Techno-economic evaluation of microalgae-based supply chain: Review on recent approaches

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Abstract. Third generation biomass-derived products such as biofuel has been garnering attention as a viable alternative energy source recently as it does not necessarily require fresh water and vast land for cultivation as compared to first-generation and second-generation biomass. However, extensive studies have to go into the feasibility evaluation for third generation biomass utilization prior to upscaling the process to commercial level. Other than comprehensive technical evaluation such as experimental studies to understand the microalgae productivity, economic evaluation of the utilization of third-generation biomass is also critical specifically in the perspective of supply chain. Therefore, the objective of this review is to lay out an overall picture to the readers the various option of approaches or methods utilized in feasibility evaluation of the microalgae-based supply chain. The outcome of the review paper indicated that approximately 58% of the papers reviewed opted for mathematical modeling with optimization whereas the remaining 42% opted for mathematical modeling without optimization.

1. Introduction

As stated by the International Renewable Energy Agency (IREA), the utilization of renewable energy source has vastly exceeded non-renewable energy source since 2015 [1]. One of the renewable energy sources that has been garnering attention is biomass. Biomass-derived energy source and products have been in the highlights in recent years that in turns slowly phasing out fossil fuels. Biomass can be further categorized into first, second, and third-generation biomass. First generation biomass is crop-like and usually edible biomass such as sugarcane, barley, and corn [2]. Apart from that, second-generation biomass consists of a wide variety of biomass usually inedible lignocellulosic biomass (i.e., wood chips, forest remains, or domestic solid wastes) [2]. Lastly, third-generation biomass is general algal biomass [3]. By definition, unicellular and basic multi-cellular microorganisms are both categorized under prokaryotic microalgae (i.e., cyanobacteria and eukaryotic microalgae) [3]. Researches are now leaning towards third-generation biomass such as microalgae utilization due to
multiple reasons. One among these is the high lipid content of certain algal species (i.e., *Chlorella* that has lipid content of approximately 60 to 70%), which allows higher production of biodiesel [4]. Additionally, microalgae can be cultivated in distinct origin of water namely saline water, wastewater, brackish water, and fresh water [5]. The capability of microalgae to be cultivated in wastewater has significant benefits as the discharge of wastewater into the environmental ecosystem can result in the increase of chemical oxygen demand (COD), which further causes the imbalance in ecosystem, contamination towards the environment specifically groundwater, and may pose risk to human health [6]. According to Posadas *et al.* [7], the development of low cost and green treatment for effluents such as wastewater is critical as industries are discharging large volumes of wastewater into the aquatic ecosystem. Although microalgae utilization in the renewable fuels sector is a favorable alternative, Tan [8] stated that the identification of reliable markets for microalgae to venture into has been unsuccessful due to an undesirable return on investment. Furthermore, Andrade *et al.* [9] mentioned that only a few published papers had studied the feasibility of microalgae-based supply chain. Therefore, it is critical to consider the different evaluation approaches available when evaluating the feasibility of the microalgae-based supply chain. As the microalgae-based supply chain is still in its infancy, a more comprehensive study is required to ensure that all aspects have been considered and to avoid any unnecessary losses whether in time or monetary aspects. Furthermore, Madugu and Collu [10] added that careful analysis of the microalgae-based supply chain is critical to for the assurance of the long-term sustainability of microalgae conversion process. According to Chew *et al.* [11], one of the foundation tools that can be adopted to perform feasibility evaluation of microalgae processing is techno-economic analysis.

Therefore, this review paper is equipped with the objective to compile the presently available approaches and methodology utilized in performing techno-economic analysis of microalgae-based supply chain. Subsequently, a list of recent reviews related to microalgae-based supply chain has been listed in table 1. Some of the works listed in this table such as Efroymson *et al.* [12] briefly illustrated a framework for better management practices (BMPs) to achieve sustainability objective that includes techno-economic analysis and provide brief description on the integration of economic indicators with environmental indicators. Nonetheless, they did not provide a discussion on the methods or mathematical models available to be used for techno-economic analysis. Generally, BMP can be obtained from techno-economic analysis and life cycle assessment (LCA) coming hand-in-hand to achieve sustainability objectives such as the reduction of greenhouse gas (GHG) emissions. Apart from that, Doliente *et al.* [13] also reviewed techno-economic analysis of first, second, and third-generation biomass-derived bio-aviation fuel. They however, only provided a cost breakdown for the delivered cost of first-generation and second-generation biomass specifically corn stover, switch grass, oil palm, miscanthus, eucalyptus, forest residues, and sugarcane. However, they did not go on to discuss more comprehensively on the approaches or methods available in performing techno-economic analysis. Aside from that, Rizwan *et al.* [14] discussed the optimization of microalgae-based biorefinery superstructure, which is based on deterministic and stochastic approach alongside the discussions on uncertainties revolving around microalgae-based biorefinery. However, they did not critically review the alternative techno-economic analysis approaches that can be performed without the need for optimization. In contrast, these approaches will be discussed in the current review. Apart from that, the type of microalgae and the corresponding conversion process are outlined in this review as well.
Table 1. A list of current available reviews related to techno-economic analysis of microalgae-based supply chain.

| Year | Author          | Review Scope                                                                                                                                 |
|------|-----------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| 2021 | Efroymson et al. [12] | • Provided description on algae and algae-derived biofuel production<br>• Discussed the framework for BMPs that relies on LCA, techno-economic assessment, and resource analysis.<br>• Provided examples for BMPs such as the quantity and quality of water |
| 2020 | Teng et al. [15] | • Discussed the integration of artificial intelligence (AI) in microalgae in different fields such as genetic engineering, experimental analysis, and process integration<br>• Listed the essential databases used for microalgae bioinformatics<br>• Discusses the optimization approaches used with the integration of AI in microalgae-based biorefineries |
|      | Andrade et al. [9] | • Focused on Brazilian Microalgae Production Chain (BPMC)<br>• Discussed briefly the studies performed on BPMC<br>• Discussed a few significant elements of BPMC (Shortcomings, threats, challenges, opportunities, efficiency, and demand)<br>• Highlighted a few ways to reduce the BPMC cost |
|      | Doliente et al. [13] | • Review the bio-aviation fuel supply chain and their components: microalgae feedstock, conversion pathways, and logistics that include storage and transport<br>• Provide a summary of supply chain studies that include environmental and economic for bio-aviation fuel<br>• Discussed the advantages and limitations of bio-aviation fuel conversion pathways |
| 2019 | Rizwan et al. [14] | • Discussed microalgae-based biorefinery superstructure optimization<br>• Focus on the description of formulation of optimization models that are mixed-integer linear programming (MILP) and mixed-integer non-linear programming (MINLP) |
| 2018 | Deprá et al. [16] | • Review microalgae biorefineries including microalgae cultivation and co-products produced during conversion process<br>• Discussed application of process integration and LCA to microalgae biorefineries<br>• Discussed the microalgae biorefineries’ bottlenecks |
| 2017 | Chew et al. [11] | • Discussed briefly the economic viability of microalgae biofuels. However, did not go in-depth towards the method and approach adopted<br>• Emphasized more on microalgae biorefinery (inclusive of their conversion processes), components of microalgae, and potential application of each component of microalgae |
The main purpose of this review paper is to provide a compilation of techno-economic studies performed for third-generation biomass utilization. Section 2 illustrates the review methodology adopted in this paper. Subsequently, a brief description of microalgae-based supply chain is included in Section 3. Section 4 then presents the compilation of the methods and approaches covered in this review paper. The concluding remarks and future works are outlined in Section 5.

2. Review methodology and scope of review

The review methodology utilized in this study is illustrated in figure 1. The review began with inputting the desired keyword “microalgae” into the database. The database used for this study is Scopus. After obtaining the search outcome from the keyword that includes 29,594 relevant papers, the next step involved refining the search result to the scope of “techno-economic” and further refined the search result to the scope of “supply chain”. The total resulting article was 208 relevant papers that were further refined to consist only journal articles, resulting in 103 total relevant papers. The scope of this review paper is the articles from the recent five years (2017 to 2021). Thus, 74 relevant papers were reviewed in this study. Manual methodology screening was conducted on each paper to determine whether the methodology of study adopted by the papers are relevant to be discussed in this review. After methodology screening, 51 papers (approximately 68% of the total papers obtained from the search results) were found to be less relevant towards the scope of this review paper.

Although specific keywords and article screening have been implemented and the result of the papers obtained are significant and insightful studies but less relevant towards the scope of this review paper (see tables 2A and 2B). For instance, review papers such as Kusmayadi et al. [17] found in the search results was screened out. The author briefly addressed the tools that can be used to evaluate the feasibility of production and conversion pathways that are techno-economic analysis and life cycle assessment. However, the paper focuses on the nutritional components of microalgae where the considered application is merely on using as animal and human feed. The largest category of papers is contributed by experimental studies (e.g., Vigor et al. [18], Wang et al. [19], and etc). Some of the papers performed mathematical modeling as well however did not perform techno-economic analysis. For instance, Andersson et al. [20] investigated the potential of process integration (material and heat integration) in microalgae processes (i.e., lipid extraction with transesterification, hydrothermal liquefaction (HTL) with catalytic hydrothermal gasification (CHG) for microalgae, Nannochloropsis and macroalgae, Laminaria saccharina, respectively). They studied the reuse of heat generated from the co-located oil refinery for algae-derived biofuel production process via heat integration. On the other hand, material integration was used to evaluate the potential reuse of hydrogen stream with purity content reaching 90% (categorized as waste stream) from the refinery process. The outcome of the studies was that heat integration and material integration have positive impacts on the biofuel process by reducing the net energy demand and process efficiency. On the other hand, Ryu et al. [21] formulated a generic mathematical model to describe the behavior of microalgae under heterotrophic culture conditions. They validated the results using two case studies—lipid production from the microalgae species, Chlorella protothecoides and lutein production from Chlorella protothecoides CS-41. The last study that performed mathematical modelling without performing techno-economic analysis is the study performed by Goffé and Ferrasse [22]. They studied the impact of stoichiometry ratio (i.e., carbon conversion ratio, energy ratio, and hydrogen conversion ratio) on the process conversion efficiency. Taking hydrogen conversion ratio as an example, it is taken as the amount of hydrogen within the particular biomass that is converted into value-added products.

Although all the listed works are insightful, they do not have direct relevance to the current review that focuses on the techno-economic analysis of microalgae-based supply chain. The brief explanation of microalgae-based supply chain is presented in the subsequent segment of this paper.
Figure 1. Review methodology.

Table 2A. Categorization of papers not reviewed in current paper. Note: R, Exp, Env, M, D and S denotes review paper, experimental works, environmental studies, mathematical modeling that does not consist of performing techno-economic analysis, decision making method, and simulation studies, respectively.

| Year | Author                  | R | Exp | Env | M | D | S |
|------|-------------------------|---|-----|-----|---|---|---|
| 2021 | Kusmayadi et al. [17]   | ✓ |     |     |   |   |   |
|      | Chen et al. [23]        |   |     | ✓   |   |   |   |
|      | Lu et al. [24]          | ✓ |     |     |   |   |   |
|      | Maiolo et al. [25]      |   |     |     | ✓ |   |   |
|      | Hu et al. [26]          | ✓ |     |     |   |   |   |
|      | Dalheim et al. [27]     | ✓ |     |     |   |   |   |
|      | Serrano et al. [28]     | ✓ |     |     |   |   |   |
|      | Chauton et al. [29]     | ✓ |     |     |   |   |   |
|      | Andersson et al. [20]   |   |     |     | ✓ |   |   |
|      | Culaba et al. [30]      |   |     |     | ✓ |   |   |
|      | Nguyen et al. [31]      | ✓ |     |     |   |   |   |
|      | Deprá et al. [32]       | ✓ | ✓   |     |   |   |   |
|      | El-Dakar et al. [33]    | ✓ |     |     |   |   |   |
|      | Branco-Vieira et al. [34]| ✓|     |     |   |   |   |
|      | Maiolo et al. [35]      | ✓ |     |     |   |   |   |
|      | Vigor et al. [18]       | ✓ |     |     |   |   |   |
|      | Hossain et al. [36]     | ✓ |     |     |   |   |   |
|      | Morales et al. [37]     | ✓ |     |     |   |   |   |
|      | Pankratz et al. [38]    | ✓ |     |     |   |   |   |
|      | Wahlen et al. [39]      | ✓ |     |     |   |   |   |
|      | Naeini et al. [40]      | ✓ |     |     |   |   |   |
Table 2B. Categorization of papers not reviewed in current paper. See table 2A caption for the description of abbreviations used here.

| Year | Author | R | Exp | Env | M | D | S |
|------|--------|---|-----|-----|---|---|---|
| 2020 | Lee et al. [41] | ✓ |     |     |   |   |   |
|      | Ryu et al. [20] |     | ✓   |     |   |   |   |
|      | Desjardins et al. [42] |     |     | ✓   |   |   |   |
|      | Callegari et al. [43] |     |     |     | ✓ |   |   |
| 2019 | Rizwan et al. [14] |     |     |     |   |   | ✓ |
|      | Azari et al. [44] |     |     |     |   | ✓ |   |
|      | Morales et al. [45] |     |     |     |   | ✓ |   |
|      | Lee and Sun [46] |     |     |     | ✓ |   |   |
|      | Zhang and Kendall [47] |     |     |     |   | ✓ |   |
|      | Song et al. [48] |     |     |     |   |   | ✓ |
|      | Sawant et al. [49] |     |     |     |   |   |   |
| 2019 | Sun et al. [50] |     |     |     |   | ✓ |   |
|      | Goffé and Ferrasse [21] |     |     |     |   | ✓ |   |
|      | Bacci di Capaci et al. [51] |     |     |     |   |   | ✓ |
|      | Wang et al. [19] |     |     |     |   |   | ✓ |
| 2018 | Montero-Lobato et al. [52] |     |     |     |   | ✓ |   |
|      | Pedersen et al. [53] |     |     |     |   | ✓ |   |
|      | Foteinis et al. [54] |     |     |     |   |   | ✓ |
|      | Poddar et al. [55] |     |     |     |   | ✓ |   |
|      | Sturme et al. [56] |     |     |     |   |   | ✓ |
|      | Giraldo-Calderón et al. [57] |     |     |     |   |   | ✓ |
|      | Chen et al. [58] |     |     |     |   | ✓ |   |
|      | Pan et al. [59] |     |     |     |   |   | ✓ |
|      | Phusunti et al. [60] |     |     |     |   |   | ✓ |
|      | Tang et al. [61] |     |     |     |   |   | ✓ |
|      | Chen et al. [62] |     |     |     |   |   | ✓ |
| 2017 | Qiu et al. [63] |     |     |     |   |   | ✓ |
|      | Tan et al. [64] |     |     |     |   |   | ✓ |
|      | Sabu et al. [65] |     |     |     |   |   | ✓ |
|      | Chew et al. [11] |     |     |     |   |   | ✓ |
3. Microalgae-based supply chain

The microalgae-based supply chain is said to consists of microalgae cultivation followed by harvesting and then the conversion process (inclusive of pre-requrement prior to actual conversion process such as lipid extraction for biofuel production) and lastly, reuse or disposal [12] or transfer to the end users. Microalgae cultivation and harvesting differ from first-generation and second-generation biomass. Doliente et al. [13] mentioned that second generation biomass such as waste biomass are co-produced from ago-forestry activities such as lignocellulosic by-products often obtained as a result of post-harvest activities (i.e., wood processing, milling, and etc.). On the other hand, the cultivation of microalgae can be categorized into four types of cultivations (i.e., photoautotrophic, heterotrophic, mixotrophic, and photoheterotrophic) [66], where they can potentially be cultivated in either open ponds, raceways, or sealed photobioreactors (PBR) [12]. Apart from cultivation area, the cultured medium can be specially formulated to contain all required elements (i.e., zinc, copper, calcium, and etc.) [66] on top of the commonly available types that are fresh water, saline water, wastewater, and brackish water [5]. Apart from cultivation methods and medium, there are also various microalgae harvesting methods such as dewatering, wash methods, pumps, drying [12], flocculation, centrifugation, filtration, flotation, sedimentation, and electrolytic process [67]. Furthermore, different components of the microalgae can be extracted for different types of conversion processes. For instance, the carbohydrates and lipids obtained from microalgae can be utilized for fuel production, while microalgae polysaccharides can be used for cosmetic additives or natural therapeutic agents [11]. Apart from the specific components of microalgae, the microalgae biomass as a whole can undergo thermochemical conversion (i.e., liquefaction, pyrolysis, gasification, and direct combustion), biochemical or biological conversion (i.e., photobiological hydrogen production, anaerobic digestion, and alcoholic fermentation), transesterification (i.e., acid or base catalysis, and supercritical fluid), and photosynthetic microbial fuel cell process to produce value-added products as well [11].

All in all, microalgae-based supply chain has a very wide variety of cultivation and harvesting methods on top of the wide range of conversion processes. Hence, it is critical to understand the current techno-economic evaluation methods available and select the more suitable approach in evaluation to better achieve the desired objective.

4. Techno-economic analysis of microalgae-based supply chain

This section describes the techno-economic analysis methods used for microalgae-based supply chain evaluation. The evaluation methods can be separated into two sections—mathematical modeling without optimization and mathematical modeling with optimization.

4.1. Mathematical modelling without optimization

Recently, Wu et al. [68] performed a comparative LCA and economic analysis on four production scenarios (i.e., scenario 1 and 2 that focus on natural gas feedstock; scenario 3: anaerobic co-digestion to produces methanol; scenario 4: electrolysis of salt water that produces hydrogen) with the objective of generating fuel for either hydrogen or methanol fuel cell. In their work, microalgae were fed into the anaerobic digester (scenario 3) where three products, i.e., biogas, liquid digestate, and solid digestate are generated. To efficiently utilize all these products, biogas was proposed to be fed into combined heat and power (CHP) generation system and/or converted into methanol, whereas the liquid and solid digestates were used as the nutrient sources for microalgae cultivation. Based on their cost analysis, the capital expenditure (CAPEX) for scenario 3 is 94% higher than that of the CAPEX for scenario 1 given that approximately 50% of the CAPEX stemmed from conversion of biogas to methanol (i.e., methanol synthesis process, methanol storage, utility, and land). However, the operating expenditure (OPEX) for scenario 3 is slightly lower as compared to scenario 1 due to the higher price of natural gas. As a result, the overall levelized cost of methanol (LCOM) for scenario 3 is 18.6% higher than that of scenario 1. Similarly, Sano Coelho et al. [69] performed cost calculation of an economic evaluation indicator, the minimum biodiesel price, to assess the feasibility of utilization of heterotrophic microalgae (Auxemochlorella protothecoides) for biodiesel production.
They found that the microalgae biomass production session accounts for more than half of the total equipment cost (i.e., 64% of total equipment cost for fed-batch process and 55.5% for continuous process). On top of that, 95% of the overall equipment cost for the production of microalgae section originates from the bioreactor. Furthermore, a sensitivity analysis was performed to study the influence of various factors towards the minimum biodiesel price ($2.51 for fed-batch process and $2.27 for continuous process). The results showed that the molasses (substrate generated from the sugar crystallization process that act as substrate for microalgae lipid accumulation) price and bioreactor price are the two most influential factors, which need to be considered by the investors. Additionally, they also benchmarked the feasibility of a stand-alone microalgae plant with another microalgae plant, which is integrated with sugarcane bio-refinery. The result showed that the integrated plant offers a lower gross profit (approximately $4.2 million lower) because of the increase in expenses and decrease in revenue as a result of the decrease in ethanol produced. The results obtained shows that there is a need to consider all configuration options for conversion process and thereby, identifying all the bottlenecks that may lead to unfavorable outcomes. By identifying the bottlenecks, potential steps taken that can prevent the bottlenecks can be implemented.

Furthermore, table 3 also reveals that Chlorella represents a favorable microalgae type due to its characteristics, e.g., (i) high protein content with substantial vitamins and minerals content as well as a balanced composition of amino acids that make it suitable for human consumption [70]; and (ii) high lipids content making them suitable for biofuel production [4].

Some authors highlighted the concern regarding the price variation. For instance, Schade and Meier [71] investigated the impact of variation in future prices for input materials on the economic performance. Therefore, they performed 1,000 simulation runs with the Geometric Brownian motion to estimate the future prices for input materials then used the mean obtained from the 1,000 simulation results as input data for economic evaluation.
Table 3. Summary of the works adopting mathematical modeling without optimization.

| Year | Author | Type of Microalgae | Conversion Process/Product | Mathematical Model Adopted |
|------|--------|--------------------|---------------------------|---------------------------|
| 2021 | Wu et al. [68] | *Chlorella vulgaris* | Microalgae production | LCA, manual cost calculation |
|      | Sano Coelho et al. [69] | *Auxenochlorella protothecoides* | Lipid extraction for biodiesel production | Process simulation, manual cost calculation |
|      | Silva et al. [72] | *Chlorella vulgaris* | Effluent treatment, lipids and biogas production | Experiment, mass and energy balance, manual cost calculation |
|      | Schade and Meier [71] | *Nannochloropsis sp.* \*Phaeodactylum tricornutum* | Dry biomass or protein-rich biomass and microalgae oil | Manual cost calculation |
| 2020 | Nappa et al. [73] | - | Microalgae biomass production (closed and open system) | Mass and energy balance, manual cost calculation |
|      | Choudhary and Srivastava [74] | *Chlorella sp.* | Integrated crude oil heating system with anaerobic digester and solar PV module | Mass and energy balance, manual cost calculation |
|      | Mennella et al. [75] | *Chlorella sp.* | Food and biodiesel production | Experimental, manual cost calculation |
|      | Archanaa et al. [76] | *Rhodococcus opacus* \*Chlorella vulgaris* | Biodiesel production via transesterification process | Experimental, manual cost calculation |
| 2019 | Tasca et al. [77] | *Chlorella vulgaris* | Biomethane production via anaerobic digestion | LCA, manual cost calculation |
| 2018 | Beal et al. [78] | *Desmodesmus sp.* | Fish oil and fishmeal replacement via lipid extraction and drying process | Energy and mass balance, energy impact, GHG impact and accounting, manual cost calculation |
4.2. Mathematical modelling with optimization

A compilation for the authors adopting mathematical modeling with optimization are presented in tables 4A and 4B. Such model can be used not only to evaluate the performance, but also to determine the set of operational parameters that can provide the best possible performance [79]. Generally, mathematical modeling with optimization can be categorized into deterministic optimization and stochastic optimization. In short, deterministic optimization is an optimization model that does not account for uncertainties surrounding the supply chain [80]. In the case of Kang et al. [81], a two-stage MILP model integrated with geographic information system (GIS) is presented to determine an optimal microalgae-based supply chain with an aim to minimize the total supply chain cost. The proposed study considers 13 biorefineries where various conversion technologies (e.g., HTL, fermentation, and protein extraction) are used in their models. The outcome of the study is that the fermentation pathway was not favorable due to the high CAPEX and OPEX. When evaluating from a single biorefinery perspectives, Nannochloropsis sp. indicated better economic outcome as compared to Chlorella sp. due to the utilization of Nannochloropsis sp. in protein extraction process that offset larger revenue from protein sales. However, due to the higher transportation cost required for Nannochloropsis sp. as a result of constraints in resource availability and longer distance from supply source, it was only used in six out of the 13 biorefineries. This highlighted the importance of incorporating the supply chain cost to ensure the optimality of the microalgae selection. Nevertheless, they also found that the minimum fuel selling price of the microalgae-derived biodiesel of $10.92 per gallon of biodiesel is higher than that of the current market price for biodiesel ($3.51 per gallon of biodiesel) in 2019. To address this issue, various strategies (e.g., implementing storage for overproduced microalgae during summer season to be used in winter or autumn season) are proposed to enhance the economic viability. Mathematical modeling with optimization is not limited to merely maximizing total supply chain’s economic profitability. In fact, the optimization can be performed to assist in multi-criteria decision analysis (MCDA) to select the best microalgae strain for conversion process. Taking the study performed by Kokkinos et al. [82] as an example, they utilized three models that are fuzzy analytic hierarchy process (FAHP), fuzzy technique for order of preference to ideal solution (FTOPSIS), and fuzzy cognitive mapping (FCM) to select an optimal microalgae strain for biofuel production. The outcome from the studies showed that Chlorella vulgaris sp. was the best option amongst the four microalgae investigated given the relatively higher daily lipid productivity of Chlorella vulgaris sp. (134 mg L\(^{-1}\) d\(^{-1}\)) amongst the four types of microalgae strain and thus, able to produce greater amount of biofuel. This shows the significance in taking into consideration the microalgae composition (i.e., lipid content) requirement for specific conversion process during techno-economic analysis evaluation.

According to Shabani et al. [80], deterministic optimization models are not necessarily enough to reflect the reality of the actual performance of the biomass supply chains specifically when there are uncertain variables involved such as prices and yields. Thus, stochastic models should be applied to capture these uncertainties. Kangas and Kangas [83] mentioned that there can be many definitions or interpretations brought forth for uncertainty, however, it can be defined as the lack of information that can qualitatively or quantitatively describe or predict numerically a system or its characteristics. Fasahati et al. [84] highlighted that there are a few uncertainties surrounding biorefinery design such as productivity and residence time of cyanobacteria, supply mode for carbon dioxide, carbon dioxide demand required by cyanobacteria (influenced by potential leakage of carbon dioxide and ratio of cell to product mass), the water and nutrient supply, which is highly dependent on the output from wastewater treatment plant, and etc. Although they did not directly incorporate the uncertainties into their developed mathematical model, they performed sensitivity analysis to evaluate the impact of the uncertainties on the economic performance of the biorefinery.

Apart from performing sensitivity analysis, stochastic optimization model represents another way to incorporate uncertainties directly into the developed economic model. For instance, Beal et al. [78] applied Monte Carlo model to study the combined effect of investment cost, energy and material flows and labor cost uncertainty on the NPV, energy return on investment (ERoI), and GHG emissions. The
microalgae productivity was determined as the most influential factor due to the large range of historical data (8.5 to 42.85 g/m²-day). The incorporation of uncertainty has led the NPV value to decrease from $26.3 million in the base case to a median NPV of $15.8 M. The result obtained emphasized the importance of consideration of uncertainties as the base case NPV is relatively an overestimated value as compared to the median NPV, which may lead to unnecessary losses if not considered more comprehensively. Rizwan et al. [14] highlighted in their review that uncertainties tend to be the process parameters (i.e., lipid contents, yield, and productivity, microalgae biomass quality, raw material pricing, utility cost, and consumption). However, as observed in table 4A and table 4B, current studies that perform stochastic optimization to study uncertainties are still scarce. Hence, as a summary of the above discussion, it is critical to consider uncertainties when performing evaluation on the microalgae-based supply chain as a whole and not only consider the microalgae conversion process alone.

Table 4A. Summary of the works adopting mathematical modelling with optimization.

| Year | Author | Type of Microalgae | Conversion Process/Product | Mathematical Model Adopted | Model Type |
|------|--------|--------------------|----------------------------|----------------------------|------------|
| 2021 | Kokkinos et al. [82] | *Chlorella vulgaris sp.* *Schizochytrium limacinum SR21* *Arthrospira (Spirulina) Platensis* *Nannochloropsis sp.* | Biofuel production | FAHP, FTOPSIS, FCM | D |
| | Correa et al. [85] | - | Biofuel production | Integer linear programming (LP) | D |
| | Correa et al. [86] | *Nannochloropsis sp.* | Microalgae cultivation for biofuel production | LP | D |
| 2020 | Ahn et al. [87] | - | Biodiesel production | Two-stage stochastic model | S |
| | Sarker et al. [88] | *Schizochytrium sp.* *N. oculata* | Fish oil and fishmeal replacement | Hedonic regression analysis | S |
| | Kang et al. [81] | *Chlorella sp.* *Nannochloropsis sp.* | Biofuel with animal feeds and bioethanol produced as by-products | MILP | D |
| 2019 | Fasahati et al. [84] | Cyanobacteria | Biochemical production | MINLP | D |
| | Correa et al. [89] | - | Biodiesel production | GIS-based MCDA and LP | D |

*a The mathematical model type indicates whether the model is categorized under deterministic (D) or stochastic (S) optimization.
Table 4B. Summary of the works adopting mathematical modelling with optimization.

| Year | Author | Type of Microalgae | Conversion Process/Product | Mathematical Model Adopted | Model Typea |
|------|--------|--------------------|----------------------------|----------------------------|-------------|
| 2019 | Shirazi et al. [90] | - | Algae-derived syngas via supercritical water gasification (SCWG) | Genetic algorithm |            |
|      | Thomassen et al. [91] D & S | Dunaliella salina | Superstructure of processes including lipid extraction, thermal and biological process | Multi-objective MINLP, Monte Carlo model | D & S       |
|      | Thomassen et al. [91] D & S | Haematococcus pluvialis | | | |
|      | Thomassen et al. [91] D & S | Nannochloropsis sp. | | | |
| 2018 | Beal et al. [78] S | Desmodesmus sp. | Fish oil and fishmeal replacement via lipid extraction and drying process | Monte Carlo | S           |
| 2017 | Gong and You [92] D | - | Biodiesel production | Mixed integer nonlinear fractional programming (MINFP) | D           |
|      | Garcia Prieto et al. [93] D | Haematococcus pluvialis | Astaxanthin, biodiesel, poly(hydroxybutyrate) (PHB) production | MINLP | D           |
|      | Gong and You [94] S | - | Poly-3-hydroxybutyrate (PHB) and biodiesel production | Two-stage adaptive robust mixed integer fractional programming (ARMIFP) | S           |

The mathematical model type indicates whether the model is categorized under deterministic (D) or stochastic (S) optimization.

5. Possible research exploration areas
As microalgae-based feedstock is still in its infancy, modeling approaches on microalgae-based supply chain to evaluate the feasibility of microalgae utilization should consider a wider scope. For instance, the optimization of microalgae-based supply should consider the different types of microalgae, cultivation medium and environment, locations of microalgae cultivation (i.e., on-site of processing site or off-site), and etc. On top of that, stochastic optimization studies should consider multiple uncertainties so that the risk associated to the microalgae-based supply chain can be assessed. For example, the variation of microalgae productivity should be considered as it is influenced by multiple environmental conditions such as solar irradiation. This is where artificial intelligence (AI) can be integrated into the study. As an exemplification, an AI model can be developed that is capable of predicting the microalgae productivity based on the fluctuation of environmental conditions.
Microalgae productivity will indirectly impact the production of end-value product. Thus, it can be essential to integrate the prediction of microalgae productivity based on fluctuating environmental conditions into techno-economic evaluation model. Along the years, there has been advancement in government’s policy that encourages the exploration of AI. For instance, Malaysia’s government had launched a new policy regarding the Fourth Industrial Revolution— National 4IR Policy whereby AI is one of the key technologies that will be focused on [95]. Generally, the implementation of AI can provide few advantages such as acceleration of optimization solving procedures, reduction of uncertainty, and etc [96].

6. Conclusion
The quest for diversification of current energy profile around the world has led to the hunt for potential renewable energy sources. Third-generation biomass is slowly becoming the focus of attention as a potential feedstock for biofuel production. Therefore, comprehensive studies are required to evaluate the feasibility in upscaling the utilization of third-generation biomass to commercial scale. This review presented a compilation of current approaches used in techno-economic evaluation for microalgae-based supply chain. The current findings highlighted that approximately 58% of the studies opted for mathematical modeling with optimization whereas approximately 42% of the papers opted for mathematical modeling without optimization. Amongst the studies adopting mathematical modeling with optimization, deterministic model is deemed as a favorable option. Regarding potential future works, a larger scope of evaluation when performing superstructure analysis that comprises of different cultivation medium and cultivation environment can be substantial due to the wide varieties of cultivation medium and environment that come with their respective costs. Apart from that, it is also critical to consider the regional weather conditions (i.e., solar irradiation, seasonality, rain, and etc.) when selecting a location for the microalgae cultivation or when choosing macroalgae species. Specifically, when performing stochastic techno-economic analysis, it is important to consider the impact of variation of environmental conditions or microalgae species on the overall microalgae productivity of microalgae to attain a more accurate estimation on its economic feasibility. Furthermore, AI model, which is capable of predicting the influence of variation in environmental conditions on the microalgae productivity can be incorporated into the techno-economic analysis model and serves as another promising path to explore.

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