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# Bioeconomic Assessment of Microalgal Production

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Didem Özçimen, Benan İnan, Anıl Tevfik Koçer and  
Meyrem Vehapi

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## Abstract

Today, microalgae play an important role for the worldwide biofuel demand, together with the production of high value-added products used in pharmaceutical, nutraceutical and cosmetic industries. In 2014, the European Union adopted a strategy for developing the bioeconomy, by utilizing microalgae which represent an emerging biological resource of great importance for its potential applications in different fields. Huge potential of tiny microalgae could support a microalgae-based biorefinery and microalgae-based bioeconomy opening up vast opportunities in the global algae business. Nevertheless, in spite of having been studied for over 50 years now, there are still only just a few corporations that are cultivating algae on a large or commercial scale due to operational and capital cost. Techno-economic modeling is a powerful tool for guiding research priorities and assessing the economics, environmental impact and sustainability of microalgal productions. In this chapter, microalgal productions are assessed within bioeconomical aspects and case-studies on microalgal biorefinery are discussed.

**Keywords:** microalgae, bioeconomy, microalgal biorefinery, bioproducts, biofuel, techno-economic analysis

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## 1. Introduction

Increase of the human population has necessitated industrialization and manufacture since the industrial revolution. Experts estimate that the world population will reach about 9.5 billion by 2050 [1]. As a result, demand for natural resources such as food, feed, clean water, energy, housing and materials for clothing as well as demand for education and health services are increasing continuously. However, depletion of the natural resources, CO<sub>2</sub> emissions, and climate changes etc., decrease the quality of human life [2]. To solve

this problem, associations and governments are trying to put forward new approaches within the framework of sustainable development. The concept of sustainable development, which started to gain importance with the beginning of the twenty-first century, has accompanied the search for an appropriate economic model. At this point, the terms biotechnology and bioeconomics have gained more meaning and promise great hopes for the future [3]. The term of bioeconomic refers to an economic system in which biological resources are used instead of fossil resources in production processes. Therefore in bioeconomic strategies, economic growth is linked to environmental sustainability [1]. There are basically three factors in the emergence of bioeconomic strategies: limitation of fossil feedstocks, the negative effects of human activities on the environment and the innovative progresses in science and technology [4]. In this respect, bio-economic is central to all economic sectors for a higher standard of living. A bioeconomy involves three elements: biotechnological knowledge, renewable biomass, and integration across applications. The first element, biotechnological knowledge, is the principal of the bioeconomic model. Biotechnology offers technological solutions to health, natural resource and ecosystem sustainability issues and allows for increased productivity in different industries with new products and processes such as biopharmaceuticals, recombinant vaccines and industrial enzymes. R&D studies and innovation are essential for the development of biotechnology [1]. The second element is the use of renewable biomass. Renewable biomass covers a wide range from primary sources such as energy plants, trees and grasses; to agricultural and industrial wastes [5]. The third element is integration between knowledge and applications, based on generic knowledge and value-added chains that cross applications [4]. Due to the fact that most renewable biomass resources are also used in the food sector, a very important ethical question has arisen: Is it right to use food materials in different areas while many countries on earth have starvation problems? This problem is one of the most controversial issues today [6]. Researchers suggest the use of waste biomass for these discussions. However, there are some limitations on the use of wastes. For example, the production of chemicals for use in the pharmaceutical industry from wastes is not appropriate. Therefore, microalgae, which can be used in many different areas, are thought to be able to solve this problem [7]. Especially, developed biorefinery strategies and bioprocesses about microalgae are promising for the future in order to achieve economic sustainability. In biorefinery systems where microalgae are used as raw material, important biofuels such as biodiesel, bioethanol and biogas are produced and valuable chemical substances used in fields such as pharmaceutical, nutraceutical and cosmetic industries are produced. It is also possible to use microalgae as food and animal feed because of the high protein content [8]. Nevertheless, in spite of having been studied for over 50 years now, there are still only just a few corporations that are cultivating algae on a large or commercial scale. Because, algal investment is not economically feasible due to operational and capital cost. The rate of return is not short as it is expected. The operation cost is affecting the total cost significantly. The main part, which makes the process expensive due to operation and capital costs, are algae growth, harvesting, and dewatering. Although many innovations are performed in production of algal biomass day by day, in order to carry out sustainable and economical productions, algal biorefinery is the best choice for reducing production cost and obtaining various products with maximum efficiency [9]. In this chapter, definition of bioeconomy and its classification are described, techno-economic analysis of microalgal

productions are presented in detail and cost-effective approaches are evaluated case by case in basis. And all results were evaluated from a bioeconomic point of view.

## 2. Definition of bioeconomy

Although the term of bioeconomy has gathered much attention in recent years, it has existed since the development of the life sciences and biotechnology [10]. Usage of the term “bioeconomy” has become widespread due to the relationship between economy and biology in the world [11]. In order to reduce the effects of environmental problems and global warming, it is important to utilize bio-based products instead of fossil-based product [12]. A biomass based economy instead of fossil based product represents a significant shift in socio-economic, agricultural, energy and technical systems. The concept of a bioeconomy which is also called the “bio-based economy” in some reports, can be defined as an economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources [13, 14]. The bioeconomy comprises the parts of using renewable biological resources from land and sea such as crops, forests, fish, animals and micro-organisms to produce food, materials and energy and also their use in a wide range of sciences such as, life sciences, agronomy, ecology, food, biotechnology, nanotechnology, and engineering [12, 15]. The bioeconomy entails the use of biotechnology on a large scale [16]. Biotechnology makes use of biological systems and processes to manufacture various products: such as industry (white biotechnology), medicine (red biotechnology), agriculture (green biotechnology), aquaculture (blue biotechnology), and pollution removal and bioremediation (gray biotechnology) [16]. Establishing an bioeconomy in Europe have a great potential, because economic growth and jobs in rural, coastal and industrial areas can be carried out, fossil fuel dependence can be reduced and the economic and environmental sustainability of primary production can be developed [17]. Biotechnology has various industrial applications including the manufacture of chemicals and biopharmaceuticals, bio-polymers and bio plastics, food, feed and biofuels [16]. White biotechnology or industrial biotechnology uses enzymes and micro-organisms to make bio-based products, including chemicals, food and feed, bioenergy, and textiles [10, 18–22]. Gray biotechnology is comprised from technological solutions created to protect the environment, like in the case of oil spills and purifying sewage water [23]. Green biotechnology is practiced to agricultural processes such as developing genetically modified crops or improve plant breeding techniques by using life science knowledge [24]. Blue biotechnology is a term that has been used to describe the marine and aquatic applications of biotechnology [19]. Red biotechnology relates to the health sector and production of pharmaceuticals [10, 25, 26].

## 3. Bioeconomy concept in Europe and the World

### 3.1. Bioeconomy in Europe

Europe has set a course for a resource-efficient and sustainable economy which is more innovative and promotes usage of renewable biological resources for industrial purposes, while ensuring biodiversity and environmental protection. In order to carry out this goal, the

European Commission has set a Bioeconomy Strategy and action plan [27]. This plan focuses on three key aspects as; developing new technologies and processes for the bioeconomy; developing markets and competitiveness in bioeconomy sectors; and pushing policymakers and stakeholders to work more closely together [27].

According to the reports, The German Bioeconomy Council had described that the share of produced or processed biomass, or in which biotechnological processes were used on bioeconomy innovation amounts to 4.9% of gross value added for and 6.3% of the working population was employed by these sectors in the EU-25 in 2005. Among the bio-industries, mostly food and wood industries are dominate the share of the bioeconomic gross value added in Germany as well as in the EU-25. The bioeconomy in Germany can be split into two parts: (1) “production and processing of biological resources” which holds 50% of value added and 40% of employment and (2) “trade and services related to biological resources” which captures the other half of value added and 60% of employment in the year 2010 [28].

As for France, in order to develop bioeconomy in France, studies are started to carry out in 2005. Industries and Agro-Resources (IAR) was focused on four strategic fields as; bio-based chemicals (bio lubricants, glues, building blocks, bio surfactants etc.), bio-based materials for the construction sector and transportation, bioenergy with advanced biofuels and biogas production, and ingredients for food and feed. In order to carry out this, IAR also takes into consideration life cycle analysis and environmental benefits as well as the production of sustainable renewable resources. These four topics are now in line with the definition of the Bioeconomy with the publication in February 2012 of the European bioeconomy roadmap. It is now widely recognized that the industrial biotechnologies are called to play an important role in the future of the bioeconomy in Europe and all around the world [29].

Spain sets its own strategy on bioeconomy in January 2016, which perform a sustainable and efficient production and utilization of biological resources. The targeted sectors are food, agriculture and forestry, conditioned by water availability. It also includes the production of industrial bioproducts and bioenergy obtained from the use and valorisation of wastes and residues and other non-conventional sources of biomass. The main focus of the bioeconomy in Spain is the use of biological resources to produce food and feed like as Germany [30].

According to the reports, almost 1.5 million jobs are related with the bioeconomy sector in Italy. Reports show that, Italy ranks 10th in the world as for exports of bio-based products, with a share of around 3%. It is stated that Italian Bioeconomy has great potential for growth which has stronger interactions between public and private stakeholders, different sectors and disciplines from the harvest to the various final products [31].

With having the sixth-largest economy in Europe, the Netherlands’s industrial activity is consist of food processing, chemicals, petroleum refining, and electrical machinery. As for bioeconomy, their approaches and strategy are carry on slower than expected when it is compared to the other European countries. However, it is stated that the structure and strengths of its economy lend itself well for the transition to a bioeconomy. Another disadvantage with respect to the bioeconomy is that The Netherlands has no forestry biomass; the only potential



raw material is agricultural biomass. Since it does not have huge biomass potential, a large share of biomass will need to be imported [32].

### 3.2. Bioeconomy in USA and Canada

The US national bioeconomy strategy was drafted by the Office of Science and Technology Policy and the Executive Office of the President, under participation of different federal agencies. Individual persons and institutions from scientific and industrial areas were consulted for this strategy. The “National Bioeconomy Blueprint” which was the document of bioeconomy strategy of USA, is divided into two distinctive parts. The background and impact of the current bioeconomy is explained in the first part and the strategic objectives are described later. In USA, genetic engineering, DNA sequencing and automated high through-put manipulations of biomolecules, these three technologies are focused as the strategic fields for the bioeconomy. In the document, the possible contributions of government departments and funding agents were also reported. According to the document USA already has a bioeconomy strategy and some of the results which are aimed to achieve are listed. It was stated that, federal departments and agencies supporting biological research. As the focus of the strategy is biological research, the perspective is national with little outlook to the rest of the world [14, 34]. As for the Canada, “Canadian Blueprint: Beyond Moose and Mountains” was the equivalent of the USA’s blueprint of bioeconomy strategy. However, there is no official strategic document for the development of a bioeconomy in Canada, nor any signs of one being prepared. Yet, the document present the requirement for actions and goals within the selected priority areas of capital, people and operational environment. In the bioeconomy strategy of Canada, the forest sector and agriculture, life science and clean technology play important role. Canada’s largest producers of agricultural products is from Alberta and there are a lot of significant producer of forest products. Biomaterials, biochemical, and bioenergy are the areas which have taken marginal roles in Alberta’s economy but are foreseen to grow [14].

### 3.3. Bioeconomy in Asia

According to the studies on bioeconomical approaches in Asia, four bio-industries as biopharmaceutical, biohydrogen, bioplastics and genetically modified crops come into prominence for bio-based economies through 2050. Provided forecasts reported that, development of the biohydrogen industry will be fastest in India, China and Malaysia, and China will be the largest supplier in 2050. The growth of the bio-pharmaceutical industry will be fastest in India, Malaysia, and China and India and Japan will be the two largest suppliers of biopharmaceutical products. Growth of the bio-plastic industry will be fastest in India, Malaysia and China; China will be the biggest supplier of bioplastics. Growth of GM crops will be fastest in Malaysia, India and China; India and China will be the two largest suppliers. In terms of the output values for the four bio-industries, the largest bioeconomies will be in India, China and Japan followed by Korea, Malaysia and Taiwan [33]. In these countries, bio-pharmaceuticals will be the most important bio-industry. Transitioning toward bioeconomy by developing industries based on biological processes will be fast if government should pay more efforts on R&D, biotechnology, human resources and its related infrastructure, industrial supply and sales chain [33].

## 4. Techno-economic assessment

Techno-economic assessment is a term which has been used since 2010 [35]. In this assessment, technical performance or potential and the economic feasibility of an innovative technology are evaluated [36]. This assessment can help making right choices during process development and the success rate of market introduction can be raised. It is important to perform a techno-economic assessment in an early development stage of an innovative technology. Therefore, the specific components which will be taken into account, should be considered carefully [35, 37]. Economic potential based on technical information and assumptions can be evaluated via techno-economic analysis. To design a commercial-scale industry or to make a decision for investment, the equipment information must be collected, and profits must be calculated [38]. For various industrial and biosystems evaluation, such as production of biofuel, and fine chemicals from biomass, techno-economic assessment is a useful method [39]. Engineering design, technical information, and costs and profits can be gathered with techno-economic assessment. It can provide support not only for a long-term business decision, but also for on-going process and improvement. In this assessment, system boundaries, flowcharts and assumptions are required, and main technical and economic parameters must be identified, respectively. By using these data, mass and energy balance are determined. According to the model, capital and operating costs are calculated, and profits are calculated to the economic potential [40, 41].

### 4.1. Techno-economic assessment of microalgae-based productions

Microalgae are microorganisms which have not very complex cell structures, can be single-celled or multicellular and can grow in aqueous media. It is estimated that more than 50,000 species of microalgae are presented in reports and studies. There are many studies on cultivation of algae. However, each algal species is worth studying separately, because algae species have different mechanism for adapting the cultivation medium and cultivation system. According to their structural properties, growth of each algae can show different growth pattern in these systems and medium. Microalgae species and production conditions should be determined according to the products [42]. Microalgae are produced in open (open ponds) and closed systems (photobioreactors). Considering productivity and obtaining special products such as nutraceuticals and pharmaceuticals, closed systems are more preferable than open systems. However, investment and operating costs of closed systems are higher than those of open systems [43]. Therefore, a very comprehensive economic analysis is required when establishing pilot scale systems. In the production of microalgae, biological factors, non-biological factors and operating parameters are influential. Biological factors include pathogens such as viruses and bacteria, and other algae species; non-biological factors include light, temperature, pH, salinity and nutrients; operating parameters comprises mixing, dilution rate and harvesting frequency [44]. In this section, techno-economic assessments of some microalgae based production systems in the literature have been examined and system costs (investment and operating costs) are shown in **Table 1**. As can be seen in **Table 1**, generally, techno-economic approaches have been carried out for biofuel production. Thomassen et al. [45] developed four different scenarios (basic, intermediate, advanced,

Species	Product	System	Investment cost	Operating cost	Ref.
<i>D. salina</i>	$\beta$ -carotene	Open	66,020 €/tonnes	78,474 €/tonnes	[45]
<i>D. salina</i>	$\beta$ -carotene	Open	63,226 €/tonnes	46,686 €/tonnes	[45]
<i>D. salina</i>	$\beta$ -carotene	PBR	253,760 €/tonnes	77,977 €/tonnes	[45]
<i>H. pluvialis</i>	Astaxanthin	PBR	271,449 €/tonnes	80,782 €/tonnes	[45]
<i>C. vulgaris</i>	Bio-oil	Open	3.73 M \$/tonnes	0.63 M \$/tonnes	[46]
NA	Biofuel	Algal turf scrubber	339.64 \$/tonnes	171 \$/tonnes	[47]
NA	Biofuel	Open	351.2 \$/tonnes	322.4 \$/tonnes	[47]
<i>N. salina</i>	Biofuel*	PBR	327.74 MM \$	\$86.52 MM \$	[48]
<i>C. vulgaris</i>	Biofuel**	PBR	5,352,657 \$	1,977,831 \$	[49]
NA	Biogas	Open	48,157 €/ha	7560 €/ha.yr	[50]
NA	Biodiesel	Open	390 MM \$	37 MM \$/yr	[51]
NA	Biodiesel***	PBR	990 MM \$	55 MM \$/yr	[51]

\*For 10 million gallon of biofuel.

\*\*Algae or fuel amount is not given.

\*\*\*For 10 million gal/yr biodiesel.

**Table 1.** Investment and operating costs of microalgae based production.

alternative) to produce 170 tonnes (dry weight) microalgae per year in Belgium. They used open systems in basic and intermediate scenarios and photobioreactors (PBR) in advanced and alternative scenarios. As a result of the techno-economic assessment, it was seen that the investment costs of photobioreactors were about four times that of open systems and the most profits were in open ponds. It is also stated that this profit can be increased four times by recycling fractions. Juneja and Murthy [46] conducted plant design to produce *Chlorella vulgaris* using 227 million liters of wastewater per day and produce bio-oil from this microalgae. In this design, the bio-oil production process model is divided into five parts (growth, harvesting, hydrothermal liquefaction, bio-oil hydrotreating and co-product recovery). The investment cost of the plant, which will be set up for 28,111 tons of algae per year and 10 million liters of renewable diesel from these algae, is \$ 105 MM; the operating costs would be \$ 17.88 MM. They also stated that the total cost of open pond was \$ 38,645/ha. In the study of Hoffman et al. [47], techno-economic analyzes of microalgae production in algal turf scrubber and open raceway pond systems was performed. As a result of the analysis, the total cost of algal turf scrubber and open raceway pond were \$ 510/tonnes biomass and \$ 673/tonnes biomass, respectively. It can be seen that capital costs are close for both systems; but operating costs are much higher than for open raceway ponds. Dutta et al. [52] conducted techno-economic analysis of algal biomass cultivation and biofuel production in two different regions (Portugal and USA). Biofuel production was designed as Case A (Portugal) which was carried out by solvent extraction, trans-esterification and product purification processes and as Case B (USA), it was performed by fermentation, distillation, and hydrodeoxygenation processes. Microalgae cultivation and dewatering (centrifuge and filtration) processes

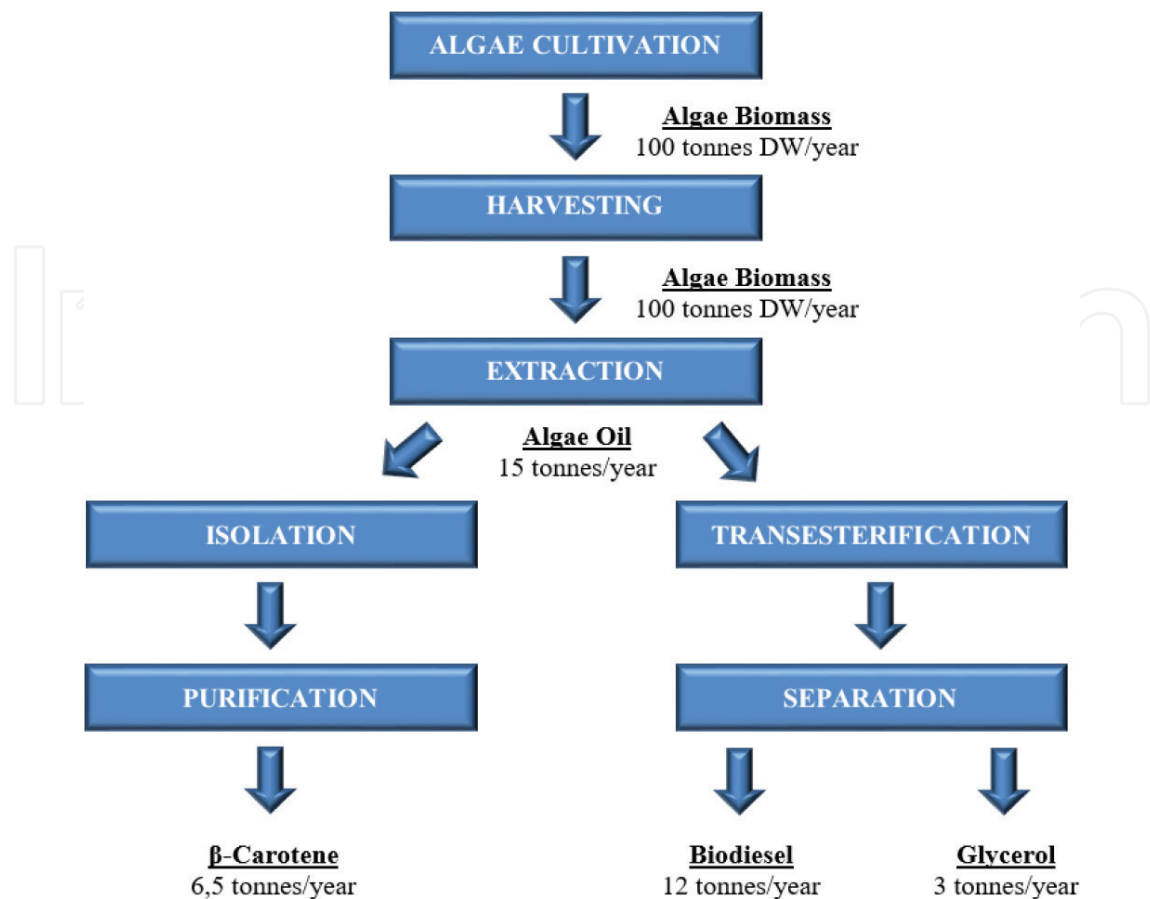


are common for both cases. As a result of the analysis, the costs in Case A and Case B were calculated as \$ 1279/tonnes and \$ 430/tonnes respectively. The main reason for this difference is that the bioethanol and biogas produced in Case B reduce the energy input to the process. In the case study of Brownbridge et al. [53] techno-economic evaluation of biodiesel production from algae was carried out. The global sensitivity analysis revealed that the algal biodiesel production cost was sensitive to the following parameters: algae oil content > algae annual productivity per unit area > plant production capacity > carbon price increase rate. It is also estimated that for a large-scale plant (100,000 tonnes biodiesel per year), the production cost of biodiesel is 0.8–1.6 €/kg. Batan et al. [48] reviewed the technical and economic feasibility of a closed microalgae cultivation system (photobioreactor) for 10 million gallons of biofuel production per year. As a result of the techno-economic analysis, it is seen that 63% of the total cost is the operating cost, 30% is the investment cost and the remaining 7% is the land purchase. It was also found that the total investment cost was \$ 327.74 MM and the operating cost was \$ 86.52 MM/year. Barlow et al. [54] investigated the feasibility of producing renewable diesel by hydrothermal liquefaction of algal biomass produced in an algal biofilm reactor. Sensitivity analysis shows that the algal productivity is the most important parameter for fuel sales price. In addition, it has been stated that the use of wastewaters in microalgae cultivation has significantly reduced environmental problems. Xin et al. [49], have designed a pilot system for algal-based biofuel production. In the designed pilot scale system, microalgae production was carried out in photobioreactors and the total cost of production was calculated as \$ 0.33/kg biomass. In this system, because of microalgae production in wastewater, the operation cost is reduced. Also chars produced as by-products in the system have been evaluated in the drying stage.

#### 4.2. Case study for algal biorefinery

In our study, *Chlorella vulgaris* was chosen to produce  $\beta$ -carotene and biodiesel by presenting two scenarios. Production stages were illustrated in **Figure 1**. *Chlorella vulgaris* is highly used in the industrial field because of its high productivity (1.56 g/L.day), high rate of CO<sub>2</sub> fixation (1.99 g/L.day) and high tolerance to environmental conditions [55, 56]. One of the most important of application areas is biodiesel production (due to high lipid content). The lipid content of *Chlorella vulgaris* is approximately 15–25%; carbohydrate and protein contents of *Chlorella vulgaris* are 9 and 55%, respectively [45, 57]. Apart from these, *Chlorella vulgaris* contains high-grade carotenoids. This microalga contains approximately 75  $\mu$ g/g dry mass of  $\beta$ -carotene [58]. The two scenarios each produce 100 tonnes of dry weight (DW) biomass per year. Each scenario assumes optimal growth conditions as found in the literature. All scenarios produce two products:  $\beta$ -carotene or biodiesel and a fertilizer, consisting of the residual biomass. In addition, glycerol as a by-product will be obtained in the production of biodiesel. The algal-based biorefinery is operated for 270 days per year. The other days cannot be used for cultivation because of inappropriate climate conditions and maintenance requirements.

PBR was selected as cultivation method for the production of the microalgae. *Chlorella* cultures were cultivated in BBM medium. The maximum biomass concentration was assumed to



**Figure 1.** Illustration of the β-carotene and biodiesel production stages.

be 1.56 gr/L day [55]. The maximum specific growth rate was assumed to be  $0.28 \text{ day}^{-1}$ , based on the study of Yang et al. 2011. The reactor volume in cultivation stage was  $300 \text{ m}^3$  (R-101). A centrifuge (C-101) was used to harvest the microalgae (between streams 5 and 6). The centrifuge was assumed to have a biomass recovery rate of 97% and an energy consumption of  $1.4 \text{ kWh/m}^3$  culture medium [59]. A drying step increased the solid concentration of the biomass flow was increased by drying step (between stream 6 and 7). The technological specifications for the drying step were based on the study of Leach et al. [60]. To calculate the total energy consumption of this spray dryer (S-101), a factor of 2.9 was used to account for the heat exchanger energy transition efficiency. The total energy consumption equaled 5.1 MJ per kg of removed water. Lipid extraction (R-102) was carried out with via using a ratio of 1:1 of hexane in (between streams 7 and 8). The filtration step separated the liquid fraction, which contained the lipids dissolved in the hexane, from the solid fraction, which contained the residual biomass (between streams 11 and 19). No energy consumption was required in this step. The solid fraction went to an evaporation (S-101) step to recycle the hexane. The remaining fraction was sold as fertilizer (stream 19). Hexane mixed with microalgae oil was distilled in a vacuum distillation to obtain a relatively pure stream of oil. The calculation of the energy consumption used the same heat transfer efficiency factor as the drying and evaporation step. In the first case, algae oil was used for biodiesel production where transesterification process (R-103) was carried out with 80% efficiency in

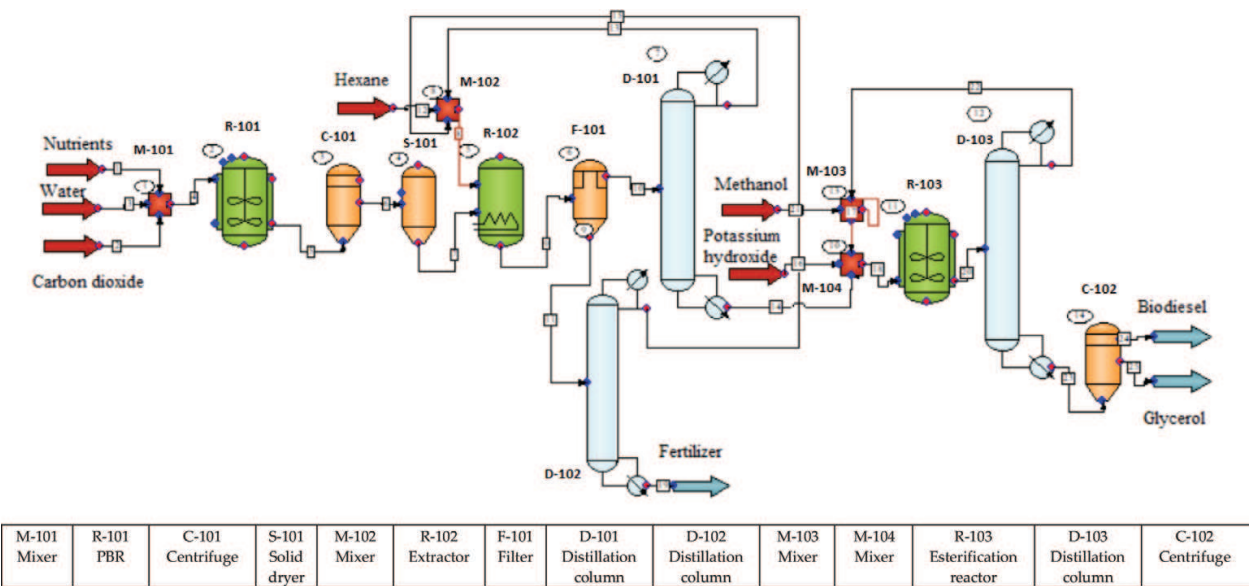


Figure 2. Process flow diagram of biodiesel production from microalgae.

Figure 2 which was created by Chemcad program (between streams 14 and 25). As for the second case,  $\beta$ -carotene production from microalgae after isolation and purification was assumed to be approximately 45%. Dry microalgae biomass was extracted (R-102) with acetone and  $\beta$ -carotene was obtained after sonication process in Figure 3 (between stream 14 and 18). Inputs and outputs of  $\beta$ -carotene and biodiesel production from microalgae were given in Table 2.

Table 3 illustrates the main economic results for the two scenarios. When Table 3 is examined, it is seen that the investment and operating costs are very close to each other in the two scenarios. The investment costs are the highest of all scenarios, due to the costs of the photobioreactor. The photobioreactor installation accounts for about 50% of the investment costs. Nutrients and chemicals account for about 30% of operating costs; and salaries constitute about 20% [49]. When revenues are examined, it is seen that there is a great difference. Because of this situation,  $\beta$ -carotene is a more valuable product than biodiesel. The average selling price of  $\beta$ -carotene is € 1370 per kg and the selling price of biodiesel is € 0.82/kg [45, 61, 62]. Table 3 shows that this system is more suitable for  $\beta$ -carotene production. In order for biodiesel production to become economical, investment and operating costs must be reduced very seriously. In particular, the use of open ponds instead of photobioreactor will significantly reduce the investment cost. Furthermore, the use of an oil-rich microalga, production in wastewater and the use of recycled fractions will make biodiesel production more economical [45].

As mentioned in the introduction section, unlike the classical economy, bioeconomy includes the concepts of innovation, competition, knowledge based value added, and employment and sustainability. Within this approach, biological based productions or innovations are evaluated not only with techno-economic aspects, but with their systematic evaluation of the environmental effects of inputs and outputs at all stages in their life cycle. Life cycle involves modeling the life cycle of a product or production system. Life cycle analysis shows

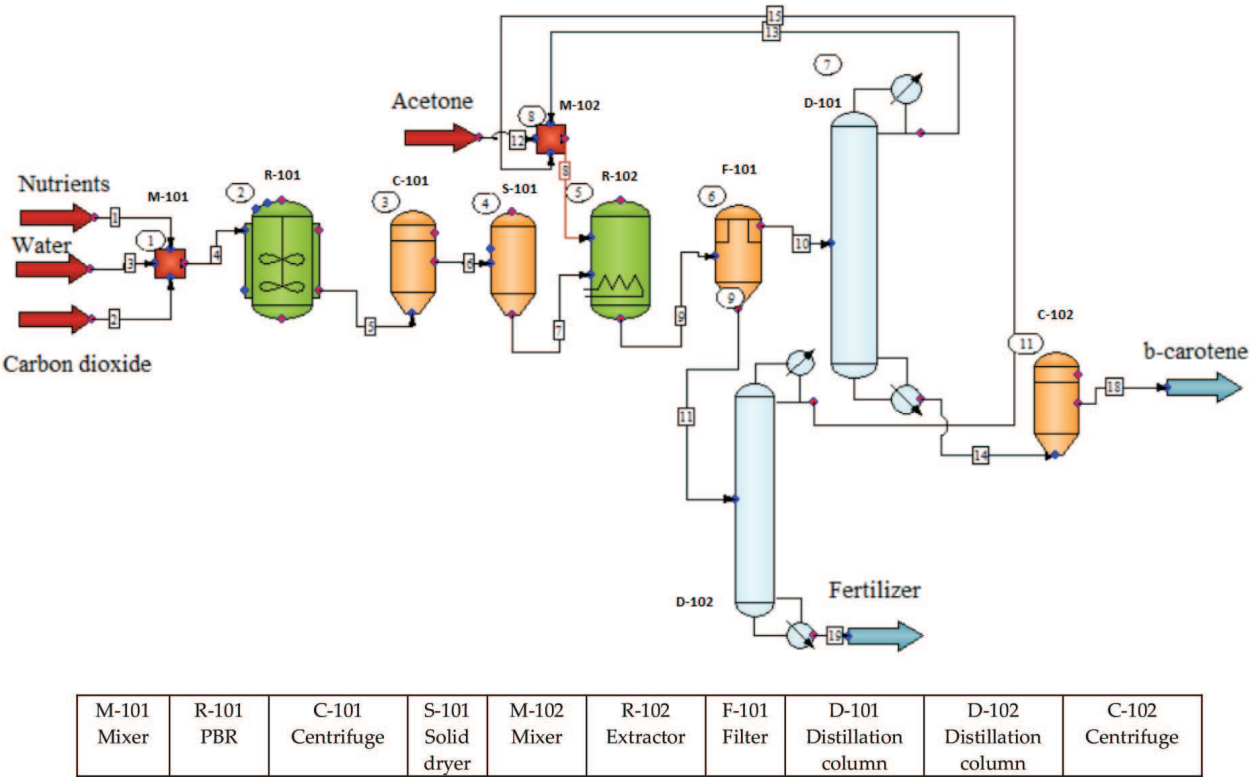


Figure 3. Process flow diagram of  $\beta$ -carotene production from microalgae.

	$\beta$ -carotene	Biodiesel
Inputs		
Water (tonnes/yr)	81,000	81,000
CO <sub>2</sub> (tonnes/yr)	142,688	142,688
Nutrient (tonnes/yr)	9871	9871
Hexane (liter)	–	628.29
Acetone (liter)	4000	–
Electricity (GJ/yr)	10,675	9985
Heat (GJ/yr)	2231	2231
Land use (ha)	1.5	1.5
Outputs		
Product (tonnes/yr)	6.5	12
By-product* (tonnes/yr)	–	3*
Waste algae paste (tonnes/yr)	93.5	85

\*Glycerol.

Table 2. Inputs and outputs of  $\beta$ -carotene and biodiesel production from microalgae.

	$\beta$ -carotene	Biodiesel
Investment cost (€)	1,736,614	1,766,909
Operational costs (€/yr)	504,710	501,277
Revenues (€/yr)	4,270,500	11,698

**Table 3.** The economic results for the two scenarios.

all environmental impacts of an action; a system which comprises of evaluation of raw materials from the nature, and all the wastes that are returned to the nature. This assessment includes all the effects on the air, water and soil during the production, use and eventual destruction of the raw materials, including energy, as far as the product which is processed. This analysis is used both to identify and measure the effects directly (emissions produced during production and energy used etc.) as well as indirect (raw material disposal, product disposal, consumer use and disposal, etc.). These effects are directly connected with sustainability which is the ability to continuously process without consuming the basic resources of a society, an ecosystem or other similar interactive systems and without adversely affecting the environment. In this context, potential impact indicators are necessary for the selection and development of energy systems for the future. These indicators provide a common basis for comparing and evaluating different energy systems [63]. Bioethanol and biodiesel obtained from agricultural sources have lower global warming potentials, on the other hand, there are other environmental problems such as eutrophication, resource depletion and ecotoxicity that occur. Algal biotechnological production is a promising biotechnological area because of high photosynthesis efficiency, and low area requirement for cultivation of algae, and also nitrate and phosphate ions in wastewater can be a food source for algae. In addition to that, algae can utilize industrial CO<sub>2</sub> emissions directly as a carbon source [64]. In the recent life cycle analysis studies on algae systems show that sustainable productions seem to have increased. In these studies, it has been found that CO<sub>2</sub> emissions are effectively reduced in comparison of other production facilities [65]. Algae can recycle of pollutant nitrogen in wastewater. The use of a toxic substance such as urea by algae also shows the contribution of algae to the environment [66]. When all stages of the algal process are taken into consideration, it is seen that requirement of electricity occurs mostly during the cultivation of the algae. The energy requirements of all stages and global warming potentials are much lower than the growth phase. The energy requirement in the algal system and global warming potential depend on the oil productivity during growing, the circulation rate of algae during growing, and the industrial CO<sub>2</sub> gas concentration [67]. 40% of CO<sub>2</sub> emissions are generated from electricity generation, and 30% are from vehicle fuels. In 2013, global CO<sub>2</sub> emissions are 36 gigatonnes. Natural processes absorb half of this amount. Therefore, carbon dioxide shows a net increase of 18 gigatonnes per year in the atmosphere. One tonne of carbon is equivalent to  $MW_{CO_2}/MW_C = 44/12 = 3.7$  tonnes of carbon dioxide. In the equation,  $MW_{CO_2}$  is the molecular weight of carbon dioxide,  $MW_C$  is the molecular weight of carbon,  $e_{CO_2}$  is the carbon dioxide emission (kg<sub>CO<sub>2</sub></sub>/kWh),  $C_f$  is the carbon content in the fuel (kg<sub>C</sub>/kg<sub>fuel</sub>), and  $E_f$  is the energy content of the fuel (kWh/kg<sub>fuel</sub>). Carbon dioxide emissions can be calculated from the following formula:



$$e_{\text{CO}_2} = (C_f/E_f)(\text{MW}_{\text{CO}_2}/\text{MW}_C) \quad (1)$$

In the case study of this chapter, carbon dioxide emission was found as 0.033 t<sub>CO<sub>2</sub></sub>/kWh which was lower than emissions of CO<sub>2</sub> from the combustion of the same amount of coal (anthracite) and natural gas. This indicates the advantage and positive contribution of the algal productions over fossil fuel sources. There is no global warming impact of the bio-diesel process. Sander and Murthy [68], reported that; net CO<sub>2</sub> emissions are -20.9 and 135.7 kg/functional unit for a process utilizing a filter press and centrifuge in harvesting of algae. Furthermore, the -13.96 kg of total air emissions per functional unit, 18.6 kg of waterborne wastes, and 0.28 kg of solid waste are calculated as output. The largest energy input (89%) is in the natural gas drying of the algae. While net energy for filter press and centrifuge processes are -6670 and -3778 MJ/functional unit, CO<sub>2</sub> emissions are positive for the centrifuge process but they are negative for the filter press process. Moreover, 20.4 m<sup>3</sup> of wastewater is lost from the growth ponds during evaporation in the 4-day growth cycle. LCA has one major obstacle in algae technology: the need to efficiently process the algae into its usable components. LCA clearly shows a need for new technologies to make algae biofuels a sustainable, commercial reality. Another study reported that; when algal bio-fuel production modeled, substantial reductions in GHG emissions were achieved in the model due to the non-fossil treatment of the carbon in the biofuel and because substantial energy and nutrient recovery credits from processing of residuals were included. Fugitive emissions of methane and N<sub>2</sub>O respectively totaled 14 and 23% of the whole pathway GHG emissions. Techno economic modeling must choose technologies that control these emissions. LCA requires superior data on fugitive emissions and must account for unrecovered nitrogen leading to N<sub>2</sub>O. Nitrogen transported to fields to displace mineral fertilizers maybe has the potential to produce N<sub>2</sub>O emissions. Nitrogen fraction, especially that which produces N<sub>2</sub>O, a potent greenhouse gas with global warming potential 298 times that of CO<sub>2</sub>. Agricultural techniques may be reduce capital costs substantially; however, these techniques need attentive evaluation with regard to fugitive emissions of N<sub>2</sub>O. Lipid fraction and productivity are two strong drivers of economic viability. The large global warming potential for methane could make the costs for controlling methane emissions higher than the economic value returned and in that case, sustainability and economic drivers would be at odds [69]. Clarens et al. [66], reported that, the impacts associated with algae production were determined using a stochastic life cycle model and compared with switchgrass, canola, and corn farming. The results of this study indicate that these conventional crops have lower environmental impacts than algae in energy use, greenhouse gas emissions, and water regardless of cultivation location. The algae cultivation is driven dominantly by impacts, such as the demand for CO<sub>2</sub> and fertilizer. To reduce these impacts, flue gas, wastewater and novel biofuel production methods such as supercritical process, ultrasound and microwave assisted processes could be used to stabilize most of the environmental loads associated with algae [70]. To represent the benefits of algae production coupled with wastewater treatment, was expanded to include three different municipal wastewater as sources of nitrogen and phosphorus. The use of source-separated urine was found to make algae more environmentally beneficial than the terrestrial crops.

## 5. Conclusion

Algae have come into prominence as a future carbon-neutral biofuel feedstock because of their several advantages. Despite of having been studied for over 50 years now, there are still only just a few corporations that are cultivating algae for biofuel production on a large or commercial scale. The economics of producing algae for biofuel or bioproducts are not cost effective. For this reason, it is necessary to perform a techno-economic assessment and life cycle analysis before the pilot or large-scale microalgal productions to foreseen the pros and cons of the considered algal production system. In this chapter, before the evaluation of algal production with bioeconomical aspects, firstly, bioeconomy term has been described and its classification is given in detail. Also bioeconomy approaches of European countries and the world are presented to show the importance of microalgal production. Techno-economic assessment is explained and techno-economic assessment of microalgal productions are presented in detail and cost-effective approaches are evaluated case by case in basis. Also, two case studies are presented by us, to compare the economical inputs and outputs and environmental effect of the systems such as CO<sub>2</sub> emission and global warming potential has given. It is clear that, a biorefinery system which utilize wastewater or flue gas are economically viable. On the other hand, in the case of obtaining special products which will be utilize in pharmaceutical or food industry, genetic improvements, innovative and optimum design of cultivation systems which have different configuration or working principle, or various recycling systems should be considered to reduce the operational cost. And microalgae, which captured CO<sub>2</sub>, should be used in many sectors, especially in biorefinery concept from the point of view of bioeconomy which comprises using renewable biological resources and sustainability.

## Author details

Didem Özçimen\*, Benan İnan, Anıl Tefvik Koçer and Meyrem Vehapi

\*Address all correspondence to: [ozcimen@yildiz.edu.tr](mailto:ozcimen@yildiz.edu.tr)

Bioengineering Department, Faculty of Chemical and Metallurgical Engineering,  
Yıldız Technical University, Istanbul, Turkey

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