

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900

Open access books available

186,000

International authors and editors

200M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Techno-Economic Analysis of Biogas Production from Microalgae through Anaerobic Digestion

Na Wu, Cesar M. Moreira, Yingxiu Zhang, Nguyet Doan, Shunchang Yang, Edward J. Phlips, Spyros A. Svoronos and Pratap C. Pullammanappallil

Abstract

Microalgae are a promising feedstock for bioenergy due to higher productivity, flexible growing conditions, and high lipid/polysaccharide content compared to terrestrial biomass. Microalgae can be converted to biogas through anaerobic digestion (AD). AD is a mature technology with a high energy return on energy invested. Microalgae AD can bypass energy intensive dewatering operations that are associated with liquid fuel production from algae. A techno-economic assessment of the commercial feasibility of algae-based biogas production was conducted using *Cyanothece* BG0011 biomass as an example. BG0011 is a naturally occurring, saline cyanobacterium isolated from Florida Keys. It fixes atmospheric nitrogen and produces exopolysaccharide (EPS). Maximum cell density and EPS concentration of 2.7 and 2.1 g afdw¹/L (for total algae biomass concentration of 4.8 g afdw/L) were obtained by air sparging. For an areal cell and EPS productivity of 12.4 and 9.6 g afdw/m²/day, respectively, the biomethane production cost was 14.8 \$/MMBtu using covered anaerobic lagoon and high-pressure water scrubbing for biogas purification. Electricity production from biogas costs 13 cents/kwh. If areal productivity was increased by 33% from the same system, by sparging air enriched with 1% CO₂, then biomethane cost was reduced to 12.16 \$/MMBtu and electricity cost to 11 cents/kwh.

Keywords: microalgae, anaerobic digestion, biogas, techno-economic analysis, *Cyanothece* BG0011

1. Introduction

Resource depletion and carbon emissions caused by using fossil fuels have increased interest in alternative fuel sources. Utilization of biomass resources is one option to meet the energy requirements for rapid industrialization and

¹ Ash free dry weight.

population growth with potential environmental and economic benefits. Energy could be derived from a variety of terrestrial, renewable, bio-based feedstocks like sugar-based biomass (e.g. corn, sugarcane, sugarbeet) and lignocellulosic biomass (e.g. wheat straw, corn stover, sugarcane bagasse, forestry residues, switchgrass, energy cane, sorghum, short rotation woody crops). However, production and conversion of these feedstocks could entail risks associated with disruption of the food chain and biodiversity, depletion of freshwater resources and eutrophication.

Aquatic biomass like microalgae is a promising feedstock with many advantages over terrestrial plants. Its use dates to 1940s [1, 2]. To meet an energy shortage during this period, microalgal biomass was proposed to be used as a source for lipids. Microalgae have higher yield from incident solar energy and higher areal productivity. The photosynthetic efficiency of microalgae (around 3–8%) is substantially higher than that of terrestrial plants (typically 0.5%) due to their simple structure and convenient access to nutrients [3–5, 108]. Therefore, less land area is required and non-arable, non-productive land could be used for their cultivation. Some species could be cultivated using low quality water such as seawater, brackish water, desalination reject water and wastewater. A microalgae production facility could be operated as a closed loop system by allowing for recycling of water, nutrients and energy from downstream production processes [6, 7, 144]. Microalgae are characterized by high lipid/starch/protein content with a lack of lignin, which makes them well-suited for different conversion technologies [8–10]. Besides, microalgae cultivation has less potential to interfere with food and feed production. With such versatility, microalgae appear to be a promising biorenewable resource that has the potential to completely replace fossil resources [11]. Research in microalgae biotechnology has increased dramatically since 2005 and has been a very active field in recent years, especially to produce biomass and biofuels [12, 110, 111, 117, 118, 136, 143].

Though microalgae may demonstrate benefits over terrestrial feedstocks, the major challenges for their production include significant utilization of nutrients, high energy input for harvesting and dewatering, and complex downstream conversion processes for usable fuels like ethanol and biodiesel [6, 8, 100, 109, 131]. An alternative which can potentially decrease the energy footprint could be biogas production through anaerobic digestion [122, 125, 127, 137]. Anaerobic digestion (AD) is a biochemical process that mineralizes organic compounds to biogas through the synergistic and concerted action of microorganisms under anaerobic (O_2 free) conditions. Dry biogas is primarily a mixture of methane and carbon dioxide with traces of ammonia, volatile organic compounds and hydrogen sulfide. Methane content of dry biogas usually ranges between 50 and 70% (by volume). Methane has a higher heating value on a mass basis when compared to liquid fuels, such as biodiesel and bioethanol [13, 145]. AD has been recognized as a mature technology to treat organic waste streams and is widely practiced due to its high energy output to input ratio, environmental benefits, as well as for its process simplicity—compared to bioethanol/biodiesel processes [13, 14]. It is suitable for organic feedstock with high moisture content [15] and so can directly be applied to wet algae biomass feedstock with perhaps little dewatering. Besides, no harsh pretreatment is necessary for algal biomass due to the negligible lignin content [14]. The algal biorefinery could be engineered to be resource efficient by recycling phosphorus and nitrogen nutrients in the digestate effluent and carbon dioxide from biogas upgrading processes for microalgae cultivation [13, 14, 16, 17].

In addition to the physical and chemical properties of the fuel as specified by technical standards, the characteristics desired by the stakeholders, distributors

and, consumers could also include sustainability indices related to environmental, social and economic performance. Techno-economic analysis (TEA) establishes a capital and operating cost profile to determine the potential economic viability of the production process for realizing its commercial feasibility. It can be an integral tool to direct research during development of specific technology and assist with investment by averting unnecessary expenditures. A number of techno-economic assessments have been completed to evaluate the economic feasibility of biodiesel derived from microalgae [9, 22, 69, 140, 141]. However, there is a lack of techno-economic analysis on anaerobic digestion of microalgae for biogas production, especially full-scale production taking the characteristics of algae species into consideration. In this chapter, the entire production process from algae cultivation to biogas upgrading will be discussed emphasizing the key cost drivers. TEA literature is reviewed for methodology and state of art technologies. An example of TEA was conducted based on the biogas production process from a microalgae/cyanobacteria species *Cyanothece* BG0011 [82].

2. Anaerobic digestion

An anaerobic digestion (AD) process can biochemically convert the whole, wet biomass rather than specific components. The emissions and effluents from the process can be captured for reuse of components like carbon dioxide, ammonia, and phosphorus, and therefore has the potential for economic and environmental benefits. The general biochemical steps in the AD process include: (1) hydrolysis: the breakdown of macromolecules like proteins, lipids, polysaccharides into simpler compounds such as amino acids, sugars, fatty acids and glycerol; (2) acidogenesis and acetogenesis: the hydrolyzed molecules are converted to volatile fatty acids, primarily acetate, hydrogen, and carbon dioxide; (3) methanogenesis: methane production from acetate, hydrogen and carbon dioxide. The hydrolysis step plays a crucial role in determining the successful production of methane [37, 145]. The biochemical processes in AD also occur in nature. AD technology is well established and recognized as a robust technology to convert biomass to bioenergy [146].

Despite the potential, questions related to the economic feasibility and the net energy output are the main hurdles hampering the development of biogas production from microalgae [14, 18–20]. For example, due to the specific structure and composition of the microalgae cell wall, the yield of biogas could be low. Pretreatment to disrupt the cell walls could require high energy inputs. The algae productivity could be low and cultivation cost could be high. Thus, the viability of microalgal biogas production may depend on improvements of efficiency and economic performance. Ongoing efforts include developing inexpensive biomass feedstock, maximizing energy return on investment, and minimizing environmental risks. As only a few studies are available in the literature on the economic feasibility of microalgal biogas exploitation [14], the evaluation and analysis of microalgal biogas production cost will be based on conversion efficiency, technological design aspects as well as available cost information.

3. Key drivers of microalgal biogas production cost

The production of biogas from microalgae feedstock entails a series of steps starting with algae cultivation. Implementation of each step involves capital and

operational expenditures. The key drivers such as algal biomass productivities, harvesting and dewatering techniques, AD designs, biogas utilization options, integration of algal production, and AD with other bioprocesses were addressed. The production cost breakdown was illustrated in a harmonized framework and a dynamic connection between the technological and economic/environmental assessments was established.

3.1 Microalgae cultivation, harvesting and dewatering

A photobioreactor is the essential component of an algae cultivation facility. An open raceway pond (ORP) and a closed photobioreactor (PBR) are two major cultivation platforms. These two platforms for algae biomass production have been extensively studied [22–27, 83–85, 101]. The main differences are highlighted in **Table 1**. In addition, the steps from inoculum preparation to obtaining the wet algal paste typically include systems for culture circulation, growth medium supply, air/flue gas supply, culture cooling, culture harvesting, and process monitoring. Heat exchangers, pumps, and a piping network are also required. The location and climate are important factors for algae cultivation.

Due to the high methodological variation of TEA in literature, drawing a generic conclusion over the economic feasibility of microalgal cultivation could be impossible. From the technological and economic perspective, the factors presented below are the ones most prominent in the existing literature and identified as important topics in the development of algae fuels.

1. *Microalgae productivity and culture stability.* According to Davis et al. [23], achievable productivity has a strong influence on the economics. Productivity of more than 25 g/m²/day annual average is critical for maintaining a relatively low minimum biomass selling price. A significant increase in productivity has to be achieved to reduce cost substantially [25]. The cultured strain should have high growth rate and a steady biomass composition. GMOs or extremophiles could provide culture robustness [22]. However, due to lack of regulations for managing GMOs, it is unlikely permits could be obtained for commercial cultivation of GMO algae strains. For commercial outdoor systems, uncertainties could be associated with seasons of the year and across multiple locations. Thus, the productivity data should be integrated with meteorological data for geographically and seasonally resolved assessments using a robust strain.
2. *Photobioreactor design, construction, and operating conditions.* For the open pond system, pond liners were found to be one of the primary cost contributors [22, 23, 28]. The location of the pond facilities could be selected according to the nature of the soil. For example, ponds built on soil with high native clay content could avoid full liners to reduce the cost. Ación et al. [26] presented a cost analysis of microalgae production using tubular photobioreactors. In these systems, photobioreactors were found to be one of the significant cost contributors. Generally, open raceway ponds are economically advantageous by more than a factor of 2, compared to closed photobioreactors [29]. However, due to increased productivity and culture stability, closed photobioreactors still have the potential for commercial applications.
3. *Energy consumption.* Primary energy consumption is due to the energy required for mixing, circulation, aeration and CO₂ sparging. The energy consumption for mixing at experimental scales usually exceeded commercial-scale

operations requirements and needs to be optimized to determine the minimum energy requirement [27, 28]. Mixing devices such as the paddle wheels are significant capital cost contributors besides the photobioreactors.

4. *Nutrients and carbon dioxide supply.* Higher productivity usually involves higher consumption of nutrients. Thus, nutrient input needs to be adjusted to balance the tradeoff against productivity [23]. Carbon dioxide was found to be the most expensive consumable among the raw materials [26]. Siting algae cultivation facilities on land adjacent to industrial CO₂ sources like flue gases may be effective in reducing cost. However, the substantial logistical and practical constraints of using flue gases in facilities of varying sizes are still a challenge [23].
5. *Land and water.* Even though, microalgae can be cultivated on nonarable land, the soil composition, climate, solar radiation have a substantial influence on their growth. The most suitable location should be warm places or close to the equator where insolation is not less than 3000 h/year [24]. Water is required during algae cultivation to compensate for evaporation or for cooling purposes. Availability of water at low cost is critical for process success. Water reuse, wastewater, seawater, brackish water and reasonable distance to the water source has the potential to reduce costs.
6. *Scaling.* It is critical to quantify the economy of scale for algae production to achieve economic viability [23]. However, large uncertainties and unrealistic assumptions will exist in the research where the productivity potential for microalgae at large-scale is being estimated through linear extrapolation for laboratory-based growth data [30]. Data variability and growth modeling considering geographical information should be considered in large-scale assessments.
7. *Labor and depreciation.* Tredici et al. [21] performed a TEA of the microalga *Tetraselmis suecica* production based on a 1-ha plant in Tuscany, Italy. Cost data were collected from manufacturers and suppliers as well as operating data from pilot and commercial facilities. This study found that the major fraction of cost was labor at small scales (1 ha) and when the pilot plant is scaled to 100 ha, capital expenses contribute the most to the production cost. This assessment is site and strain-specific, but still provides valuable insights for the economic evaluation.

Algae harvesting and dewatering methods include gravity settling, chemical coagulation, flocculation, filtration, centrifuge, and drying. The economic feasibility and energy consumption are two criteria for assessing the performance of unit operations for harvesting and dewatering methods. It was found that the cost of separation takes 20–30% of the biomass production costs [32, 33]. Gravity settling, chemical coagulation, and flocculation usually concentrate the microalgal slurries to 2–7% while filtration and centrifugation concentrate microalgal slurry to 15–25% of total suspended solids [32]. The suitability of microalgal dewatering methods has been investigated for scalability, species flexibility, and downstream processing efficacy [33–36]. Dewatering methods reaching high biomass concentrations are usually associated with high energy input and cost. Thus, a combination of dewatering methods such as flocculation followed by filtration is generally considered to be economical due to the increased harvest efficiency. For downstream processing, methods such as flocculation using flocculants comprised of cationic and anionic

	Open raceway	Closed bioreactor
Biomass productivities	Low	High
Harvesting biomass concentration	Low	High
Total capital cost (CAPEX)	Relatively low	High
Total operational cost (OPEX)	Relatively low	High
Reliability (low contamination risk, stable yield)	Low	High
Net energy ratio (energy output/input)	>1	>1 in some cases
Area required	High	Low
Process control	Low	High
CO ₂ loss	High	Low
Water evaporation	High	Low
Photosynthesis efficiency	Low	High
Scale-up	Easy	Difficult

Table 1.

A comparison of the open raceway and closed bioreactor systems for algae cultivation.

poly-electrolytes, synthetic polyacrylamide polymers and starch-based polymers can be employed. However, the detrimental effect of these flocculants on the subsequent microbial processes need to be considered. For example, anaerobic digester stability and gas production could be affected by metal contamination. Future work should include replacing chemical coagulants with natural and low-cost organic ones for harvesting algal biomass.

3.2 Anaerobic digestion systems

3.2.1 Pretreatment

The efficiency of biogas production has been shown to be species-dependent [39]. One crucial factor is the differences in structure of microalgae cell walls. The role of the cell wall in the microbial degradability of algae biomass is highlighted in many investigations [6, 13, 37, 38, 40–43]. Many microalgae species (e.g. *Chlorella kessleri*, *Scenedesmus*) have recalcitrant cell walls, which make it difficult for anaerobic cultures to hydrolyze microalgal intracellular organic matter. Thus, to improve the biodegradability of microalgal biomass, pretreatments methods have been developed to disrupt or solubilize cell walls [112–116]. General insights from these studies are: (1) pretreatment methods are species-specific and their success depends on the nature of the cell wall; (2) mechanical pretreatments which consume electricity are more energy intensive than thermal, chemical and enzyme pretreatments; (3) chemical pretreatments usually have a low cost but produce inhibitory substances which could hamper the AD process; (4) for pretreatment mechanisms such as disruption of microalgal cell walls, the synergistic effects of the enzymes need further investigation; (5) combined pretreatments may provide energy and cost-effective options; (6) multi-objective optimization techniques could be used to obtain a high biogas yield with a positive energy balance; (7) enzyme/biological pretreatments have high selectivity, low inhibitory effects and higher probability of positive energy return [147]; (8) research on pilot/demonstration scale pretreatments is rare; (9) thermal pretreatments have been employed widely and proven to be the most efficient in microalgae pretreatment for AD; and (10) a detailed economic/energy analysis of microalgal AD for biogas production with pretreatment is still missing.

3.2.2 Hydraulic retention time (HRT), organic loading rate (OLR), and reactor configurations

The capital cost of the anaerobic digester could be reduced by using reactors designed for high OLR and low HRT [37]. The OLRs are typically between 1 and 6 g VS/L/d while the HRT varies between 10 and 30 days [37, 38]. Although high OLR will increase the methane productivity, overloading will decrease the biogas production efficiency due to the accumulation of inhibitors such as ammonia and acids [6, 37, 38]. Also, prolonged HRT could lead to ammonia inhibition due to slow liquid removal rate [41], while a low HRT could cause the washout of the anaerobic bacteria community [6]. Thus, an optimized OLR and HRT should be applied to achieve the expected specific methane yield. Possible solutions could be improving anaerobic digester configurations such as using membrane reactors or upflow anaerobic sludge blanket reactors to decouple the OLR and HRT [37, 119] and on-line control of anaerobic digester operation [124]. These have not been applied for digesting algal biomass. Additional costs for land and infrastructure and energy expenditures for heating the digesters should be included in the economic analysis.

3.2.3 Temperature, pH, salinity, sulfur, and lipids content

AD microorganisms can grow in three temperature regimes: (1) psychrophilic (5–20°C); (2) mesophilic (25–45°C); and (3) thermophilic (45–65°C). The temperature effect on AD has been discussed [13, 37, 41]. The beneficial temperature regime for AD operation is anaerobic digester is species-specific [44, 45]. The rate of methane generation can be enhanced under mesophilic and thermophilic conditions. The increased temperature could improve enzymatic activity for degrading microorganisms, and at the same time, the photosynthesis activity of viable microalgae within the digester could be reduced [13, 37]. However, an increase in temperature beyond the tolerable range of each temperature regime could cause inactivation of the microbes. Thermophilic temperature may cause increased hydrolysis of nitrogenous compounds which may increase ammonia levels and in turn can cause inhibition [6]. For large-scale biogas productions, the energy required for heating may be more than 1/3 of the total energy output in the form of biogas [46]. Thus, the net energy production from algae biogas may still be limited due to the high heat input associated with a low concentration of algae substrates.

The pH needs to be maintained at an appropriate level for efficient conversion of biomass to biogas. The growth of microbes, enzyme activity, and the biogas compositions are influenced by the pH [47]. The optimum pH level depends on each step of AD [41]. Generally, the pH values are maintained between 7 and 8 for single stage anaerobic digesters [13, 41].

Microalgae grown in a saline environment offer a sustainable alternative to other biomass by utilizing non-arable land and seawater. Marine microalgae can usually grow in a salinity range of 35–125 ppt [48]. However, when a highly saline culture is processed in an anaerobic digester, the high salinity could be inhibitory to the AD process. The effects of salinity and concentration of sodium are discussed in previous studies [6, 38]. Adaptation of anaerobic digester microbial consortiums under different saline conditions was investigated by Mottet et al. [121]. In a promising study, methane production was observed from anaerobically digesting *Dunaliella salina* biomass at 35 g/L of salinity.

Sulfide is a required micronutrient for anaerobic microorganisms, but high concentrations of sulfide (200 mg/L) could be toxic [6]. For saline microalgal species, the sulfur inhibition may occur due to the presence of oxidized sulfur compounds in saline algae growth medium. Proper inoculum selection for anaerobic digesters could favor the growth of methanogenic bacteria and limit the growth sulfate-reducing bacteria [49].

Lipids can also be inhibitory to the AD process [6, 18, 50] although lipids have a high theoretical methane potential. Generally, inhibition would occur when lipids concentrations are higher than 30%. In this case, the high-lipid microalgae are suitable for lipid extraction for production of liquid fuels.

3.2.4 C/N ratio

Microalgae biomass generally has a higher composition of protein than terrestrial plants [6, 37]. The degradation of protein will cause ammonia accumulation and inhibit the methanogenesis process. The optimum C/N ratio for AD is between 15 and 30 while this C/N ratio for microalgal AD is generally below 10 [13, 38, 41]. Thus, increasing C/N ratio and reducing the ammonia toxicity are important to enhance the biogas yield and productivity from microalgae. Possible solutions to this issue could be; (1) using ammonia-tolerant inoculum generated either by bioaugmentation or by acclimation [37, 38]; (2) using microalgae biomass that was cultivated under nitrogen-limitation [41, 99, 102, 130]; (3) co-digestion with sludge, oil-greases, waste paper and food wastes [13, 41, 54]; and (4) using a two-stage AD for better control of the anaerobic microbial communities [6]. However, these solutions may add more complexity to the system, in which the economic and energetic performance is still clear. For example, the co-substrate needs to be secured for co-digestion; the digester volume and cost may increase due to the loading of the co-substrate; more environmental burdens may be associated with the shipping of biomass, and nitrogen-limitation cultivation may affect microalgae productivity.

3.2.5 Other factors

Many other factors could affect the biogas yield and production of microalgal biomass. For example, the harvesting time influences the composition and biodegradability of algal biomass. Thus, it is essential to harvest algae in the appropriate stage of growth [13]. Storage conditions such as temperature also have an impact on biomass quality like macromolecular distribution and the content of organic compounds. Besides, inoculum to substrate ratio control is instrumental in avoiding inhibition problems such as drop in pH [51].

3.2.6 Biochemical methane potential (BMP) of microalgae biomass

The overall biogas yields depend on the chemical composition of the algae strains. The target strain should be highly digestible. The volatile solids/ash-free dry weight of microalgae plays a significant role in predicting theoretical biogas production potential, which is a critical factor in determining biogas productivities. Theoretically, the methane yield from different components of microalgae is as follows: lipids—1 L CH₄/g VS, proteins—0.85 L CH₄/g VS, carbohydrates—0.42 L CH₄/g VS at standard conditions. Although the lipids have a high theoretical methane yield in AD, a high lipid content (more than 40%) will produce inhibitory substances such as long chain fatty acids [6]. Thus, for high-lipid content microalgae, lipid removal for biofuels production may be a better solution than biomass sent directly to AD.

The impact of the algae cell wall is another critical factor affecting methane yield. Some species either lack cell wall or have cell walls rich in easily-biodegradable proteins as in *Dunaliella salina*, a halophilic microalgae and *Chlamydomonas reinhardtii*, a fresh water green microalgae [38]. Even easily degradable cell wall alone does not ensure efficient methanization. Factors such as the presence of methanogenesis inhibitors, anaerobic microbial community, hydraulic retention

Components	Species			
	<i>Scenedesmus</i> sp.	<i>Chlamydomonas</i> <i>reinhardtii</i>	<i>Chlorella</i> <i>vulgaris</i>	<i>Nannochloropsis</i> <i>salina</i>
Protein % of DW	33	65	64	19
Carbohydrates % of DW	35	23	18	45
Lipids % of DW	22	13	10	36

Table 2.

Approximate compositions of four microalgal species: *Scenedesmus* sp., *Chlamydomonas reinhardtii*, *Chlorella vulgaris*, and *Nannochloropsis salina* [41].

time, organic loading rates, salinity, carbon to nitrogen ratio, and the concentration of digestible substrate will also affect the final methane yield of microalgae.

The microalgal strains which have been investigated extensively include *Scenedesmus*, *Chlamydomonas*, *Chlorella*, and *Nannochloropsis* [12]. The compositions of these four species are shown in **Table 2**. AD conversion process with biochemical methane potential (BMP) to theoretical methane potential (TMP) ratio $\geq 70\%$ are considered highly efficient. *Chlamydomonas reinhardtii* could achieve a 74% BMP (405 ml methane/g VS) to TMP (549 ml methane/g VS) ratio without any pretreatment [52]. Schwede et al. [53] achieved high digestibility of *Nannochloropsis salina* with thermal pretreatment. The methane yield significantly increased from 0.2 to 0.57 m³ kg VS⁻¹ under batch conditions with a BMP to TMP ratio increasing from 31 to 89%. Similarly, *Chlorella vulgaris* shows a significant increase in BMP after pretreatments: from 54 to 85% BMP/TMP ratio [41, 52] under an enzyme pretreatment; and from 62 to 78% BMP/TMP ratio under a biological pretreatment [55, 123]. *Scenedesmus* sp. did not show a BMP/TMP ratio higher than 60%, even after enzyme or thermal pretreatments [56, 57]. The BMP varies from species to species, but no significant difference was found between fresh water microalgae and saline microalgae [58].

4. Techno-economic analysis

In published TEA works, the process complexity was often simplified in terms of limited pathways, few choices of economic drivers and implicit assumptions regarding the growth conditions, process modeling factors and financing of the production facility. Existing reviews in anaerobic digestion of microalgae biomass such as Ward et al. [6] focus on the integration of anaerobic digestion into biodiesel refineries. Considering that diesel or ethanol are more valuable products, anaerobic digestion was suggested to treat the residual biomass to improve the economic viability and sustainability of overall microalgae biodiesel/ethanol stages. Global research in various pathways is going on towards the sustainable development of algae biofuels. The following sections will review these works, highlight the variability of methods of estimating microalgal biogas production cost, find the key drivers of cost contributors, pointing out the convergence and difference in published results, and give a view of the whole value chain towards scaling-up and commercialization when performing a techno-economic analysis (TEA).

4.1 TEA framework

To achieve an optimal facility design, it is necessary to evaluate the tradeoff resulting from the interactions between technical advances and financing

parameters. The technical objectives include maximizing microalgal biomass productivity, maximizing biogas yield via AD of biomass, and process stabilization. The economic objectives are to minimize the production cost and maximize the economic benefits. **Figure 1** shows the TEA framework for the sustainability analysis of biogas production from microalgal biomass through anaerobic digestion. The whole biomass processing value chain is determined by the technology framework and progress through experimentally validated process specifics. Economic analysis is based on the process design, which includes the cost assessments and investment analysis. A decision-making platform is built for raw material suppliers, producers and stake holders in an economic perspective. Correspondingly, the economic consequences will direct the research & development of new technologies, which could form a dynamic connection and optimization framework.

Environmental TEA (E TEA) extended the TEA framework with an environmental assessment based on a life cycle analysis [70]. The E TEA is based on the technology readiness level, which means the assessments are performed using the available data based on technology maturity. This would avoid a mismatch between the assessment methodology and the technology readiness level. For example, the whole biogas life cycle includes phases from the biomass cultivation to the final usage and end of life. Under current technology maturity, the whole data set is unavailable, which limits the assessments to certain life cycle phases.

4.2 State of the art: TEA of microalgal biogas

Biorefinery optimization and full utilization of biomass addressing in the economic viability and environmental sustainability of the production of algae biofuels can be found in [39, 71, 72]. Dutta et al. [72] analyzed the sustainability of microalgae-derived biofuel production by performing a TEA and life-cycle assessment and found that coproducts valorization is more energy efficient than the processes focusing on specific components such as lipids. Biorefineries with coproducts and byproducts could have better utilization of the algal biomass and can increase the revenue, thus show greater possibility of achieving economic feasibility. In microalgae biodiesel and bioethanol productions, anaerobic digestion is usually integrated into the biorefinery to treat the residues for energy and nutrient recovery. Sialve et al. [18] compared the energy recovery ratio for two scenarios: direct AD of the whole algae biomass and AD of residue biomass after lipid extraction. Direct AD of

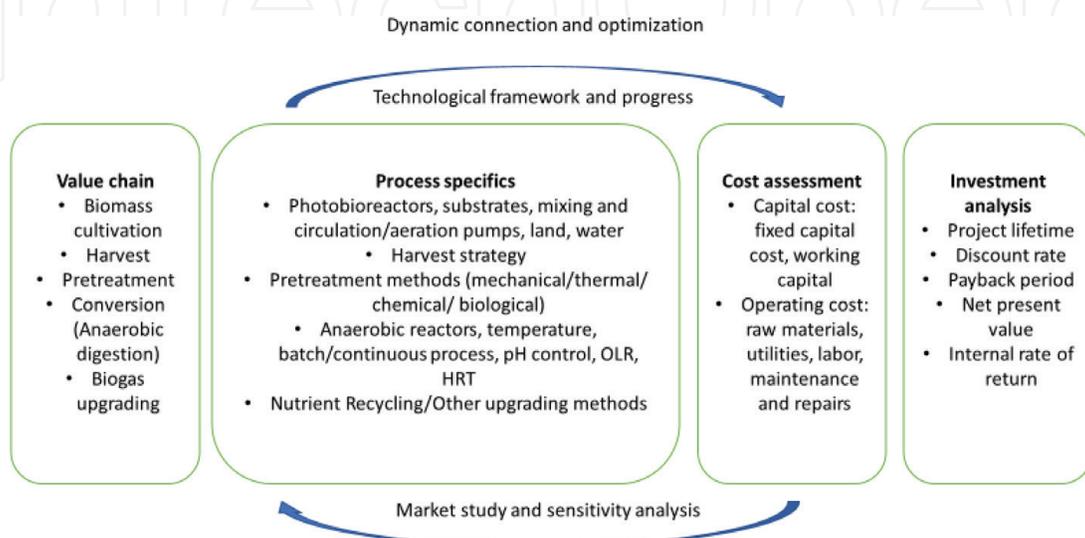


Figure 1. TEA framework for biogas production from algae biomass.

the whole biomass was considered to have a higher energetic recovery when the cell lipid content does not exceed 40%. Also, increased lipids content in microalgae is not generally compensated with increased productivity due to nitrogen limitation. The potential of direct AD of microalgae biomass was addressed in their research, taking into account the energetic recovery and necessary nutrient recycle for large-scale productions. Chia et al. [73] discussed the economic potential of biohydrogen and biogas production in Germany and Spain. Two processes were compared: direct AD of microalgae biomass (DAD) and coupled hydrogen and biogas production (CHB). In the CHB process, hydrogen was first produced by dark fermentation then effluent from hydrogen fermentation was used for biogas production. The CHB was found to have a lower operating cost due to no additional water and nutrients requirements for the bioreactor feed while the DAD process requires algal biomass in combination with other feedstocks. Both cases have production costs 13–16 times higher than the market price for natural gas. A 1/3 higher biogas yield and a 1/2 lower labor cost did not change the economic status of both processes, due to the high cost of fertilizer and building photobioreactors for microalgae cultivation. Milledge and Heaven [74, 129] performed an energy balance of biogas production from microalgae. Their research emphasized a combination of dewatering methods, as well as the efficient exploitation of the heat generated by the combustion of biogas in combined heat and power (CHP) units to show the energetic viability of the whole process.

Chew et al. [68] assessed the potential of microalgae biorefineries for producing high-value products such as pigments, proteins, lipids, carbohydrates, and vitamins. The high-value products were added to improve the biorefinery economics. Open pond cultivation and medium recycling were mentioned to have better economic performance than other biorefinery structures. Water, land usage and capital cost were challenging for the economic viability of algal biofuels. The high-value products also need to improve aspects such as separations method, energy consumption, and control of product loss. AD was emphasized to recycle a considerable amount of nutrient usage to make microalgal fuels head towards its large-scale production. Several authors [13, 17, 37, 38, 75, 133, 134] synthesized scientific literature on biogas production from algae and suggested integration of the technology with other technologies as well as co-digestion with other substrates for an optimized biorefinery that sustainably produces biogas. Singh and Gu [76] recommended integrated processes that combine algae cultivation and wastewater treatment for methane production, which could offset the higher cost in comparison to methane production from corn and woody biomass.

Zamalloa et al. [8] evaluated the techno-economic potential of methane production from microalgae. The assessment was carried out using high rate anaerobic digesters (10–20 kg COD/m³/d) and pre-concentrated algae biomass from a full-scale open pond. The energy production cost from microalgal biogas was estimated to be 0.087–0.17 euro/kWh with an algae biomass cost of 86–124 euro/tonne. The result was based on a feed-in tariff of 0.133 euro/kWh and a carbon credit of 30 euro/ton of carbon dioxide. This study is one of the limited works that has been done on a comprehensive technological and economic assessment of electrical and thermal energy produced by biogas through AD of microalgae.

Collet et al. [77] performed a life-cycle assessment (LCA) of biogas production from the microalgae *Chlorella vulgaris* and found that electricity consumption and the impacts generated by the production of methane from microalgae are strongly correlated. Decreasing mixing and heating cost in different production steps or increasing the efficiency of AD were important to reduce the overall cost.

The studies surveyed show considerable variability in the calculated fuel cost and identifying the significant cost contributors. The varied results come from

different conversion pathways, technical assumptions (productivity, reactor design, process parameters, etc.) and economic factors (interest rate, raw material cost, etc.), diverse environmental and social conditions (consideration of season and location), and validation of sub-process models (lab/pilot plant/commercial scales). Nevertheless, the contributors to the production cost are mainly identified as microalgal strain selection, biomass cultivation and harvesting, AD operating conditions, biogas upgrading methods, waste management, and type of biorefinery. Thomassen et al. [78] evaluated the methodological reason for the wide variation in the results of multiple environmental and economic assessments. They proposed an environmental techno-economic assessment which can help to solve the challenges for a sustainability assessment: framework for methodology, harmonized assumptions, and integration of different dimensions (stages of technological maturity, technological process). This method is based on the dynamic technological process parameters and the same system boundaries for an integrated TEA and LCA.

4.3 Cost management

Gnansounou and Dauriat [79] investigated TEAs following different types of cost management systems in value engineering, target costing and a combination of value engineering and target costing. Value engineering includes process design via data collection and process flowsheeting. Process simulators such as Aspen Plus enables the evaluation of the whole process chain based on scale up of the pilot plant, state of art technologies and price quotes. For microalgae to biogas technologies, key issues along the process chain include the suitable choice and operation options of the microalgae species, harvesting/dewatering strategies, pretreatment methods, AD configurations, recycling the digestate, and energy integration. Not all the steps are necessary for technologies with simplified processes and high economic potential. Target costing is a market-oriented method, which means a target selling price was set for the cost evaluation based on market and societal values. Following the target price, the target cost of the final product and each step of the supply process will be estimated, which means the cost allowance will play a key role in the process design. Target costing could integrate with value engineering in the cost management activities, so the cost allowance and cost target could be reconciliated. In the case of biogas production, the target costing evaluation seems unfeasible for the whole process due to the weak financial position of the natural gas market [80].

Real options analysis framework was employed by Kern et al. [81] for TEA. The model was adapted to accept stochastic price data for energy and agricultural commodities as well as static operating parameters assumptions for the algal biofuel plants. The TEA work was combined with life cycle analysis in a dynamic system—the fluctuations in market prices for energy and agricultural commodities will influence the operation decisions of the biofuels plants and its associated environmental impacts. Areas such as carbon tax, resource shortage and market forces could be investigated for their impact on biofuel plant design and operations in a dynamic system in the future. This gives the stake holders and suppliers more flexibility in making decisions.

4.4 TEA limitations

The limitations of TEA include the potential competition for resources. For example, the microalgae biomass could have non-energy applications and has the potential for producing high value products besides biofuels. Then the biomass cost for the process will be influenced not only by the biomass production

activities but also the market price which is determined by both the suppliers and purchase competitors.

The sustainability of biogas production from microalgae will depend on not only the commercial viability but also environmental improvements such as greenhouse gas emission reduction, lack of direct and indirect impacts on land-use as well as biodiversity and eutrophication. The scope of TEA is limited for the environmental impact assessment, while these impact categories are appropriate for the goals of the overall sustainability analysis. Thus, an ETEA would allow assessing the sustainability of the entire value chain. Besides, TEA is not reflecting social impacts such as social awareness of algal biofuels' non-food competitive characteristics, rural development, and public recognition.

5. Case study: TEA of anaerobic digestion of *Cyanothece* BG0011

The microalgae used for this case study is a cyanobacterium, *Cyanothece* sp. BG0011 isolated from a shallow lake in Florida Keys [82]. Compared to other algal species, this species is endowed with unique features. First, cyanobacterium *Cyanothece* sp. BG0011 is a saline species and can be adapted to a wide range of salinities (10–70 psu). Second, it fixes dinitrogen in the air, which means it does not require nitrogenous nutrients in the culture water. Third, it produces exopolysaccharide (EPS) which can be converted to a variety of bioproducts. The aim of this case study is to assess the economic feasibility of biogas production using *Cyanothece* sp. BG0011 as feedstock by conducting a techno-economic assessment. The analysis investigated alternatives to decrease the cost and energy requirement of the cultivation and anaerobic digestion of algae. Utilization of biogas to produce electrical and thermal energy or upgrading to produce pure methane (renewable natural gas) was also considered. A comprehensive TEA was carried out based on experimental data and a set of operational assumptions which could be conceivably achieved in near term. The process flowsheet for biomass to biogas conversion through anaerobic digestion and biogas purification processes was implemented in Aspen Plus V8.8 to obtain mass balance and energy requirement results. The discussion focused on the preliminary exploration of the conceptual design of a microalgae cultivation and bioconversion system as well as an investigation on improvements that could result in the greatest system flexibility, energy yield and cost reductions.

5.1 *Cyanothece* BG0011 cultivation

Results from many experiments [149] conducted in the Bioprocess Engineering Laboratory, Department of Agricultural and Biological Engineering, University of Florida gave an average growth rate of 67.5 mg afdw/L/day (20.25 g afdw/m²/day) for BG0011 cell biomass and an EPS production rate of 52.5 mg afdw/L/day (15.75 g afdw/m²/day), resulting in cell density of 2.7 g/L and EPS concentration of 2.1 g/L. The areal rates were calculated by assuming that the depth of culture was 30 cm, which is typically the case for open ponds. In the laboratory, the cultures were cultivated under air sparging, a constant illumination of 1200 μmol photons m⁻² s⁻¹ light and 13 h to 11 h light-dark cycle. Open raceway ponds are generally used for large-scale commercial production of algal biomass [86]. Productivity in industrial-scale raceway ponds is generally lower than in small experimental reactors. In literature, algae biomass productivity performance claims range from 7 to 35 g afdw/m²/day [23, 87–89] with corresponding net photosynthetic efficiencies from under 1–4%. Among these, for studies involving techno-economic analyses, the baseline

productivity assumed was 20 g/m²/day, with an optimistic value of 25–30 g afdw/m²/day, and a conservative value of 15 g afdw/m²/day. In this study, which assumed that BG0011 is cultivated in current large commercial open ponds, an average productivity of 12.4 g afdw/m²/day (corresponding to a net photosynthetic efficiency of under 1%) was used. Similar growth rates were obtained by [148] when the algae was cultivated by air sparging and exposed to a lower light intensity of 122 μmol photons m⁻² s⁻¹ light and 13 h to 11 h light-dark cycle. Here, laboratory-scale BG0011 cell biomass growth rate is comparable to algae cell growth rates reported from other studies, however, in the case of BG0011, it also produces EPS. The average mass ratio between EPS and cell biomass is 0.778: 1 and also EPS production is cell-growth associated, so for this study it is assumed that in the commercial system, in addition to BG0011 cells, EPS would be concomitantly produced at 0.778 × 12.4 g afdw/m²/d = 9.6 g afdw/m²/day. The total algae biomass productivity used was 22 g/m²/d. Henceforth, the term “algae biomass” will include both BG0011 cells and EPS.

The scale of algae cultivation in literature for techno-economic analysis ranges from 200 to 700 ktonne afdw/year [22, 27, 72, 89]. In the present study, the scale of algae cultivation was determined based on a hypothetical 20 million gallons per year ethanol plant. The sugar required for such a plant would be 128 ktonnes afdw/year (assuming yield of around 0.42 g ethanol/g sugar, and 1.1 g sugar/g polysaccharide). Assuming this amount of sugar will be supplied in the form of EPS, the scale of the algae cultivation pond would be 293 ktonnes of algal biomass/year, which also includes BG0011 cell biomass. This scale falls into the range of values found in literature for TEA. To meet a production capacity of 293 ktonnes/year at algal biomass productivity of 22 g afdw/m²/day, land area required would be 3660 hectares (approximately 4 × 4 miles). For a sanity check, this cultivation area was compared to land area required to supplying corn grain for a 20 million gallon per year corn-ethanol plant. Based on annual corn grain yield of 7000 kg/ha with starch content of 72% [150], and assuming a conversion of 0.5 kg ethanol/kg of starch, land required would be 23,700 ha. In this case the total above ground biomass productivity of corn, including corn grain, stover and cobs, is 16,700 kg/ha/year [150] whereas for BG0011 it is anticipated to be 80,300 kg/ha/year.

The BG0011 cultivation cost was estimated based on vendor quotes, literature, or engineering estimates. The installed pond capital cost includes civil work, liner, piping, electrical, other pond costs (such as paddlewheels). In addition, pumps for pumping water from ponds to refinery and for refilling the pond and required land also incur significant capital costs. Plastic lined earthen ponds were chosen for its lower cost compared to concrete ponds. Larger pond sizes would enable economically viable algal biomass production [23]. Here, the installed capital cost was estimated based on “dollars/hectare” of growth ponds for simplicity. The installed pond cost was set to be 80,000 \$/ha. Literature value ranges from 46,000 \$/ha to more than 150,000 \$/ha (value adjusted for inflation) due to different liner scenarios (partial or full) and specific design (e.g. with or without equipment to minimize dead zones) [23, 86] which was not included here. A land cost of 3080 \$/acre [90] was used for low-value land. The operation cost for algae cultivation such as utilities, chemicals, labor, overheads, maintenance, insurance tax, etc. were estimated using engineering estimates [91]. BG0011 was assumed to be cultivated in seawater or brackish water. The only fertilizer used for BG 0011 cultivation is phosphorus since it uses dinitrogen in air as a nitrogen source, and seawater would supply rest of micronutrients. From laboratory experiments it was determined that the phosphorous requirement of BG001 is 8.9 mg/L [149], so the annual requirement of phosphorous will be 1186.7 tonnes. Here, triple superphosphate (Ca(H₂PO₄)₂ H₂O) which contains 24.6% P is used as phosphorous source with a price of 270 \$/tonne (Source: World Bank, 2017). The requirement of triple superphosphate is 4945 tonne/year.

The fixed capital investment was assumed to be borrowed at an interest rate of 10% for 20 years. The plant operates 24 h a day and 360 days annually. The prices were adjusted for Year 2017 using Chemical Engineering Plant Cost Index (CEPCI). These assumptions were also used for the analysis of subsequent biogas production, conversion and upgrading processes. The production cost was calculated as follows:

$$\begin{aligned} &\text{Unit production cost} \\ &= (\text{Annual capital charges} + \text{Total operating cost} \\ &\quad - \text{Coproduct credits}) / \text{Annual production} \end{aligned} \quad (1)$$

Here, the annual capital charges are calculated as follows:

$$\begin{aligned} &\text{Annual capital charges} \\ &= \text{Total capital cost} * \text{Interest rate} * (1 \\ &\quad + \text{Interest rate})^{\text{Loan period}} / \text{Interest rate}^{\text{Loan period}} - 1 \end{aligned} \quad (2)$$

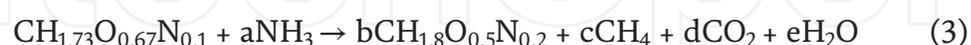
* Total capital cost = Total fixed cost + Working capital.

* Working capital is 10% of fixed capital.

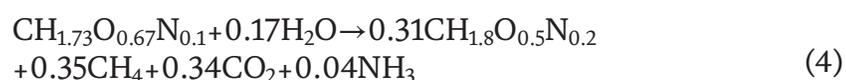
5.2 Anaerobic digestion

The anaerobic digester was designed to treat the un-dewatered whole algae culture from the pond. The energy-intensive steps like algae harvesting and dewatering are avoided in this process which is different from most research [8, 22, 23]. The product biogas was analyzed for economic performance in two different applications: biogas purification or electricity production through combined heat and power.

The first step in modeling mass flow rate of reactor outputs and determining energy requirements is to establish the stoichiometry of reactions. The stoichiometry of methane fermentation of algae biomass was developed based on the following assumptions: (1) microbial cells (cyanobacteria and bacteria) can be represented by the empirical formula $\text{CH}_{1.8}\text{O}_{0.5}\text{N}_{0.2}$ [151]; (2) EPS is pure polysaccharide represented by the empirical formula $\text{C}_6\text{H}_{10}\text{O}_5$; (3) algae biomass can be represented by an empirical formula containing the elements C, H, O and N in the mass ratios in which cells and EPS are produced that is 1:1.2; and (4) methane yield from laboratory assays corresponds to complete decomposition of substrate. The empirical formula for algae biomass was $\text{CH}_{1.73}\text{O}_{0.67}\text{N}_{0.1}$. The stoichiometry for methane formation is written as follows:



Methane yield from algae biomass was measured in the laboratory to be 300 ml at STP $(\text{g afdw})^{-1}$. This corresponds to 0.35 moles of methane (mole algae biomass) $^{-1}$, which is equal to value of 'c' in the above stoichiometry. The other stoichiometric coefficients can now be solved from elemental balances for C, H, O and N. The stoichiometry is



In the anaerobic digester it was assumed that 98% of the algae biomass is converted. Different scenarios (three anaerobic digester types) were investigated to evaluate the economic and energetic performance. A schematic of biorefinery scenarios are shown in **Figure 2**.

Case 1. Above ground mesophilic anaerobic digester. In Aspen, the influent to the reactor was 15 ktonne/h. The temperature was maintained at 37°C. It was operated at an HRT of 25 days.

Case 2. Above ground low-temperature anaerobic digester. Anaerobic digestion at low temperatures (LTAD) was applied to improve the energy balance. In this scenario the digester is operated in the psychrophilic range (12–20°C) [92–94]. However, with the same flow rate, the digester volume is larger to achieve a higher HRT for LTAD than mesophilic and thermophilic anaerobic digestion. Here, the temperature of LTAD is set to 20°C with an HRT of 50 days.

Case 3. Covered anaerobic lagoon. Covered anaerobic lagoon (CAL) does not require additional energy for the biogas production because no heating or mixing processes are involved. Besides, it is economical to construct and operate. The CAL in this research was 6 meters deep and covers an area of 1.5 hectares based on literature data [95]. The HRT was set to 50 days. The cost includes anaerobic lagoon excavation, cut and fill, lagoon liner, inlet and out structures, lagoon cover, ancillaries, pipework & installation, contingencies, design, engineering, etc. Operating costs including utility usage are minimal.

In all three cases above, the capital cost of anaerobic digester was estimated using vendor quotation or literature values. The operating cost was estimated by Aspen Process Economic Analyzer.

5.3 Biogas purification

Several biogas upgrading or purification methods are available such as high-pressure water scrubbing, membrane, pressure swing, gas permeation and chemical scrubbing. High pressure water scrubbing and chemical scrubbing (using amine solutions—MEA) are two of the most commonly used processes.

The MEA scrubbing method uses aqueous monoethanolamine (MEA) for acidic gas removal. The concentration of amine for acidic gas absorption is usually below 30% (by weight). The amine process has two main steps, absorption and stripping [96]. The detailed MEA scrubbing process is shown in **Figure 3**. Raw biogas goes

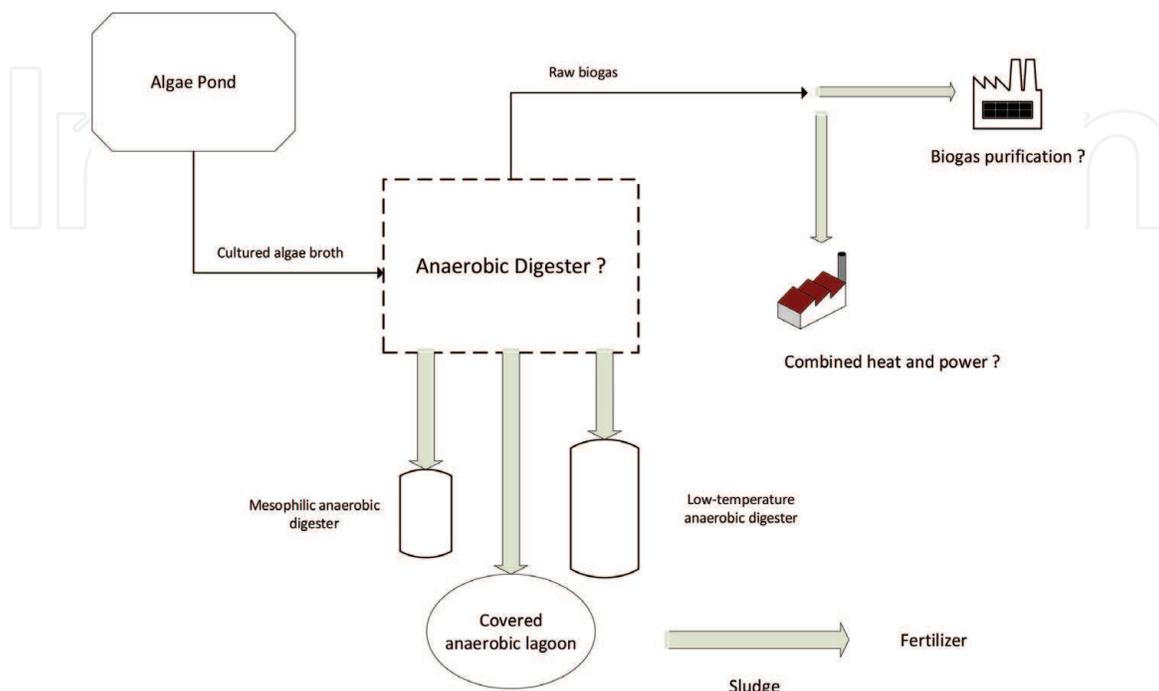


Figure 2. Schematic diagram showing biorefinery scenarios.

through a scrubbing column in which MEA is flowing counter-current to biogas. The CO₂-rich MEA is collected at the bottom of the scrubbing column and pumped into a stripping column to remove CO₂ and regenerate MEA by heating. Similar to MEA scrubbing, high pressure water scrubbing was also employed for biogas upgrading: biogas is fed to the bottom of scrubber after compressing it to 10 bar. At the top of scrubber, pressurized water is fed. CO₂-rich water is then transferred to a flash column with a lower pressure of 3 bar to release gases for feed recirculation and minimizing methane loss. Then the CO₂-rich water goes through a CO₂ desorption process from the water stream by air [97]. Both biogas purifying approaches

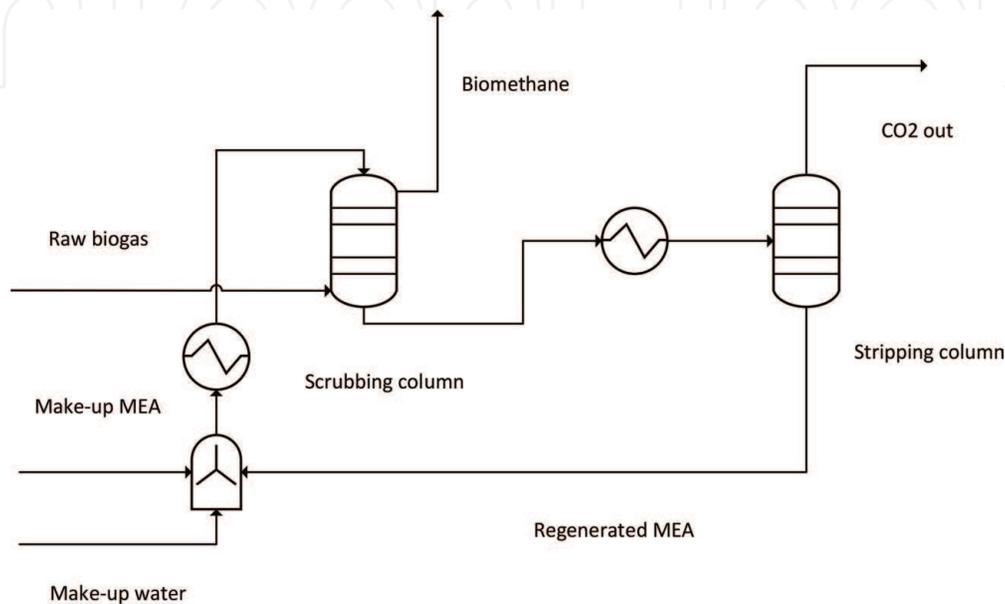


Figure 3.
 MEA scrubbing for biogas upgrading.

Specification	MEA	High pressure water scrubbing
Thermodynamic method	ELECNRTL	PSRK
Scrubbing column	RadFrac, 15 stages, pressure: 1.2 bar	RadFrac, 10 stages, pressure: 10 bar
Stripping column	RadFrac, 15 stages, pressure: 8 bar	RadFrac, 10 stages, pressure: 1 bar
Make up chemicals	Water: 150 kmol/h MAE: 750 kmol/h	Water: 11500 kmol/h
Solvent recycle rate	MEA: 0.99	Water: 0.95
Methane loss	1%	0.3%
Product methane purity	95 wt%	99.2 wt%
Capacity (raw biogas flow rate)	948.5 kmol/h	948.5 kmol/h
Capital cost (million \$)	8.2	12
Operating cost (million \$/year)	20	4.6
Utility cost (million \$/year)	17	2
Purification cost (\$/kg of methane)	0.3	0.09

Table 3.
 Technical and economic aspects of the biogas purifying systems in ASPEN V 8.8.

were simulated in ASPEN Plus to determine the economics of each approach. The technical specification details are shown in **Table 3**. The table shows high pressure water scrubbing to be a more economical alternative and was chosen for the integrated process.

5.4 Power generation from biogas

While the raw biogas can be purified to obtain biomethane, another option is to use the raw biogas to produce heat and power. Steam and electricity can be generated by burning the raw biogas through a combined heat and power (CHP) system. For reference, the CHP system uses General Electric Jenbacher JGS 420 system which is a 1425 kw generator. The total capital cost is \$ 1,150,000 (including installation, tax, etc. 2007), which is 807 \$/kw. The working capital is 10% of the total capital. The operating cost includes direct operating cost such as operating labor, supervised labor, maintenance and repairs, as well as indirect operating cost such as overhead, taxed, insurances. It is assumed that 40% biogas energy is for electricity, 50% for steam, 10% loss.

5.5 Techno-economic analysis of integrated system

5.5.1 Biomass cultivation economics

The BG0011 cultivation economics analysis details are shown in **Table 4**. In the literature algae production costs range from 150 to 6000 \$/tonne [19, 22, 27, 72, 89, 142], however, the studies vary from assumptions (production scale, chemical prices, plant life, etc.) to differences in technical specification (photobioreactor design, algal species, etc.). Some of the estimates also account costs for dewatering of algae [22, 27]. Thus, it is difficult to make a direct comparison between different studies. Besides, specific assumptions in each study could be based on different social-economic conditions, which makes comparisons more complicated [98].

Parameters	Values
Production scale	
BG0011 cells production (ktonne/year)	165
BG0011 EPS production (ktonne/year)	128
Total algae biomass production (ktonne/year)	293
Capital cost (including fixed, installed and working capital)	
Pond (million \$)	308
Land (million \$)	26.6
Pump (million \$)	7.85
Total capital cost (million \$)	342.45
Annual capital charges (million \$/year)	40.22
Operating cost	
Chemicals (P fertilizer: Ca (H ₂ PO ₄) ₂ H ₂ O) (million \$/year)	1.3
Other operating cost (including utilities, maintenance and repairs, labor etc.) (million \$/year)	3.26
Total operating cost (million \$/year)	4.56
BG0011 algae biomass production cost (\$/tonne)	153

Table 4.
Algae cultivation economics.

5.5.2 Economics of anaerobic digestion

Details of the production cost of renewable natural gas for the three anaerobic digestion scenarios are shown in **Table 5**. Case 2 contains two scenarios: The size of anaerobic digester in Case 2(a) is two times of that in Case 1. This is because the hydraulic retention time is longer under lower temperature, the volume of digester needs to be larger to keep the same production scale (the inflow rate). The size of anaerobic digester in Case 2(b) is the same as Case 1. Keeping the digester volume same as Case 1, because the temperature is lower, the productivity will be lower as well. Thus Case 2(b) has a lower production scale compared to other cases. The effect of temperature was incorporated by using the empirical relationship that for every 10°C rise in temperature the degradation rate is doubled. As the difference between the temperature for Case 1 and Case 2 is 17°C, it is expected that in Case 1, the digester has a processing capacity twice as much as that of the digester in Case 2b. The main contributor to the production cost of biogas is the biomass cost. Considering a carbon credit of 10 \$/tonne of CO₂, the production cost of biogas only drops 0.5 \$/MMBtu. The results are comparable to Zamalloa et al.'s [8] research (the only paper focusing on the economics of renewable energy through AD, to our best knowledge): 32.2–61.5 \$/MMBtu with the algae biomass cost of 115.4–166.4 \$/tonne (0.087–0.17 euro/kwh with an algae biomass cost of 86–124 euro/tonne, 2011). The methane yield is 0.012 MMBtu/kg of VS biomass, which is in close agreement to our experimental result 0.0124 MMBtu/kg of VS biomass.

Item	Case 1 (mesophilic anaerobic digester)	Case 2(a) (low- temperature anaerobic digester)	Case 2(b) (low- temperature anaerobic digester)	Case 3 (covered anaerobic lagoon)
Biogas production scale (10 ⁶ MMBtu/year)	3.7	3.7	1.85	3.7
Fixed capital cost of anaerobic digester (million \$)	67.12	102	67.12	7.5
Capital cost except anaerobic digester (million \$)	16.3	16.3	12.3	16.4 (including land: \$11400)
Annual capital charges (million \$/year)	9.8	13.9	9.3	2.8
Total raw materials (algae biomass) cost (million \$/year)	44.8	44.8	44.8	44.8
Other operating (labor, utility, indirect, etc.) cost (million \$/year)	25.8	7.1	4.4	7.1
Utility cost (million \$/ year)	21	2.3	1.4	2.3
Renewable natural gas production cost (\$/ MMBtu)	21.7	17.8	31.6	14.8

Table 5.
 Process and economic assessment for purified biogas production through anaerobic digestion of *Cyanothece* BG0011 biomass.

Item	Value
Electricity capacity (million kwh/year)	435
Total capital cost of the CHP system (million \$) (including fix capital cost and 10% working capital)	52.4
Capital charges (million \$/year)	6.2
Steam credits (million \$/year)	3.7
Raw biogas cost (million \$/year)	47.7
Other operating cost (million \$/year)	9.5
Electricity production cost (\$/kwh)	0.13

Table 6.
The economics of biogas—electricity and steam system.

5.5.3 Electricity production cost

On an energy potential basis, 40% of total methane produced per year could support a 50 MW power plant. Current residential electricity price is around 12 cents/kwh, while industrial price is around 7 cents/kwh. As shown in **Table 6**, the electricity production cost from biogas is 13 cents/kwh. Renewable energy technologies are usually more expensive than fossil fuel technologies. The reasons could be environmental costs associated with fossil fuels that are not paid by the rate payers, mechanical difficulty in bioenergy production, start-up issues and so on. European countries such as Germany and UK governments subsidize the production of renewable energy by introducing feed-in tariffs. These tariffs may be important to make bioenergy industry profitable.

6. Cost minimization approaches

6.1 Nutrient recycling and biogas upgrading

Nutrient (mostly nitrogen and phosphorous) recycling such as utilizing the digestate or wastewater for microalgae cultivation was highlighted in various studies [59–63, 104–107, 126, 128, 138, 139]. Recycling the effluent from the anaerobic digester for algae cultivation could mitigate the costs associated with supplying nutrient for algal biomass growth and effluent treatment. Erkelens et al. [59] validated that microalgae *Tetraselmis* sp. could utilize its digested effluent as a growth medium and thus form a closed loop system. Also, Prajapati et al. [60] showed that algal liquid digestate have good potential to be utilized as nutrient supplement (30% concentration) in rural sector wastewater for biomass cultivation. The biomass production level is closer to the case in which conventional medium is used. Although there are still technological obstacles when growing microalgae on digestate such as low growth rate due to poor nutrient ratios, shading, ammonia inhibition and bacteria growth, the performance of the nutrient recycling process could be further developed by scale up/optimizing strategies such as controlling inoculum and substrate concentrations, bacteria growth as well as harvesting strategies [59, 61, 64, 132].

One option to increase algae biomass productivity and its concentration in the culture is to enrich the air with CO₂. It has been shown that enriching the air with 1% CO₂ increases cell concentration to 3.46 g afdw/L and EPS concentration to 2.91 g afdw/L, giving an algae biomass concentration of at least 6.37 g afdw/L

[149], which is 1.33 times more than that used in the case study above. The increased productivity of algae biomass will reduce further the cost for biomass production. The CO₂ released from the biogas upgrading process or waste gases from biogas combustion containing CO₂ could be recycled to the algae growth ponds for enriching the air. The economic analysis for this scenario was also performed assuming algae biomass concentration is 1.33 times the previous value of 293 ktonne/year. The estimated production cost for *Cyanothece BG 0011* algae biomass is 121.6 \$/tonne. This was calculated by accounting for the following additional costs: (1) capital cost associated with pipes and pumps to take CO₂ from biogas purification system or biogas combustion output to the pond and (2) operating costs resulting from more nutrient addition to maintain higher cell density and power consumption of compressing CO₂ for sparging [152]. Only biogas production from covered anaerobic lagoon as in Case 3 was considered here. Algae production cost was lowered by 20%. The estimated cost of renewable natural gas is now reduced to 12.16 \$/MMBtu and the electricity production cost from biogas is only 10.98 cents/kwh.

Upgrading biogas by fixation of the CO₂ in biogas via photosynthesis by microalgae has been investigated with respect to CO₂ removal capability, biomass productivity and O₂ desorption minimization [16, 63–67]. Toledo-Cervantes et al. [16] optimized the biogas upgrading process by studying the influence of the recycling liquid to biogas ratio. The biomethane produced met specification for injection into natural gas grids. However, this technique requires closed photobioreactors. Hydrogen sulfide (H₂S) is another contaminant to be removed from the biogas. Hydrogen sulfide removal was realized by the oxidation of H₂S to sulfate by sulfur oxidizing bacteria that used the oxygen produced photosynthetically in situ. In this case, the algae-bacteria symbiosis was employed in the photobioreactors [67]. Nutrient recycling and biogas upgrading provides not only the opportunity for AD of microalgal biomass to be cost-effective, but also the potential to reduce the environmental impacts.

To move industrial application of biogas production from microalgal biomass towards commercialization, additional assessment is required regarding large scale operations. These include (1) strain robustness, outdoor productivity, location and seasonal effects, yield from real production systems, and harvesting strategy for algae cultivation (2) for biomass to biogas conversion processes, the conceptual process design needs to take the following factors into consideration: costs associated with digester heating, land, and infrastructure as well as operational parameters such as maintaining pH, temperature, mixing, power consumption, and production of coproducts like fertilizer.

6.2 Dynamic growth models

The uncertainty of large-scale algae cultivation is still a challenge which prevents commercialization; process modeling could provide useful information about the performance of microalgae cultivation systems by estimation and optimization of microalgae productivity under different conditions [103]. A growth kinetic model is critical in a process model simulating microalgae cultivation which has a direct impact on downstream conversion processing systems [135] Lee et al. [31] classified the existing kinetic models into three groups: a single limiting substrate (phosphorus, or dissolved CO₂ concentration), a physical limiting factor (light intensity or temperature), and multiple factors (e.g. both substrate and light). Based on their study, there was a tradeoff between the accuracy of the model representation and real-world usability. A future modeling framework should consider along with limiting nutrients, integration of light and temperature, and incorporation of species diversity.

6.3 Biorefinery concepts

AD can be integrated to biorefineries which produce high value products from algae such as chemicals for cosmetics, nutraceuticals and pharmaceuticals. This requires diversified business strategies which benchmark the market potential for the total raw materials and alternative products. In the economic perspective, three approaches could be possible for the development of microalgae AD: (1) implementing AD for biogasification of cell debris or waste streams in microalgal based processes such as biodiesel/bioethanol/high-value bioproducts (e.g. PHA)/fuel cell/hydrothermal liquefaction/hydrogen production [68, 120]; (2) investigation of high-value products from intermediate metabolites produced during AD such as carboxylic acids [37]; (3) electricity production from microalgae derived biogas. In previous sections, the cost of electricity from microalgae derived biogas is comparable with market value while cost of the renewable natural gas from microalgae is much higher than the current market value of natural gas.

7. Conclusion and future work

This chapter reviewed the literature on TEA of biogas production from algae. The key drivers to the overall production cost were identified and possible process improvements to reduce cost were discussed. The need for harmonization of resource, life cycle and techno-economic assessments in the methodology of TEA was highlighted. Modeling efforts, based on well-informed, rigorous engineering-based process models, should be integrated on a baseline framework such that different process technologies, subprocesses and alternative pathways can be directly compared at a system level. TEA model improvements include strategic planning and using reliable input data from simple mass balance calculations to geographically and seasonally specific assessments, as well as risk analysis for large-scale productivity. Nutrient recycling process has the potential to reduce both cost and environmental burdens.

The cultivation of microalgae BG0011 and its economic feasibility as an energy source through anaerobic digestion was evaluated through a techno-economic analysis. The main contribution to the biogas cost is the biomass production cost. The best-case estimate was a biomethane production cost of 14.8 \$/MMBtu using covered anaerobic lagoon and high-pressure water scrubbing purification. The cost of electricity production from biogas was estimated to be 13 cents/kwh. Even though these costs are higher than commercial prices in the United States, these are much lower than those costs with production of liquid fuels like ethanol or biodiesel from algae.

Improved algal biomass productivities could be essential for lowering the cost of algae-derived biogas. This could be achieved by recycling the CO₂ released during biogas upgrading or combustion for algae cultivation. Algal biogas economics could be further improved by marketing the digester sludge as a soil-amendment product, considering that nitrogen in the sludge was fixed from atmospheric dinitrogen.

Acknowledgements

The authors gratefully acknowledge funding provided by Office of Energy, Florida Department of Agricultural and Consumer Services under contract number 92420 for this project.

Conflict of interest

The authors declare that there are no potential financial or other interests that could be perceived to influence the outcomes of the research.

IntechOpen

Author details

Na Wu^{1*}, Cesar M. Moreira^{1,2}, Yingxiu Zhang^{1,3}, Nguyet Doan^{1,4}, Shunchang Yang¹, Edward J. Philips⁵, Spyros A. Svoronos⁶ and Pratap C. Pullammanappallil¹

1 Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, USA

2 Faculty of Mechanical Engineering and Production Sciences, ESPOL Polytechnic University, Guayaquil, Ecuador

3 School of Environmental Science and Engineering, Tianjin University/China-Australia Centre for Sustainable Urban Development, Tianjin, China

4 An Giang University, An Giang, Vietnam

5 Department of Fisheries and Aquatic Science, University of Florida, Gainesville, FL, USA

6 Department of Chemical Engineering, University of Florida, Gainesville, FL, USA

*Address all correspondence to: wuna8703@ufl.edu

IntechOpen

© 2019 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. 

References

- [1] Wijffels RH, Barbosa MJ. An outlook on microalgal biofuels. *Science*. 2010;**329**(5993):796-799
- [2] Borowitzka MA. High-value products from microalgae—Their development and commercialisation. *Journal of Applied Phycology*. 2013;**25**(3):743-756
- [3] Brennan L, Owende P. Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews*. 2010;**14**(2):557-577
- [4] Su Y, Song K, Zhang P, Su Y, Cheng J, Chen X. Progress of microalgal biofuel's commercialization. *Renewable and Sustainable Energy Reviews*. 2017;**74**:402-411
- [5] Rahimpour MR, Biniiaz P, Makarem MA. Integration of microalgae into an existing biofuel industry. In: *Bioenergy Systems for the Future*. Sawston, Cambridge: Woodhead Publishing. 2017. pp. 481-519
- [6] Ward AJ, Lewis DM, Green FB. Anaerobic digestion of algae biomass: A review. *Algal Research*. 2014;**5**:204-214
- [7] Hise AM, Characklis GW, Kern J, Gerlach R, Viamajala S, Gardner RD, et al. Evaluating the relative impacts of operational and financial factors on the competitiveness of an algal biofuel production facility. *Bioresource Technology*. 2016;**220**:271-281
- [8] Zamalloa C, Vulsteke E, Albrecht J, Verstraete W. The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. *Bioresource Technology*. 2011;**102**(2):1149-1158
- [9] Silva C, Soliman E, Cameron G, Fabiano LA, Seider WD, Dunlop EH, et al. Commercial-scale biodiesel production from algae. *Industrial & Engineering Chemistry Research*. 2013;**53**(13):5311-5324
- [10] Moreno-Garcia L, Adjallé K, Barnabé S, Raghavan GS. Microalgae biomass production for a biorefinery system: Recent advances and the way towards sustainability. *Renewable and Sustainable Energy Reviews*. 2017;**76**:493-506
- [11] Milano J, Ong HC, Masjuki HH, Chong WT, Lam MK, Loh PK, et al. Microalgae biofuels as an alternative to fossil fuel for power generation. *Renewable and Sustainable Energy Reviews*. 2016;**58**:180-197
- [12] Garrido-Cardenas JA, Manzano-Agugliaro F, Acien-Fernandez FG, Molina-Grima E. Microalgae research worldwide. *Algal Research*. 2018;**35**:50-60
- [13] Jankowska E, Sahu AK, Oleskowicz-Popiel P. Biogas from microalgae: Review on microalgae's cultivation, harvesting and pretreatment for anaerobic digestion. *Renewable and Sustainable Energy Reviews*. 2017;**75**:692-709
- [14] Montingelli ME, Tedesco S, Olabi AG. Biogas production from algal biomass: A review. *Renewable and Sustainable Energy Reviews*. 2015;**43**:961-972
- [15] Raheem A, Prinsen P, Vuppaladadiyam AK, Zhao M, Luque R. A review on sustainable microalgae based biofuel and bioenergy production: Recent developments. *Journal of Cleaner Production*. 2018;**181**:42-59
- [16] Toledo-Cervantes A, Serejo ML, Blanco S, Pérez R, Lebrero R, Muñoz R. Photosynthetic biogas upgrading to bio-methane: Boosting nutrient recovery via biomass productivity control. *Algal Research*. 2016;**17**:46-52

- [17] Dębowski M, Zieliński M, Grala A, Dudek M. Algae biomass as an alternative substrate in biogas production technologies. *Renewable and Sustainable Energy Reviews*. 2013;**27**:596-604
- [18] Sialve B, Bernet N, Bernard O. Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable. *Biotechnology Advances*. 2009;**27**(4):409-416
- [19] Ribeiro LA, da Silva PP, Mata TM, Martins AA. Prospects of using microalgae for biofuels production: Results of a Delphi study. *Renewable Energy*. 2015;**75**:799-804
- [20] Suganya T, Varman M, Masjuki HH, Renganathan S. Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: A biorefinery approach. *Renewable and Sustainable Energy Reviews*. 2016;**55**:909-941
- [21] Tredici MR, Rodolfi L, Biondi N, Bassi N, Sampietro G. Techno-economic analysis of microalgal biomass production in a 1-ha Green Wall Panel (GWP[®]) plant. *Algal Research*. 2016;**19**:253-263
- [22] Hoffman J, Pate RC, Drennen T, Quinn JC. Techno-economic assessment of open microalgae production systems. *Algal Research*. 2017;**23**:51-57
- [23] Davis R, Markham J, Kinchin C, Grundl N, Tan EC, Humbird D. *Process Design and Economics for the Production of Algal Biomass: Algal Biomass Production in Open Pond Systems and Processing Through Dewatering for Downstream Conversion*. Golden, CO (United States): National Renewable Energy Lab (NREL); 2016
- [24] Slade R, Bauen A. Micro-algae cultivation for biofuels: Cost, energy balance, environmental impacts and future prospects. *Biomass and Bioenergy*. 2013;**53**:29-38
- [25] Richardson JW, Johnson MD, Zhang X, Zemke P, Chen W, Hu Q. A financial assessment of two alternative cultivation systems and their contributions to algae biofuel economic viability. *Algal Research*. 2014;**4**:96-104
- [26] Acién FG, Fernández JM, Magán JJ, Molina E. Production cost of a real microalgae production plant and strategies to reduce it. *Biotechnology Advances*. 2012;**30**(6):1344-1353
- [27] Norsker NH, Barbosa MJ, Vermuë MH, Wijffels RH. Microalgal production—A close look at the economics. *Biotechnology Advances*. 2011;**29**(1):24-27
- [28] Rogers JN, Rosenberg JN, Guzman BJ, Oh VH, Mimbela LE, Ghassemi A, et al. A critical analysis of paddlewheel-driven raceway ponds for algal biofuel production at commercial scales. *Algal Research*. 2014;**4**:76-88
- [29] Quinn JC, Davis R. The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling. *Bioresource Technology*. 2015;**184**:444-452
- [30] Moody JW, McGinty CM, Quinn JC. Global evaluation of biofuel potential from microalgae. *Proceedings of the National Academy of Sciences*. 2014;**21**:201321652
- [31] Lee E, Jalalizadeh M, Zhang Q. Growth kinetic models for microalgae cultivation: A review. *Algal Research*. 2015;**12**:497-512
- [32] Barros AI, Gonçalves AL, Simões M, Pires JC. Harvesting techniques applied to microalgae: A review. *Renewable and Sustainable Energy Reviews*. 2015;**41**:1489-1500

- [33] Laamanen CA, Ross GM, Scott JA. Flotation harvesting of microalgae. *Renewable and Sustainable Energy Reviews*. 2016;**58**:75-86
- [34] Fasaei F, Bitter JH, Slegers PM, van Boxtel AJ. Techno-economic evaluation of microalgae harvesting and dewatering systems. *Algal Research*. 2018;**31**:347-362
- [35] Singh G, Patidar SK. Microalgae harvesting techniques: A review. *Journal of Environmental Management*. 2018;**217**:499-508
- [36] Gerardo ML, Van Den Hende S, Vervaeren H, Coward T, Skill SC. Harvesting of microalgae within a biorefinery approach: A review of the developments and case studies from pilot-plants. *Algal Research*. 2015;**1**(11):248-262
- [37] Gonzalez-Fernandez C, Sialve B, Molinuevo-Salces B. Anaerobic digestion of microalgal biomass: Challenges, opportunities and research needs. *Bioresource Technology*. 2015;**198**:896-906
- [38] Wirth R, Lakatos G, Böjti T, Maróti G, Bagi Z, Rákhely G, et al. Anaerobic gaseous biofuel production using microalgal biomass—A review. *Anaerobe*. 2018;**52**:1-8
- [39] Jones CS, Mayfield SP. Algae biofuels: Versatility for the future of bioenergy. *Current Opinion in Biotechnology*. 2012;**23**(3):346-351
- [40] Passos F, Carretero J, Ferrer I. Comparing pretreatment methods for improving microalgae anaerobic digestion: Thermal, hydrothermal, microwave and ultrasound. *Chemical Engineering Journal*. 2015;**279**:667-672
- [41] Klassen V, Blifernez-Klassen O, Wobbe L, Schlueter A, Kruse O, Mussgnug JH. Efficiency and biotechnological aspects of biogas production from microalgal substrates. *Journal of Biotechnology*. 2016;**234**:7-26
- [42] Kendir E, Ugurlu A. A comprehensive review on pretreatment of microalgae for biogas production. *International Journal of Energy Research*. 2018;**42**:3711-3731
- [43] Córdova O, Santis J, Ruiz-Fillipi G, Zuñiga ME, Chamy R, Fierro FG. Microalgae digestive pretreatment for increasing biogas production. *Renewable and Sustainable Energy Reviews*. 2018;**82**:2806-2813
- [44] Kinnunen HV, Koskinen PE, Rintala J. Mesophilic and thermophilic anaerobic laboratory-scale digestion of *Nannochloropsis* microalga residues. *Bioresource Technology*. 2014;**155**:314-322
- [45] Zamalloa C, Boon N, Verstraete W. Anaerobic digestibility of *Scenedesmus obliquus* and *Phaeodactylum tricornutum* under mesophilic and thermophilic conditions. *Applied Energy*. 2012;**92**:733-738
- [46] Carlini M, Mosconi EM, Castellucci S, Villarini M, Colantoni A. An economical evaluation of anaerobic digestion plants fed with organic agro-industrial waste. *Energies*. 2017;**10**(8):1165
- [47] Saratale RG, Kumar G, Banu R, Xia A, Periyasamy S, Saratale GD. A critical review on anaerobic digestion of microalgae and macroalgae and co-digestion of biomass for enhanced methane generation. *Bioresource Technology*. 2018;**9**:319-332
- [48] Ishika T, Moheimani NR, Bahri PA. Sustainable saline microalgae co-cultivation for biofuel production: A critical review. *Renewable and Sustainable Energy Reviews*. 2017;**78**:356-368
- [49] Aspe E, Marti MC, Roeckel M. Anaerobic treatment of fishery

wastewater using a marine sediment inoculum. *Water Research*. 1997;**31**(9):2147-2160

[50] Cirne DG, Paloumet X, Björnsson L, Alves MM, Mattiasson B. Anaerobic digestion of lipid-rich waste—Effects of lipid concentration. *Renewable Energy*. 2007;**32**(6):965-975

[51] Zhao B, Ma J, Zhao Q, Laurens L, Jarvis E, Chen S, et al. Efficient anaerobic digestion of whole microalgae and lipid-extracted microalgae residues for methane energy production. *Bioresource Technology*. 2014;**161**:423-430

[52] Mahdy A, Mendez L, Ballesteros M, González-Fernández C. Enhanced methane production of *Chlorella vulgaris* and *Chlamydomonas reinhardtii* by hydrolytic enzymes addition. *Energy Conversion and Management*. 2014;**85**:551-557

[53] Schwede S, Rehman ZU, Gerber M, Theiss C, Span R. Effects of thermal pretreatment on anaerobic digestion of *Nannochloropsis salina* biomass. *Bioresource Technology*. 2013;**143**:505-511

[54] Lu D, Zhang XJ. Biogas production from anaerobic codigestion of microalgae and septic sludge. *Journal of Environmental Engineering*. 2016;**142**(10):04016049

[55] He S, Fan X, Katukuri NR, Yuan X, Wang F, Guo RB. Enhanced methane production from microalgal biomass by anaerobic bio-pretreatment. *Bioresource Technology*. 2016;**204**:145-151

[56] Mahdy A, Mendez L, Tomás-Pejó E, del Mar Morales M, Ballesteros M, González-Fernández C. Influence of enzymatic hydrolysis on the biochemical methane potential of *Chlorella vulgaris* and *Scenedesmus* sp. *Journal of Chemical Technology & Biotechnology*. 2016;**91**(5):1299-1305

[57] González-Fernández C, Sialve B, Bernet N, Steyer JP. Thermal pretreatment to improve methane production of *Scenedesmus* biomass. *Biomass and Bioenergy*. 2012;**40**:105-111

[58] Frigon JC, Matteau-Lebrun F, Abdou RH, McGinn PJ, O'Leary SJ, Guiot SR. Screening microalgae strains for their productivity in methane following anaerobic digestion. *Applied Energy*. 2013;**108**:100-107

[59] Erkelens M, Ward AJ, Ball AS, Lewis DM. Microalgae digestate effluent as a growth medium for *Tetraselmis* sp. in the production of biofuels. *Bioresource Technology*. 2014;**167**:81-86

[60] Prajapati SK, Kumar P, Malik A, Vijay VK. Bioconversion of algae to methane and subsequent utilization of digestate for algae cultivation: A closed loop bioenergy generation process. *Bioresource Technology*. 2014;**158**:174-180

[61] Cai T, Park SY, Racharaks R, Li Y. Cultivation of *Nannochloropsis salina* using anaerobic digestion effluent as a nutrient source for biofuel production. *Applied Energy*. 2013;**108**:486-492

[62] García D, Posadas E, Grajeda C, Blanco S, Martínez-Páramo S, Ación G, et al. Comparative evaluation of piggery wastewater treatment in algal-bacterial photobioreactors under indoor and outdoor conditions. *Bioresource Technology*. 2017;**245**:483-490

[63] Prandini JM, da Silva ML, Mezzari MP, Pirolli M, Michelon W, Soares HM. Enhancement of nutrient removal from swine wastewater digestate coupled to biogas purification by microalgae *Scenedesmus* spp. *Bioresource Technology*. 2016;**202**:67-75

[64] Uggetti E, Sialve B, Latrille E, Steyer JP. Anaerobic digestate as substrate for microalgae culture: The role of ammonium concentration on the

microalgae productivity. *Bioresource Technology*. 2014;**152**:437-443

[65] Converti A, Oliveira RP, Torres BR, Lodi A, Zilli M. Biogas production and valorization by means of a two-step biological process. *Bioresource Technology*. 2009;**100**(23):5771-5776

[66] Posadas E, Serejo ML, Blanco S, Pérez R, García-Encina PA, Muñoz R. Minimization of biomethane oxygen concentration during biogas upgrading in algal-bacterial photobioreactors. *Algal Research*. 2015;**12**:221-229

[67] Bahr M, Díaz I, Dominguez A, González Sánchez A, Muñoz R. Microalgal-biotechnology as a platform for an integral biogas upgrading and nutrient removal from anaerobic effluents. *Environmental Science & Technology*. 2013;**48**(1):573-581

[68] Chew KW, Yap JY, Show PL, Suan NH, Juan JC, Ling TC, et al. Microalgae biorefinery: High value products perspectives. *Bioresource Technology*. 2017;**229**:53-62

[69] Manganaro JL, Lawal A, Goodall B. Techno-economics of microalgae production and conversion to refinery-ready oil with co-product credits. *Biofuels, Bioproducts and Biorefining*. 2015;**9**(6):760-777

[70] Thomassen G, Vila UE, Van Dael M, Lemmens B, Van Passel S. A techno-economic assessment of an algal-based biorefinery. *Clean Technologies and Environmental Policy*. 2016;**18**(6):1849-1862

[71] Dong T, Knoshaug EP, Davis R, Laurens LM, Van Wychen S, Pienkos PT, et al. Combined algal processing: A novel integrated biorefinery process to produce algal biofuels and bioproducts. *Algal Research*. 2016;**19**:316-323

[72] Dutta S, Neto F, Coelho MC. Microalgae biofuels: A comparative study on techno-economic analysis &

life-cycle assessment. *Algal Research*. 2016;**20**:44-52

[73] Chia SR, Chew KW, Show PL, Yap YJ, Ong HC, Ling TC, et al. Analysis of economic and environmental aspects of microalgae biorefinery for biofuels production: A review. *Biotechnology Journal*. 2018;**13**:1700618

[74] Milledge JJ, Heaven S. Energy balance of biogas production from microalgae: Effect of harvesting method, multiple raceways, scale of plant and combined heat and power generation. *Journal of Marine Science and Engineering*. 2017;**5**(1):9

[75] Murphy JD, Drosig B, Allen E, Jerney J, Xia A, Herrmann C. A perspective on algal biogas. IEA Bioenergy. [Internet]. 2015. Available from: http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical%20Brochures/AD_of_Algae_ebook_end.pdf [Accessed: 2018-12-05]

[76] Singh J, Gu S. Commercialization potential of microalgae for biofuels production. *Renewable and Sustainable Energy Reviews*. 2010;**14**(9):2596-2610

[77] Collet P, Hélias A, Lardon L, Ras M, Goy RA, Steyer JP. Life-cycle assessment of microalgae culture coupled to biogas production. *Bioresource Technology*. 2011;**102**(1):207-214

[78] Thomassen G, Van Dael M, Lemmens B, Van Passel S. A review of the sustainability of algal-based biorefineries: Towards an integrated assessment framework. *Renewable and Sustainable Energy Reviews*. 2017;**68**:876-887

[79] Gnansounou E, Dauriat A. Technoeconomic analysis of lignocellulosic ethanol. In *Biofuels*. Cambridge, Massachusetts: Academic Press. 2011:123-148

- [80] Ji Q, Zhang HY, Geng JB. What drives natural gas prices in the United States? A directed acyclic graph approach. *Energy Economics*. 2018;**69**:79-88
- [81] Kern JD, Hise AM, Characklis GW, Gerlach R, Viamajala S, Gardner RD. Using life cycle assessment and techno-economic analysis in a real options framework to inform the design of algal biofuel production facilities. *Bioresource Technology*. 2017;**225**:418-428
- [82] Philips EJ, Zeman C, Hansen P. Growth, photosynthesis, nitrogen fixation and carbohydrate production by a unicellular cyanobacterium, *Synechococcus* sp. (Cyanophyta). *Journal of Applied Phycology*. 1989;**1**(2):137-145
- [83] Jorquera O, Kiperstok A, Sales EA, Embirucu M, Ghirardi ML. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. *Bioresource Technology*. 2010;**101**(4):1406-1413
- [84] Raes EJ, Isdepsky A, Muylaert K, Borowitzka MA, Moheimani NR. Comparison of growth of *Tetraselmis* in a tubular photobioreactor (Biocoil) and a raceway pond. *Journal of Applied Phycology*. 2014;**26**(1):247-255
- [85] Narala RR, Garg S, Sharma KK, Thomas-Hall SR, Deme M, Li Y, et al. Comparison of microalgae cultivation in photobioreactor, open raceway pond, and a two-stage hybrid system. *Frontiers in Energy Research*. 2016;**4**:29
- [86] Chisti Y. Large-scale production of algal biomass: Raceway ponds. In: *Algae Biotechnology*. Champions: Springer; 2016. pp. 21-40
- [87] Borowitzka MA, Moheimani NR. Sustainable biofuels from algae. *Mitigation and Adaptation Strategies for Global Change*. 2013;**18**(1):13-25
- [88] Pienkos PT, Darzins AL. The promise and challenges of microalgal-derived biofuels. *Biofuels, Bioproducts and Biorefining: Innovation for a Sustainable Economy*. 2009;**3**(4):431-440
- [89] Jones SB, Zhu Y, Anderson DB, Hallen RT, Elliott DC, Schmidt AJ, et al. *Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading*. Richland, WA (United States): Pacific Northwest National Lab (PNNL); 2014
- [90] United States Department of Agriculture (USDA). National Agricultural Statistics Service. *Land Values 2017 Summary* [Internet]. 2017. Available from: <https://www.usda.gov/nass/PUBS/TODAYRPT/land0817.pdf> [Accessed: 2018-12-05]
- [91] Brown RC, Brown TR. *Biorenewable Resources: Engineering New Products from Agriculture*. Ames, IA: Blackwell Publishing Co.; 2003
- [92] McKeown RM, Hughes D, Collins G, Mahony T, O'Flaherty V. Low-temperature anaerobic digestion for wastewater treatment. *Current Opinion in Biotechnology*. 2012;**23**(3):444-451
- [93] Bialek K, Cysneiros D, O'Flaherty V. Low-temperature (10 C) anaerobic digestion of dilute dairy wastewater in an EGSB bioreactor: Microbial community structure, population dynamics, and kinetics of methanogenic populations. *Archaea*. 2013;**2013**:1-10
- [94] Gunnigle E, Siggins A, Botting CH, Fuszard M, O'Flaherty V, Abram F. Low-temperature anaerobic digestion is associated with differential methanogenic protein expression. *FEMS Microbiology Letters*. 2015;**362**(10):fzv059

- [95] United States Environmental Protection Agency (EPA). Wastewater Technology Fact Sheet EPA Anaerobic Lagoons [Internet]. 2002. Available from: <https://nepis.epa.gov/Exe/ZyPDF.cgi/P100IL5S.PDF?Dockey=P100IL5S.PDF> [Accessed: 2018-12-05]
- [96] Hassan SN, Douglas PL, Croiset E. Techno-economic study of CO₂ capture from an existing cement plant using MEA scrubbing. *International Journal of Green Energy*. 2007;**4**(2):197-220
- [97] Cozma P, Wukovits W, Mămăligă I, Friedl A, Gavrilescu M. Analysis and modelling of the solubility of biogas components in water for physical absorption processes. *Environmental Engineering & Management Journal (EEMJ)*. 2013;**12**(1):1
- [98] Gubicza K, Nieves IU, Sagues WJ, Barta Z, Shanmugam KT, Ingram LO. Techno-economic analysis of ethanol production from sugarcane bagasse using a liquefaction plus simultaneous saccharification and co-fermentation process. *Bioresource Technology*. 2016;**208**:42-48
- [99] Klassen V, Blifernez-Klassen O, Hoekzema Y, Mussnug JH, Kruse O. A novel one-stage cultivation/fermentation strategy for improved biogas production with microalgal biomass. *Journal of Biotechnology*. 2015;**215**:44-51
- [100] Heaven S, Milledge J, Zhang Y. Comments on 'Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable'. *Biotechnology Advances*. 2011;**29**(1):164-167
- [101] Huesemann M, Crowe B, Waller P, Chavis A, Hobbs S, Edmundson S, et al. A validated model to predict microalgal growth in outdoor pond cultures subjected to fluctuating light intensities and water temperatures. *Algal Research*. 2016;**13**:195-206
- [102] Zhou X, Yuan S, Chen R, Song B. Modelling microalgae growth in nitrogen-limited continuous culture. *Energy*. 2014;**73**:575-580
- [103] Blanken W, Postma PR, de Winter L, Wijffels RH, Janssen M. Predicting microalgae growth. *Algal Research*. 2016;**14**:28-38
- [104] Ji F, Liu Y, Hao R, Li G, Zhou Y, Dong R. Biomass production and nutrients removal by a new microalgae strain *Desmodesmus* sp. in anaerobic digestion wastewater. *Bioresource Technology*. 2014;**161**:200-207
- [105] Ji F, Zhou Y, Pang A, Ning L, Rodgers K, Liu Y, et al. Fed-batch cultivation of *Desmodesmus* sp. in anaerobic digestion wastewater for improved nutrient removal and biodiesel production. *Bioresource Technology*. 2015;**184**:116-122
- [106] Wang M, Yang Y, Chen Z, Chen Y, Wen Y, Chen B. Removal of nutrients from undiluted anaerobically treated piggery wastewater by improved microalgae. *Bioresource Technology*. 2016;**222**:130-138
- [107] Romero-Villegas GI, Fiamengo M, Fernández FA, Grima EM. Utilization of centrate for the outdoor production of marine microalgae at pilot-scale in flat-panel photobioreactors. *Journal of Biotechnology*. 2018;**284**:102-114
- [108] Melis A. Solar energy conversion efficiencies in photosynthesis: Minimizing the chlorophyll antennae to maximize efficiency. *Plant Science*. 2009;**177**(4):272-280
- [109] Klein BC, Bonomi A, Maciel FR. Integration of microalgae production with industrial biofuel facilities: A critical review. *Renewable and Sustainable Energy Reviews*. 2017;**82**:1376-1392

- [110] Maeda Y, Yoshino T, Matsunaga T, Matsumoto M, Tanaka T. Marine microalgae for production of biofuels and chemicals. *Current Opinion in Biotechnology*. 2018;**50**:111-120
- [111] Shuba ES, Kifle D. Microalgae to biofuels: 'Promising' alternative and renewable energy, review. *Renewable and Sustainable Energy Reviews*. 2018;**81**:743-755
- [112] Marques AD, Pinto FP, Araújo OQ, Cammarota MC. Assessment of methods to pretreat microalgal biomass for enhanced biogas production. *Journal of Sustainable Development of Energy, Water and Environment Systems*. 2018;**6**(2):394-404
- [113] Ometto F, Quiroga G, Pšenička P, Whitton R, Jefferson B, Villa R. Impacts of microalgae pre-treatments for improved anaerobic digestion: Thermal treatment, thermal hydrolysis, ultrasound and enzymatic hydrolysis. *Water Research*. 2014;**65**:350-361
- [114] Passos F, Uggetti E, Carrère H, Ferrer I. Pretreatment of microalgae to improve biogas production: A review. *Bioresource Technology*. 2014;**172**:403-412
- [115] Rodriguez C, Alaswad A, Mooney J, Prescott T, Olabi AG. Pre-treatment techniques used for anaerobic digestion of algae. *Fuel Processing Technology*. 2015;**138**:765-779
- [116] Bohutskyi P, Betenbaugh MJ, Bouwer EJ. The effects of alternative pretreatment strategies on anaerobic digestion and methane production from different algal strains. *Bioresource Technology*. 2014;**155**:366-372
- [117] Giraldo-Calderón ND, Romo-Buchelly RJ, Arbeláez-Pérez AA, Echeverri-Hincapié D, Atehortúa-Garcés L. Microalgae biorefineries: Applications and emerging technologies. *DYNA*. 2018;**85**(205):219-233
- [118] Jagadevan S, Banerjee A, Banerjee C, Guria C, Tiwari R, Baweja M, et al. Recent developments in synthetic biology and metabolic engineering in microalgae towards biofuel production. *Biotechnology for Biofuels*. 2018;**11**(1):185
- [119] Solé-Bundó M, Salvadó H, Passos F, Garfí M, Ferrer I. Strategies to optimize microalgae conversion to biogas: Co-digestion, pretreatment and hydraulic retention time. *Molecules*. 2018;**23**(9):2096
- [120] Sathyaprakasan P, Kannan G. Economics of bio-hydrogen production. *International Journal of Environmental Science and Development*. 2015;**6**(5):352
- [121] Mottet A, Habouzit F, Steyer JP. Anaerobic digestion of marine microalgae in different salinity levels. *Bioresource Technology*. 2014;**158**:300-306
- [122] Doğan-Subaşı E, Demirer GN. Anaerobic digestion of microalgal (*Chlorella vulgaris*) biomass as a source of biogas and biofertilizer. *Environmental Progress & Sustainable Energy*. 2016;**35**(4):936-941
- [123] Lü F, Ji J, Shao L, He P. Bacterial bioaugmentation for improving methane and hydrogen production from microalgae. *Biotechnology for Biofuels*. 2013;**6**(1):92
- [124] Yang S, Liu Y, Wu N, Zhang Y, Svoronos S, Pullammanappallil P. Low-cost, Arduino-based, portable device for measurement of methane composition in biogas. *Renewable Energy*. 2019;**138**:224-229
- [125] Perazzoli S, Steinmetz RL, Mezzari MP, Nunes EO, da Silva ML.

Biogas production from microalga biomass. In: Embrapa Suínos e Aves-Artigo em anais de congresso (ALICE). Simpósio Internacional Sobre Gerenciamento de Resíduos Agropecuários e Agroindustriais. Vol. 3. São Pedro, SP. Anais... São Pedro, SP: SBERA; 2013

[126] Passos F, Solé M, García J, Ferrer I. Biogas production from microalgae grown in wastewater: Effect of microwave pretreatment. *Applied Energy*. 2013;**108**:168-175

[127] Bohutskyi P, Bouwer E. Biogas production from algae and cyanobacteria through anaerobic digestion: A review, analysis, and research needs. In: *Advanced Biofuels and Bioproducts*. New York, NY: Springer; 2013. pp. 873-975

[128] Xin C, Addy MM, Zhao J, Cheng Y, Cheng S, Mu D, et al. Comprehensive techno-economic analysis of wastewater-based algal biofuel production: A case study. *Bioresource Technology*. 2016;**211**:584-593

[129] Milledge JJ, Heaven S. Energy balance of biogas production from microalgae: Development of an energy and mass balance model. *Current Biotechnology*. 2015;**4**(4):554-567

[130] Klassen V, Blifernez-Klassen O, Wibberg D, Winkler A, Kalinowski J, Posten C, et al. Highly efficient methane generation from untreated microalgae biomass. *Biotechnology for Biofuels*. 2017;**10**(1):186

[131] Juneja A, Murthy GS. Evaluating the potential of renewable diesel production from algae cultured on wastewater: Techno-economic analysis and life cycle assessment. *AIMS Energy*. 2017;**5**(2):239-257

[132] Xiang X, Ozkan A, Kelly C, Radniecki T. Importance of microalgae speciation on biogas production and

nutrient recovery from anaerobic digestion of lipid-extracted microalgae biomass. *Environmental Engineering Science*. 2018;**35**(4):382-389

[133] Mussgnug JH, Klassen V, Schlüter A, Kruse O. Microalgae as substrates for fermentative biogas production in a combined biorefinery concept. *Journal of Biotechnology*. 2010;**150**(1):51-56

[134] Wang X, Nordlander E, Thorin E, Yan J. Microalgal biomethane production integrated with an existing biogas plant: A case study in Sweden. *Applied Energy*. 2013;**112**:478-484

[135] Darvehei P, Bahri PA, Moheimani NR. Model development for the growth of microalgae: A review. *Renewable and Sustainable Energy Reviews*. 2018;**97**:233-258

[136] Kumar K, Ghosh S, Angelidaki I, Holdt SL, Karakashev DB, Morales MA, et al. Recent developments on biofuels production from microalgae and macroalgae. *Renewable and Sustainable Energy Reviews*. 2016;**65**:235-249

[137] Santos-Ballardo DU, Rossi S, Reyes-Moreno C, Valdez-Ortiz A. Microalgae potential as a biogas source: Current status, restraints and future trends. *Reviews in Environmental Science and Bio/Technology*. 2016;**15**(2):243-264

[138] Wang X, Bao K, Cao W, Zhao Y, Hu CW. Screening of microalgae for integral biogas slurry nutrient removal and biogas upgrading by different microalgae cultivation technology. *Scientific Reports*. 2017;**7**(1):5426

[139] Lu D, Zhang XJ, Liu X, Zhang L, Hines M. Sustainable microalgae cultivation by using anaerobic centrate and biogas from anaerobic digestion. *Algal Research*. 2018;**35**:115-124

[140] Harun R, Davidson M, Doyle M, Gopiraj R, Danquah M, Forde G.

Technoeconomic analysis of an integrated microalgae photobioreactor, biodiesel and biogas production facility. *Biomass and Bioenergy*. 2011;**35**(1):741-747

[141] Barlow J, Sims RC, Quinn JC. Techno-economic and life-cycle assessment of an attached growth algal biorefinery. *Bioresource Technology*. 2016;**220**:360-368

[142] Batan LY, Graff GD, Bradley TH. Techno-economic and Monte Carlo probabilistic analysis of microalgae biofuel production system. *Bioresource Technology*. 2016;**219**:45-52

[143] Saharan BS, Sharma D, Sahu R, Sahin O, Warren A. Towards algal biofuel production: A concept of green bio energy development. *Innovative Romanian Food Biotechnology*. 2013;**12**:1

[144] Stiles WA, Styles D, Chapman SP, Esteves S, Bywater A, Melville L, et al. Using microalgae in the circular economy to valorise anaerobic digestate: Challenges and opportunities. *Bioresource Technology*. 2018;**267**:732-742

[145] Kavitha S, Subbulakshmi P, Banu JR, Gobi M, Yeom IT. Enhancement of biogas production from microalgal biomass through cellulolytic bacterial pretreatment. *Bioresource Technology*. 2017;**233**:34-43

[146] Kavitha S, Banu JR, Priya AA, Uan DK, Yeom IT. Liquefaction of food waste and its impacts on anaerobic biodegradability, energy ratio and economic feasibility. *Applied Energy*. 2017;**208**:228-238

[147] Kavitha S, Kannah RY, Banu JR, Kaliappan S, Johnson M. Biological disintegration of microalgae for biomethane recovery-prediction of biodegradability and computation of energy balance. *Bioresource Technology*. 2017;**244**:1367-1375

[148] Doan NT. Assessing and Enhancing Methane Productivity from Anaerobic Digestion Using Cyanothecce BG0011 as Feedstock [Doctoral Dissertation]: University of Florida; 2017

[149] Zhang Y. Cultivation, growth optimization and modeling of a saline Cyanothecce species BG0011 for production of biofuels and bioproducts [doctoral dissertation]. University of Florida; 2018

[150] Brown RC, Brown TR. *Biorenewable Resources: Engineering New Products from Agriculture*. Hoboken, New Jersey: John Wiley & Sons; 2013

[151] Doran PM. *Bioprocess Engineering Principles*. Cambridge, Massachusetts: Academic Press; 1995

[152] McCollum DL, Ogden JM. Techno-economic models for carbon dioxide compression, transport, and storage & correlations for estimating carbon dioxide density and viscosity. [Internet]. 2006. Available from: <https://escholarship.org/uc/item/1zg00532> [Accessed: 2018-12-05]