPt, respectively. These values were lower than those obtained for GWP and EP, indicating that the influence of the process on global warming and eutrophication was more significant than on acidification, ozone depletion, and photochemical ozone formation. The weighted potentials per functional unit for GWP, EP, AP, ODP, and PCOP were 16.8 mPt, 69.6 Pt, 65 μPt, 7.5 nPt, and 10 μPt, respectively. This shows that even when applying weighting, eutrophication and global warming remain the major impacts of the process and no substantial disparity between the weighted and non-weighted potentials were observed. More importantly, the cumulative GWP values fall well below the recommended range, not representing a threat to the environment. This proves that the process was environmentally friendly and did not cause much damage to the environment in the form of toxic gases, even though β-carotene is being coproduced.

3.3 | LCC and sensitivity analysis results

The life cycle costs were calculated by summing up the preliminary costs and anticipated costs during the operational period, and the salvage value at the end of operation,[73] as given in Table 3. As given in the table, the major constituent of the LCC cost is the energy costs that is, the total electricity costs involved, from cultivation to the final product stage. The LCC cost increased by $1.6 million/y when β-carotene production was incorporated into the system.

To further understand the shifting of energy and economic balance, a sensitivity analysis was conducted to analyze how the fluctuation of certain design variables could impact energy requirements.[6] In biological systems, such as the one under investigation, enumerating all the variables that may influence the energy and cost estimations is challenging. In this work, three design variables and a market force were considered to determine an overall impact.

Case 1: For spray drying, a thermal conversion efficiency of 76% was assumed, as indicated in Section 2.1. However, with exhaust heat recovery, the efficiency of the process could increase and energy consumption costs could then decrease. With an increase in thermal efficiency to 85%, the recovered biomass would increase by 0.3 kg per functional unit, leading to a decrease of 1.7 GWh/y in energy consumption. This translates into an extra income of $0.13 million/y from the net biodiesel produced.

TABLE 3 Breakdown of the total LCC costs comparing production of biodiesel alone and coproduction of β-carotene

	Production of biodiesel		Production of biodiesel and β-carotene	
	Per year	For 10 years	Per year	For 10 years
Capital costs (C_i)	$6.3 million	$21 million	$6.3 million	$21 million
Operating costs/year (C_o)	$2.73 million	$27.3 million	$2.73 million	$27.3 million
Maintenance costs/year (C_m)	$0.63 million	$6.3 million	$0.63 million	$6.3 million
Energy costs (C_e)	$31.9 million	$319 million	$33.5 million	$335 million
End of life/disposal costs (C_r)	$0.63 million		$0.63 million	
$LCC_{total} = C_i + C_m + C_o + C_e + C_r$	$42.19 million	$374 million	$43.79 million	$389.6 million

Abbreviation: LCC, life cycle cost.

Case 2: With proper stress conditions, optimum irradiance, and nutrient supply, β-carotene contents can be increased from 12% to 14% (highest reported content). Hence, the recovered β-carotene output would increase from 0.07 to 0.084 kg, as shown in Figure 2. The increase in energy costs due to this would be insignificant. However, this 20% increase in β-carotene production, relative to 0.07 kg, per year translates into a significant added income of $9.4 million. Possible mechanisms triggering maximum accumulation of β-carotene are storage of carbon, oxygen quenching and solar radiation induction. The consideration of these mechanisms could lead to an increase in β-carotene output, which would translate to an additional profit of $9.4 million.

Case 3: An increase in the conversion efficiency of transesterification process from 88% to 92% (highest reported conversion) could increase the biodiesel capacity by 10% per cycle and reduce the energy consumption by 2.63 MWh/y, adding a production increase of 350 t/y. That could generate a revenue of $0.28 million/y, assuming biodiesel selling price of $0.7/L.

Market force: Taking the market selling price of β-carotene as $300/kg, leads to a projected revenue of $70 million/y in comparison to $47 million/y from a unit price of $200/kg.

This sensitivity analysis shows that the highest energy-saving step apart from the harvesting stage would arise from the efficiency augmentation of the dewatering process (leading to an energy saving of 1.7 GWh/y in Case 1), followed by the transesterification process (leading to an energy saving of 2.63 MWh/y in Case 3). The results from the energy consumption for all the cases were converted to tentative profits, and the modified revenues were calculated and shown in Figure 6. It was found that although maximizing β-carotene content had an insignificant effect on the energy consumption, a drastic impact on the revenue was observed. The projected revenue would increase from $49.7 million to $52.5 million, $58.7 million, or $50 million if the base case is changed to Case 1, Case 2, or Case 3, respectively. This increase would translate to 5.6%, 18.1%, 0.6% additional revenue by Case 1, Case 2, and Case 3, respectively, compared to the projected revenue of the base case. The sensitivity analysis also revealed that the market factor has a greater effect on the projected revenue than the three design variables. The market selling price of β-carotene can capitalize on the revenues generated and by increasing it to $300/kg would increase the projected revenue by more than 40% compared with the selling price of $200/kg. Increase in the three design variables, however, would result in less than 25% increase in the revenues.

Figure 7 shows the estimates of the breakdown of the production cost, including those associated with capital cost, operating cost without electricity, and electricity per year. An overview of the contributions of the different cost sectors is also shown in Figure 7. The total capital cost in the first year of production was estimated to be US$6.3 million, with the civil and mechanical works accounting for 94% of the total (Figure 7A). These works include site investigation, topographical survey, excavations, pond filling, impermeable membrane installation inside the pond, the laying of plastic pipes, and installation of aeration and water pumps. These works were preliminary demonstration-scale investigations carried

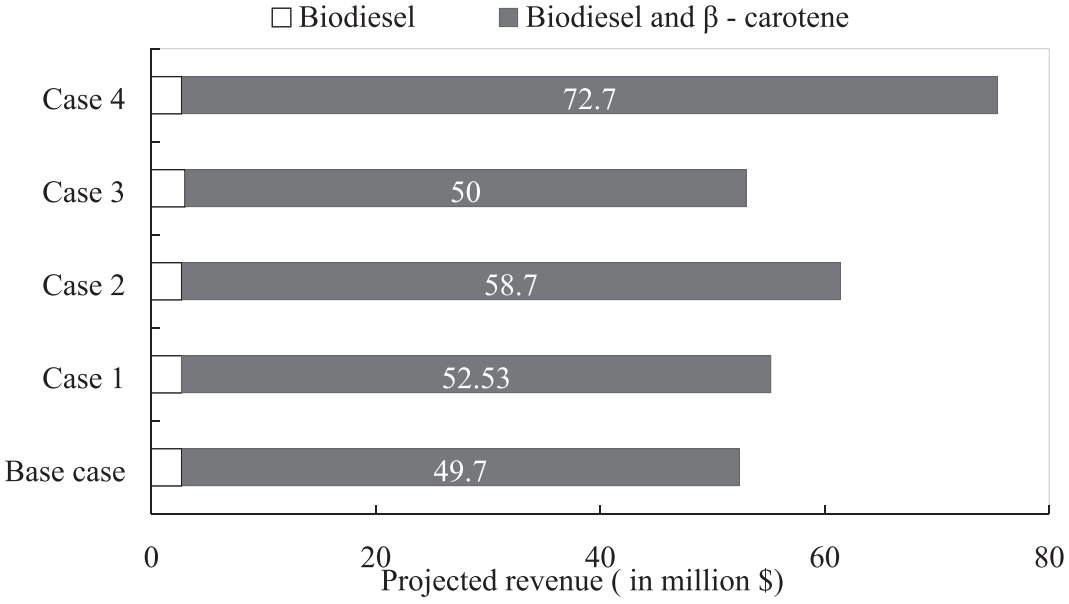


FIGURE 6 Projected revenues for all assumed cases

out at Masdar City, Khalifa University. Other capital cost components include the costs of laboratory and office building, supplies, and equipment. The operating cost without the electricity component was estimated to be US $2.73 million.

The upstream material cost accounted for 92% and transport, and labor cost accounted for the rest (Figure 7B). The total electricity cost was estimated to be US$33.5 million. The major portion of this amount was due to the electricity required for harvesting and dewatering (Figure 7C). Electricity cost accounted for 78% of the total production cost followed by capital cost, and then by the other operating costs. The contributions of capital, upstream, electricity, and transport and labor costs to the overall production cost are shown in Figure 7D. The total cost of production in the first year was estimated to be US $10.43/L, which was slightly higher than that reported for another microalgae production process, which was US

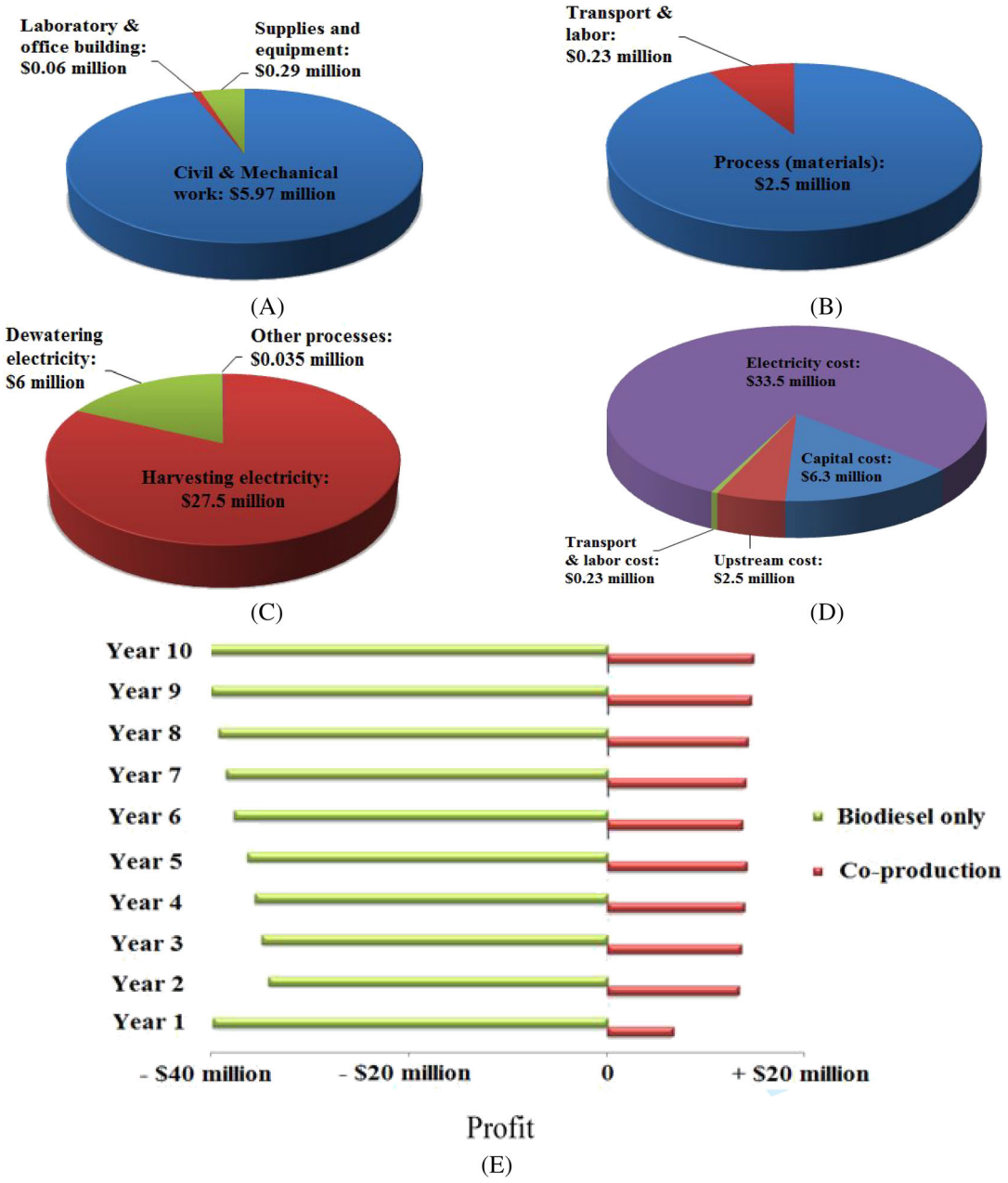


FIGURE 7 Estimates of production cost components, including A, capital cost components; B, operating cost components without electricity; C, cost of electricity consumed by unit processes; and D, an overview of the contributions of different sectors per functional unit of biodiesel; E, annual discounted profits of systems producing biodiesel only and biodiesel with β-carotene [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 NPVs of the production cost and revenue over the lifetime of biodiesel and β-carotene coproduction system

	Coproduction	Biodiesel only
NPV cost	US$ 372.5 million	US$ 372 million
NPV revenue	US$ 493.2 million	US$ 27 million

Abbreviation: NPV, net present value.

$8.47/L.[97] The discrepancy was due to the additional cost of β-carotene production, which has not been considered in the previous study.

Electricity cost accounted for the largest portion of the total cost, followed by capital cost and, then, upstream cost. Lower production costs would be required after the first year because the construction and equipment costs would no longer be included. The costs for the subsequent years (after the first year) were discounted with the current discount rate of 2% in the UAE. The NPV of the cost of production over the process lifetime of 10 years was computed as US$372.5 million, as given in Table 4.

The revenues from biodiesel and β-carotene production for the first year were estimated to be US$2.7 million/y and US$47 million/y, respectively. The overall revenues from the coproduction for the subsequent years were discounted for inflation. The NPV of the total revenue over the process lifetime was estimated to be US$493.2 million. This shows that the system was profitable, as the revenue exceeded the cost by 32%. For the second scenario, that is, the scenario whereby only the production of biodiesel was considered, the NPV cost and revenue were estimated to be US$372 million and US$27 million, respectively, as given in Table 4. The revenue obtainable from biodiesel alone would be insufficient to counterweigh the cost of the production. Figure 7E shows the annual profits, estimated as the difference between the discounted revenue and cost for both single-product and coproduct systems for each year. Losses would be accrued annually in the single-product system. The NPV of the accruable loss over the system lifetime was estimated to be US$345 million. Hence, a clear outcome of this study is that there is no economic justification for the exclusive production of biodiesel. However, for the coproduction system, the NPV of the total profit was US$120.7 million. As seen in Figure 7, due to the high-value of β-carotene, integrating the production of this natural antioxidant with biodiesel from *D. salina* can significantly improve the process economics by increasing the revenues from both products.

PBP of the coproduction process was estimated from Equation (6) to be 8 years. This is an economic advantage, when the lifetime of real operating plants is taking into consideration. The lifetime of real operating algae plants is up to 30 years.

The global market size of β-carotene in 2015 was US$425 million.[75] The global market size in 2018 was estimated to be US$464.4 million, with a compound annual growth rate over 3%. The economic value of β-carotene considered for production in this study is estimated to be only US$47 million/y. The current global market size is very much higher than the market size considered in this study. As the human body cannot synthesize β-carotene, the global demand of β-carotene as an external source of vitamin keeps increasing.[98] Foods fortified with β-carotene often contribute up to 30% of the daily supply of vitamin A.[99] Natural β-carotene, obtained from microalgal sources, is more commercially attractive than its chemically synthesized forms. The natural ones offer higher antioxidant activity, extended physiological effects, and higher bioavailability rates.[100] Therefore, it can be inferred that β-carotene production is economically profitable, but the key problem with the sole production of β-carotene is its relatively higher energy demand, which leads to more detrimental environmental effects, compared with biodiesel production.

It is important to note that an energetic analysis is not all-inclusive in this production system, since the valuable coproduct, β-carotene is not an energy source. The feasibility of the process can only be effectively addressed by looking at both environmental concerns and economic practicability. Therefore, (a) cultivating microalgae for only biodiesel production is not economically attractive; (b) β-carotene production is less environmentally friendly than biodiesel production; (c) it is preferable to combine biodiesel and β-carotene production in terms of both economic profitability and environmental impacts. The other possible routes to increasing the overall efficiency of algae-to-energy systems is that the residual biomass left after the lipid extraction could be used to generate biogas through anaerobic digestion. And in turn, the left over biomass could be employed as a fertilizer, since it contains valuable nutrients. The algal cultivation system could be set up to utilize the CO_2 coming in from industrial flue gases to combine the positive effect of reducing greenhouse gas emissions. At present, several technologies for biofuels are in the stage of conception or nascent research. Some have already been implemented worldwide in different domains and have been successful. With thorough research and technological advancements, harvesting, dewatering, and oil extraction processes can become more efficient and economical, and therefore the full potential of biodiesel from microalgae can be attained. In addition, the commercialization and feasibility of the process can be enhanced by advancement in genetic

engineering research to manipulate biochemical pathways for enhanced biomass and lipid productivities and stimulate accumulation and secretion of required valuable derivatives, facilitating its easy extraction.

4 | CONCLUSIONS

Commercial cultivation of marine microalgae is favored in countries geographically endowed with saline coastal nonarable lands and harsh desert weather due to the advantageous they hold. Nonetheless, the production of biodiesel alone from *D. salina* is not favorable economically. The energy gained from biodiesel was only 27% of the energy invested in the biodiesel production process. In this study, it was shown that, biodiesel production from *D. salina* would become profitable, if biodiesel was coproduced with β-carotene. The revenue would exceed the cost by 32%, according to the economic assessment carried. However, coproduction would require an additional energy consumption for β-carotene extraction, leading to more environmental impacts, which would not alter the environmental friendliness of the biodiesel production process. From the LCA, global warming was the major impact of the coproduction process but the cumulative GWP value of 16.8 mPt was well below the recommended range, indicating that the coproduction process was environmentally friendly. In addition, β-carotene production will not significantly influence the energy consumption of the coproduction process.

Sensitivity analysis indicated that the increase in β-carotene accumulation and market price have a clear positive effect on the revenue and profitability. Other scenarios such as increase in dewatering efficiency and biodiesel conversion efficiency during transesterification would have lower influence on the projected revenue, compared with β-carotene accumulation and market price.

ACKNOWLEDGMENT

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Mutasim Nour, Sulaiman Al-Zuhair, Hanifa Taher, and Adewale Giwa were involved in designing this research study. Fariha Khanum and Adewale Giwa performed the theoretical assessments illustrated in the manuscript. All the authors were involved in writing the manuscript.

ETHICS STATEMENT

No conflicts, informed consent, human or animal rights applicable.

ORCID

Adewale Giwa https://orcid.org/0000-0002-3509-7477
Mutasim Nour https://orcid.org/0000-0002-7285-7914
Sulaiman Al-Zuhair https://orcid.org/0000-0001-5042-9495
Hanifa Taher https://orcid.org/0000-0002-2421-2724

REFERENCES

1. Giwa A, Dindi A. An investigation of the feasibility of proposed solutions for water sustainability and security in water-stressed environment. *J Clean Prod*. 2017;165:721-733. https://doi.org/10.1016/j.jclepro.2017.07.120.
2. Gulf News Web Report. 7 billion barrels of oil found in new Abu Dhabi reserves, UAE in sixth position in global oil reserves. Gulf News. https://bit.ly/34PWM80. 2019.
3. Delrue F, Li-Beisson Y, Setier PA, et al. Comparison of various microalgae liquid biofuel production pathways based on energetic, economic and environmental criteria. *Bioresour Technol*. 2013;136:205-212.
4. NS Energy. EIA report. Top five countries for biofuel production across the globe. https://www.nsenergybusiness.com/features/top-biofuel-production-countries/. 2018.
5. Scott AS, Davey MP, Dennis JS, et al. Biodiesel from algae: challenges and prospects. *Curr Opin Biotechnol*. 2010;21:277-286.
6. Khoo HH, Sharratt PN, Das P, Balasubramanian RK, Naraharisetti PK, Shaik S. Life cycle energy and CO_2 analysis of microalgae-to-biodiesel: preliminary results and comparisons. *Bioresour Technol*. 2011;102:5800-5807.
7. Lee KT, Gui MM, Bhatia S. Feasibility of edible oil vs. non-edible oil vs waste edible oil as biodiesel feedstock. *Energy*. 2008;33:1646-1653.
8. Kim Y-S, Um B-H. Review: a chance for Korea to advance algal-biodiesel technology. *J Indus Eng Chem*. 2009;15:1-7.
9. Shahid EM, Jamal Y. Production of biodiesel: a technical review. *Renew Sustain Energy Rev*. 2011;15:4732-4745.
10. Wittayakun J, Supamathanon N, Prayoonpokarach S. Properties of Jatropha seed oil from northeastern Thailand and its transesterification catalyzed by potassium supported on NaY zeolite. *J Indus Eng Chem*. 2011;17:182-185.
11. Dhar A, Kevin R, Agarwal AK. Production of biodiesel from high-FFA neem oil and its performance, emission and combustion characterization in a single cylinder DICI engine. *Fuel Process Technol*. 2012;97:118-129.
12. Yin P, Chen L, Wang Z, Qu R, Liu X, Ren S. Production of biodiesel by esterification of oleic acid with ethanol over organophosphonic acid-functionalized silica. *Bioresour Technol*. 2012;110:258-263.
13. Mushtaq M, Tan IM, Ismail L, Lee SYC, Nadeem M, Sagir M. Oleate ester-derived nonionic surfactants: synthesis and cloud point behavior studies. *J Dispers Sci Technol*. 2013;35:322-328.
14. Mushtaq A, Khan M.A, Zafar M, Sultana S, 2011 Biodiesel from non-edible seeds: a renewable source of bioenergy. Economic effects of biofuel production.

15. Shahzad K, Nizami AS, Sagir M, et al. Biodiesel production potential from fat fraction of municipal waste in Makkah. *PLoS One*. 2017;12:e0171297.
16. Giwa A, Adeyemi I, Dindi A, et al. Techno-economic assessment of the sustainability of an integrated biorefinery from microalgae and Jatropha: a review and case study. *Renew Sustain Energy Rev*. 2018;88:239-257.
17. Taher H, Al-Zuhair S, Al-Marzouqi AH, Haik Y, Farid M. Effective extraction of microalgae lipids from wet biomass for biodiesel production. *Biomass Bioenergy*. 2014;66:159-167.
18. Quereshi S, Ahmad E, Pant KK, Dutta S. Recent advances in production of biofuel and commodity chemicals from algal biomass. *Algal Biofuels: Recent Advances and Future Prospects*. Springer, Cham; 2017:393-419. https://doi.org/10.1007/978-3-319-51010-1_19.
19. Raheem A, Prinsen P, Vuppaladadiyam AK, Zhao M, Luque R. A review on sustainable microalgae based biofuel and bioenergy production: recent developments. *J Clean Prod*. 2018;181:42-59. https://doi.org/10.1016/j.jclepro.2018.01.125.
20. González-González LM, Correa DF, Ryan S, Jensen PD, Pratt S, Schenk PM. Integrated biodiesel and biogas production from microalgae: towards a sustainable closed loop through nutrient recycling. *Renew Sustain Energy Rev*. 2018;82:1137-1148. https://doi.org/10.1016/j.rser.2017.09.091.
21. Ishika T, Moheimani NR, Bahri PA. Sustainable saline microalgae co-cultivation for biofuel production: a critical review. *Renew Sustain Energy Rev*. 2017;78:356-368. https://doi.org/10.1016/j.rser.2017.04.110.
22. Taher H, Al-Zuhair S, Al-Marzouqi AH, Haik Y, Farid M. Enzymatic biodiesel production of microalgae lipids under supercritical carbon dioxide: process optimization and integration. *Biochem Eng J*. 2014;90:103-113. https://doi.org/10.1016/j.bej.2014.05.019.
23. Taher H, Al-Zuhair S, Al-Marzouqi A, Haik Y, Farid M. Growth of microalgae using CO2 enriched air for biodiesel production in supercritical CO2. *Renew Energy*. 2015;82:61-70. https://doi.org/10.1016/j.renene.2014.08.013.
24. Giwa A. Comparative cradle-to-grave life cycle assessment of biogas production from marine algae and cattle manure biorefineries. *Bioresour Technol*. 2017;244:1470-1479. https://doi.org/10.1016/j.biortech.2017.05.143.
25. Mata TM, Martins AA, Caetano NS. Microalgae for biodiesel production and other applications–a review. *Renew Sustain Energy Rev*. 2010;14:217-232.
26. Chisti Y. Biodiesel from microalgae. *Biotechnol Adv*. 2007;25(3):294-306.
27. Jose S, Archanaa S. Environmental and economic sustainability of algal lipid extractions: an essential approach for the commercialization of algal biofuels. *Algal Biofuels: Recent Advances and Future Prospects*. Springer, Cham; 2017:281-313. https://doi.org/10.1007/978-3-319-51010-1_14.
28. Shahnazari M, Bahri PA, Parlevliet D, Minakshi M, Moheimani NR. Sustainable conversion of light to algal biomass and electricity: a net energy return analysis. *Energy*. 2017;131:218-229. https://doi.org/10.1016/j.energy.2017.04.162.
29. Fon Sing S, Isdepsky A, Borowitzka MA, Moheimani NR. Production of biofuels from microalgae. *Mitig Adapt Strat Glob Chang*. 2013;18:47-72. https://doi.org/10.1007/s11027-011-9294-x.
30. Yu HT, Tian FL, Wang HY, Hu YH, Sheng WL. An application of *Dunaliella salina* algae: biodiesel. *Adv Mat Res*. 2014;953:281-283. https://doi.org/10.4028/www.scientific.net/AMR.953-954.281.
31. Bonnefond H, Moelants N, Talec A, Mayzaud P, Bernard O, Sciandra A. Coupling and uncoupling of triglyceride and beta-carotene production by *Dunaliella salina* under nitrogen limitation and starvation. *Biotechnol Biofuels*. 2017;10(1):25. https://doi.org/10.1186/s13068-017-0713-4.
32. Rajesh K, Rohit MV, Venkata Mohan S. Microalgae-based carotenoids production. *Algal Green Chemistry: Recent Progress in Biotechnology*. Elsevier, Amsterdam; 2017:139-147. https://doi.org/10.1016/B978-0-444-63784-0.00007-2.
33. Borowitzka MA. The 'stress' concept in microalgal biology—homeostasis, acclimation and adaptation. *J Appl Phycol*. 2018;30:2815-2825.
34. Borowitzka MA, Vonshak A. Scaling up microalgal cultures to commercial scale. *Eur J Phycol*. 2017;52:407-418. https://doi.org/10.1080/09670262.2017.1365177.
35. Flores Hernandez FY, Khandual S, Ramírez López IG. Cytotoxic effect of *Spirulina platensis* extracts on human acute leukemia Kasumi-1 and chronic myelogenous leukemia K-562 cell lines. *Asian Pac J Trop Biomed*. 2017;7(1):14-19. https://doi.org/10.1016/j.apjtb.2016.10.011.
36. Gu L, Su Y, Zhang M, et al. Protection of β-carotene from chemical degradation in emulsion-based delivery systems using antioxidant interfacial complexes: catechin-egg white protein conjugates. *Food Res Int*. 2017;96:84-93. https://doi.org/10.1016/j.foodres.2017.03.015.
37. Spolaore P, Joannis-Cassan C, Duran E, Isambert A. Commercial applications of microalgae. *J Biosci Bioeng*. 2006;101(2):87-96. https://doi.org/10.1263/jbb.101.87.
38. Monte J, Sá M, Galinha CF, et al. Harvesting of *Dunaliella salina* by membrane filtration at pilot scale. *Sep Purif Technol*. 2018;190:252-260. https://doi.org/10.1016/j.seppur.2017.08.019.
39. Beal CM, Gerber LN, Sills DL, et al. Algal biofuel production for fuels and feed in a 100-ha facility: a comprehensive techno-economic analysis and life cycle assessment. *Algal Res*. 2015;10:266-279. https://doi.org/10.1016/j.algal.2015.04.017.
40. Gnansounou E, Kenthorai Raman J. Life cycle assessment of algae biodiesel and its co-products. *Appl Energy*. 2016;161:300-308. https://doi.org/10.1016/j.apenergy.2015.10.04341.
41. Groen EA, Bokkers EAM, Heijungs R, de Boer IJM. Methods for global sensitivity analysis in life cycle assessment. *Int J Life Cycle Assess*. 2017;22:1125-1137. https://doi.org/10.1007/s11367-016-1217-3.
42. Ekvall T, Azapagic A, Finnveden G, Rydberg T, Weidema BP, Zamagni A. Attributional and consequential LCA in the ILCD handbook. *Int J Life Cycle Assess*. 2016;21(3):293-296. https://doi.org/10.1007/s11367-015-1026-0.
43. Huang G, Chen F, Wei D, Zhang X, Chen G. Biodiesel production by microalgal biotechnology. *Appl Energy*. 2010;87:38-46.
44. Ben-Amotz A, Gressel J, Avron M. Massive accumulation of phytoene induced by norflurazon in *Dunaliella bardawil* prevents recovery from photoinhibition. *J Phycol*. 1987;23:176-181.
45. Oren A. A hundred years of *Dunaliella* research: 1905–2005. *Saline Systems*. 2005;1:2.

46. Dolapsakis NP, Tafas T, Abatzopoulos TJ, Ziller S, Economou-Amilli A. Abundance and growth response of microalgae at Megalon Embolon solar saltworks in northern Greece: an aquaculture prospect. *J Appl Phycol*. 2005;17:39-49. https://doi.org/10.1007/s10811-005-5553-0.
47. Borowitzka MA, Siva CJ. The taxonomy of the genus *Dunaliella* (Chlorophyta, Dunaliellales) with emphasis on the marine and halophilic species. *J Appl Phycol*. 2007;19:567-590.
48. Jahnke LS, White AL. Long-term hyposaline and hypersaline stresses produce distinct antioxidant responses in the marine alga *Dunaliella tertiolecta*. *J Plant Physiol*. 2003;160:1193-1202.
49. Pruvost J. Cultivation of algae in photobioreactors for biodiesel production. *Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels*. Elsevier; 2019:629-659. https://doi.org/10.1016/B978-0-12-816856-1.00026-9.
50. Liang Y, Kashdan T, Sterner C, et al. Algal biorefineries. *Industrial Biorefineries & White Biotechnology*. Elsevier; 2015: 35-90. https://doi.org/10.1016/B978-0-444-63453-5.00002-1.
51. Hejase HAN, Assi AH. Global and diffuse solar radiation in The United Arab Emirates. *Int J Environ Sci Dev*. 2013;4: 470-474. https://doi.org/10.7763/IJESD.2013.V4.396.
52. Guieysse B, Béchet Q, Shilton A. Variability and uncertainty in water demand water footprint assessments of fresh algae cultivation based on case studies from five climatic regions. *Bioresour Technol*. 2013;128:317-323. https://doi.org/10.1016/j.biortech.2012.10.096.
53. Assi A, Jama M. Estimating global solar radiation on horizontal from sunshine hours in Abu Dhabi–UAE. Paper presented at: Advanced in Energy Planning, Environmental Education, and Renewable Energy Sources, 4th WSEAS International Conference on Renewable Energy ; 2010:101–108.
54. Tafreshi AH, Shariati M. Pilot culture of three strains of *Dunaliella salina* for β-carotene production in open ponds in the central region of Iran. *World J Microbiol Biotechnol*. 2006;22(9):1003-1006. https://doi.org/10.1007/s11274-006-9145-1.
55. Vasudevan V, Stratton RW, Pearlson MN, et al. Environmental performance of algal biofuel technology options. *Environ Sci Technol*. 2012;46(4):2451-2459. https://doi.org/10.1021/es2026399.
56. Sturm BSM, Lamer SL. An energy evaluation of coupling nutrient removal from wastewater with algal biomass production. *Appl Energy*. 2011;88(10):3499-3506. https://doi.org/10.1016/j.apenergy.2010.12.056.
57. Uduman N, Qi Y, Danquah MK, Forde GM, Hoadley A. Dewatering of microalgal cultures: a major bottleneck to algae-based fuels. *J Renew Sustain Energy*. 2010;2(1): 012701-1-012701-15. https://doi.org/10.1063/1.3294480.
58. APV Limited. *APV Spray Dryer Technical Handbook*. Rosemount: APV; 2019.
59. Williams PJLB, Laurens LML. Microalgae as biodiesel & biomass feedstocks: review & analysis of the biochemistry, energetics & economics. *Energ Environ Sci*. 2010;3(5):554. https://doi.org/10.1039/b924978h.
60. Cao H, Zhang Z, Wu X, Miao X. Direct biodiesel production from wet microalgae biomass of *Chlorella pyrenoidosa* through in situ transesterification. *Biomed Res Int*. 2013;2013: 1-6. https://doi.org/10.1155/2013/930686.
61. Veillette M, Chamoumi M, Nikiema J, Faucheux N, Heitz M. Production of biodiesel from microalgae. *Adv Chem Eng*. 2012;10:245-260.
62. Kyriakopoulou K, Papadaki S, Krokida M. Life cycle analysis of β-carotene extraction techniques. *J Food Eng*. 2015;167:51-58. https://doi.org/10.1016/j.jfoodeng.2015.03.008.
63. Emeish S. Production of natural β -carotene from Dunaliella living in the dead sea. *Jordan J Earth Environ Sci*. 2012;4(2): 23-27.
64. Masojídek J, Torzillo G. Mass cultivation of freshwater microalgae. *Encyclopedia of Ecology*. Elsevier; 2008:2226-2235. https://doi.org/10.1016/B978-008045405-4.00830-2.
65. Kleinegris DMM, Janssen M, Brandenburg WA, Wijffels RH. The selectivity of milking of *Dunaliella salina*. *Marine Biotechnol*. 2010;12:14-23. https://doi.org/10.1007/s10126-009-9195-0.
66. Cuddon Freeze Dry. FD300 Freeze Dryer. https://www.cuddonfreezedry.com/products/fd300-freeze-dryer/. 2018.
67. Finkbeiner M. From the 40s to the 70s—the future of LCA in the ISO 14000 family. *Int J Life Cycle Assess*. 2013;18(1):1-4. https://doi.org/10.1007/s11367-012-0492-x.
68. Sala S, Crenna E, Secchi M, Pant R. Global normalisation factors for the environmental footprint and life cycle assessment. Publications Office of the European Union: Luxembourg; 2017.
69. Stranddorf HK, Hoffmann L, Schmidt A. Impact categories, normalisation and weighting in LCA. Environmental News No. 78, Danish Ministry of the Environment; 2005.
70. Kumar K, Ghosh S, Angelidaki I, et al. Recent developments on biofuels production from microalgae and macroalgae. *Renew Sustain Energy Rev*. 2016;65:235-249. https://doi.org/10.1016/j.rser.2016.06.055.
71. Raheem A, Wan Azlina WAKG, Taufiq Yap YH, Danquah MK, Harun R. Thermochemical conversion of microalgal biomass for biofuel production. *Renew Sustain Energy Rev*. 2015;49:990-999. https://doi.org/10.1016/j.rser.2015.04.186.
72. Zenouzi A, Ghobadian B, Hejazi MA, Rahnemoon P. Harvesting of microalgae *Dunaliella salina* using electroflocculation. *J Agric Sci Technol*. 2013;15(5):879-888.
73. Ellis, Byron. (2007). Life cycle cost. The Jethro Project.
74. Sainio S, Aspects E, Goodfellow H, Tähti E. *Industrial Ventilation Design Guidebook*. Academic Press; 2001:1373-1379. https://doi.org/10.1016/B978-0-12-289676-7.X5000-0.
75. Xylem Flygt. Life cycle costs for wastewater pumping systems. White Paper. June 2015
76. Global Market Insights. Beta carotene market size, industry analysis report, regional outlook. Food, Nutrition, and Animal Feed. https://www.gminsights.com/industry-analysis/beta-carotene-market. 2018.
77. Trading Economics. United Arab Emirates interest rate. http://bit.ly/2jeDXEr. Accessed January 10, 2017.
78. Ben-Amotz A, Avron M. On the factors which determine massive β-carotene accumulation in the halotolerant alga *Dunaliella bardawil*. *Plant Physiol*. 1983;72:593-597.
79. Yen HW, Hu IC, Chen CY, Ho SH, Lee DJ, Chang JS. Microalgae based bio-refinery-from biofuels to natural products. *Bioresour Technol*. 2013;135:166-174.
80. Pirwitz K, Rihko-Struckmann L, Sundmacher K. Comparison of flocculation methods for harvesting Dunaliella. *Bioresour*

Technol. 2015;196:145-152. https://doi.org/10.1016/j.biortech.2015.07.032.

81. Grima ME, Belarbi EH, Fernandez FGA, Medina AR, Chisti Y. Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnol Adv*. 2003;20(7–8):491-515.
82. Ugwu CU, Aoyagi H, Uchiyama H. Photobioreactors for mass cultivation of algae. *Bioresour Technol*. 2008;99(10):4021-4028.
83. Prieto A, Canavate JP, García-González M. Assessment of carotenoid production by *Dunaliella salina* in different culture systems and operation regimes. *J Biotechnol*. 2011;151:180-185.
84. Tran D-T, Yeh K-L, Chen C-L, Chang J-S. Enzymatic transesterification of microalgal oil from *Chlorella vulgaris* ESP-31 for biodiesel synthesis using immobilized Burkholderia lipase. *Bioresour Technol*. 2012;108:119-127.
85. Tran D-T, Chen C-L, Chang J-S. Effect of solvents and oil content on direct transesterification of wet oil-bearing microalgal biomass of *Chlorella vulgaris* ESP-31 for biodiesel synthesis using immobilized lipase as the biocatalyst. *Bioresour Technol*. 2013;135:213-221.
86. Soeder CJ. Massive cultivation of microalgae: results and prospects. *Hydrobiology*. 1980;72:197-209.
87. Show KY, Lee DJ, Tay JH, Lee TM, Chang JS. Microalgal drying and cell disruption–recent advances. *Bioresour Technol*. 2015;184:258-266.
88. Mushtaq M, Tan IM, Nadeem M, Devi C, Lee SYC, Sagir M. A convenient route for the alkoxylation of biodiesel and its influence on cold flow properties. *Int J Green Energy*. 2014;11(3):267-279.
89. Devi S, Santhanam AP, Rekha V, et al. Culture and biofuel producing efficacy of marine microalgae *Dunaliella salina* and *Nannochloropsis* sp. *J Algal Biomass Utln*. 2012;3:38-44.
90. Itoiz EZ, Fuentes-Gru¨Newald. C, Gasol CM, et al. Energy balance and environmental impact analysis of marine microalgal biomass production for biodiesel generation in a photobioreactor pilot plant. *Biomass Bioenergy*. 2012;39:324-335.
91. Dassey AJ, Hall SG, Theegala CS. An analysis of energy consumption for algal biodiesel production: comparing the literature with current estimates. *Algal Res*. 2014;4(1):89-95. https://doi.org/10.1016/j.algal.2013.12.006.
92. Monari C, Righi S, Olsen SI. Greenhouse gas emissions and energy balance of biodiesel production from microalgae cultivated in photobioreactors in Denmark: a life-cycle modeling. *J Clean Prod*. 2016;112:4084-4092. https://doi.org/10.1016/j.jclepro.2015.08.112.
93. Handler RM, Shonnard DR, Kalnes TN, Lupton FS. Life cycle assessment of algal biofuels: influence of feedstock cultivation systems and conversion platforms. *Algal Res*. 2014;4:105-115. https://doi.org/10.1016/j.algal.2013.12.001.
94. Bennion EP, Ginosar DM, Moses J, Agblevor F, Quinn JC. Lifecycle assessment of microalgae to biofuel: comparison of thermochemical processing pathways. *Appl Energy*. 2015;154:1062-1071. https://doi.org/10.1016/j.apenergy.2014.12.009.
95. Tiwari S, Agrawal M. Tropospheric ozone budget: formation, depletion and climate change. *Tropospheric Ozone and its Impacts on Crop Plants*. Cham: Springer International Publishing; 2018:31-64. https://doi.org/10.1007/978-3-319-71873-6_2.
96. Verstraeten WW, Neu JL, Williams JE, Bowman KW, Worden JR, Boersma KF. Rapid increases in tropospheric ozone production and export from China. *Nat Geosci*. 2015;8(9):690-695. https://doi.org/10.1038/ngeo2493.
97. Rosenberg JN, Betenbaugh MJ, Oyler GA. Paving the road to algal biofuels with the development of a genetic infrastructure. *Biofuel's Engineering Process Technology*. London: InTech; 2011. https://doi.org/10.5772/17173.
98. Grand View Research. Beta-Carotene market size, share, global industry growth report, 2024. Food Additives & Nutricosmetics. https://www.grandviewresearch.com/industry-analysis/beta-carotene-market. 2018.
99. Grune T, Lietz G, Palou A, et al. β-Carotene is an important vitamin a source for humans. *J Nutr*. 2010;140(12):2268-2285. https://doi.org/10.3945/jn.109.119024.
100. Ben Amortz A, Levy Y. Bioavailability of natural isomers mixture compared with synthetic all-trans b-carotene in human serum. *Am J Clin Nutr*. 1996;63:729-734.
101. Liu Z, Liu C, Hou Y, et al. Isolation and characterization of a marine microalga for biofuel production with astaxanthin as a co-product. *Energies*. 2013;6(6):2759-2772. https://doi.org/10.3390/en6062759.
102. Sun A, Davis R, Starbuck M, Ben-Amotz A, Pate R, Pienkos PT. Comparative cost analysis of algal oil production for biofuels. *Energy*. 2011;36(8):5169-5179. https://doi.org/10.1016/j.energy.2011.06.020.
103. Urreta I, Ikaran Z, Janices I, et al. Revalorization of *Neochloris oleoabundans* biomass as source of biodiesel by concurrent production of lipids and carotenoids. *Algal Res*. 2014;5(1):16-22. https://doi.org/10.1016/j.algal.2014.05.001.
104. Singh D, Puri M, Wilkens S, Mathur AS, Tuli DK, Barrow CJ. Characterization of a new zeaxanthin producing strain of *Chlorella saccharophila* isolated from New Zealand marine waters. *Bioresour Technol*. 2013;143:308-314. https://doi.org/10.1016/j.biortech.2013.06.006.
105. Chagas AL, Rios AO, Jarenkow A, Marcílio NR, Ayub MAZ, Rech R. Production of carotenoids and lipids by *Dunaliella tertiolecta* using CO2 from beer fermentation. *Process Biochem*. 2015;50(6):981-988. https://doi.org/10.1016/j.procbio.2015.03.012.
106. Lee N, Ko SR, Ahn CY, Oh HM. Optimized co-production of lipids and carotenoids from Ettlia sp. by regulating stress conditions. *Bioresour Technol*. 2018;258:234-239. https://doi.org/10.1016/j.biortech.2018.03.006.

How to cite this article: Khanum F, Giwa A, Nour M, Al-Zuhair S, Taher H. Improving the economic feasibility of biodiesel production from microalgal biomass via high-value products coproduction. *Int J Energy Res*. 2020;44:11453–11472. https://doi.org/10.1002/er.5768