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Preliminary Stochastic Techno-economic Study of Microalgae-based Supply Chain

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Utilization of microalgae as feedstock has been increasingly gaining attention in recent years due to its capability to be cultured on site at the processing plant that reduces cost of transportation of feedstocks. Certain microalgae species also contain high lipid contents that make them a favourable feedstock for Fatty Acid Methyl Ester biodiesel production process. However, microalgae-based conversion process is still in its infancy. Extensive research on the feasibility study of the microalgae-based industry is critical prior to industrial-scale commercialization to prevent unexpected losses incurred. Therefore, this study aims to perform a preliminary Stochastic Techno-economic Evaluation on Microalgae-based Supply Chain with the incorporation of uncertainties. This is achieved by incorporating four uncertainties (i.e., product selling price, microalgae productivity, cost of microalgae, and conversion process efficiency) into a Monte Carlo Simulation model. Two types of microalgae species will be evaluated and compared in this study, i.e., *Chlorella vulgaris* and *Nannochloropsis sp.*. The outcome of this study found that *Nannochloropsis sp.* is more favorable with a higher mean NPV of USD 970.48 x 10^6 (higher than *Chlorella vulgaris* by 0.89 %) and lower standard deviation of USD 695.90 x 10^6 (lower than *Chlorella vulgaris* by 12.8 %). A probability-based financial result can allow users to better perform decision-making and analyzing the risk involves in the investment.

1. Introduction

In 2015, all United Nations Member States had taken up the 2030 Agenda for Sustainable Development that presents as a blueprint to achieve peace for the present, future, people, as well as Mother Earth. Core principle of the term *sustainability* is meeting the requirement of current generations' without impacting the required use for the future generation (Klemeš et al., 2019a). The 13^{th} SDG highlighted the criticalness of combating climate change and its implications such as the rise in greenhouse gas emissions (GHGs). Lack of knowledge on the efficient utilization and management of non-renewable energy sources such as fossil fuels would cause undesirable environmental impact such as emission of harmful gases (Klemeš et al., 2019b).

Supply chain evaluation is significant in identification of each critical component within the supply chain and serves as a more comprehensive economic assessment for investors to prevent overestimation of the feasibility of the project. Comprehensive supply chain evaluation is even more critical when dealing with microalgae-derived supply chain where the process is still in infancy stage. One of the approaches that can be used to evaluate the microalgae-based supply chain (MSC) is *via* stochastic optimization approach. Stochastic optimization model is a model capable of producing random probability-based distribution graph as an output result based on the uncertainties or risk parameters incorporated (Kieffer et al., 2016). Uncertainties or risks are variables that could varied or fluctuate with respect to time and the fluctuation of the uncertainties may critically affect the financial performance of the supply chain (Lo et al., 2021). The probability distribution results extracted from the stochastic optimization model is a closer representation of the real-world situation (Zakaria et al., 2020). One of the common approaches to perform stochastic optimization is *via* Monte Carlo simulation model. An example of the utilization of Monte Carlo simulation model in MSC planning is found in the studies of Batan et al. (2016). A stochastic Monte Carlo simulation model had been formulated to perform the evaluation for the minimum fuel selling price (MFSP) for *Nannochloropsis salina*-derived biodiesel. The uncertainties incorporated into the developed Monte Carlo simulation model are co-product (lipid-extracted algae (LEA)) revenues, polyethylene price, electricity cost, cost of hexane (raw material for lipid extraction), and price of nitrogen

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fertilizer. Through the utilization of Monte Carlo simulation model, the authors were able to extract a probability profile for MFSP that can provide a bird eye view of the problem on hand. This allowed more detailed evaluation of the risk involved with the supply chain. To the extent of the authors' knowledge, comprehensive MSC planning *via* Monte Carlo simulation model is scarce and does not incorporate multiple critical uncertainties at the same time. According to Delkhosh and Sadjadi (2019), there are limited papers available that evaluated third generation biomass-based biofuel supply chain under uncertainty. Table 1 presents a tabulation of currently available studies that had conducted Monte Carlo model evaluation for MSC, together with the respective uncertainties incorporated in their studies.

Table 1. Previous uncertainties incorporated into stochastic Monte Carlo simulation model of the microalgae-derived supply chain network (O: considered; X: not considered).

Authors	Microalgae price	Microalgae productivity	Product yield	Product / co-product price	Others
Current study	O	O	O	O	X
Delkhosh and Sadjadi (2020)	X	X	X	X	O
Batan et al. (2016)	X	X	X	O	X
Ou et al. (2015)	O	X	O	X	X
Richardson et al. (2010)	X	O	O	X	X

Thus, this conference paper aims to develop a stochastic *Monte Carlo simulation* model to evaluate the MSC with the incorporation of four uncertainties that had not been incorporated simultaneously in previous studies, to the extent of the authors knowledge. The aforementioned uncertainties include price of purchasing cost of microalgae species, fatty acid methyl esters (FAME) yield productivity, product selling price, and microalgae productivity (i.e., the growth rate). The purchasing cost of a specific type of microalgae species is greatly dependent on the suppliers and the location of the microalgae species. Even for a specific type of microalgae species, the FAME yield productivity and microalgae growth productivity will have a slight deviation in their value. The combination of these four uncertainties is significant to evaluate the potential of MSC to be industrialized. A case study is presented to better demonstrate the developed model where two types of microalgae species are evaluated and compared in this study. It is expected that a more economical preferable microalgae-based supply chain can be determined with the aids of the financial probability profile extracted from the *Monte Carlo simulation* model.
This conference paper is structured as: the proposed methodology is detailed in Section 2 and Section 3 describes the case study utilized to demonstrate the adopted methodology. The results obtained are discussed in Section 4. Section 5 concludes the main outcomes and provides recommendations for future studies.

2. Methodology

The generic flow of the proposed methodology adopted in this study is illustrated in Figure 1. The first step is defining the supply chain scope such as the supply chain components to be included (i.e., raw material acquisition location, transportation, processing hub, storage, and etc.) and the uncertainties involved. Subsequently, data collection was conducted to obtain the required data associated with the supply chain components defined. For the defined uncertainties, more historical referenced values for the uncertainties were required to be collected. The data pool for the historical referenced value collected were required to undergo data processing by converting the historical statistical data obtained into the uncertainties' respective mean and standard deviation value *via* Eq (1) and Eq (2). Lastly, after collection of all required data, stochastic Monte Carlo simulation was performed for the defined supply chain scope.

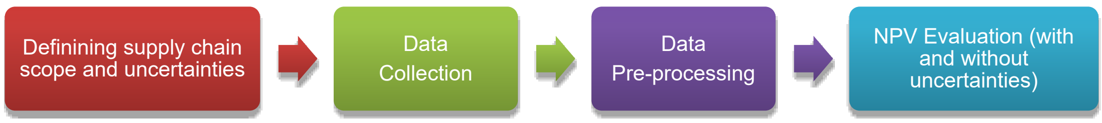

Figure 1: General Flow of Methodology for Case Study.

$$\text{Mean, } \mu = \frac{(\sum X)}{n} \quad (1)$$

$$\text{Standard deviation, SD} = \sqrt{\frac{\sum (X - \mu)^2}{n - 1}} \quad (2)$$

where X denotes the referenced value for the uncertainty, and n signifies the number of referenced value collected.

The Monte Carlo simulation is utilized in the evaluation of the economic feasibility of MSC with the incorporation of uncertainties. The economic performance indicator adopted in this study is Net Present Value (NPV) (Eq(3)):

$$\mathrm{NPV} = \sum_{n} \frac{(\mathrm{Balance})}{(1+i)^n} \tag{3}$$

$$\mathrm{Balance} = \mathrm{S}^{FAME} - \mathrm{C}^{MA} - \mathrm{C}^{\mathrm{OP}} - \mathrm{C}^{\mathrm{T}} \tag{4}$$

$$\mathrm{S}^{FAME} = \mathrm{P}^{MA} \times \mathrm{M}^{Prod} \times \mathrm{C}^{FAME} \tag{5}$$

where $\mathrm{Balance}$ denotes the remaining cash flow for each operating year, n (USD), and i represents the discount rate (%). In general, $\mathrm{Balance}$ encompasses four elements in the supply chain, i.e., FAME biodiesel sales, S^{FAME}, microalgae purchasing cost, C^{MA}, fixed operating cost of the processing plant, C^{OP} and the cost of transportation required, C^{T} (see Eq(4)). The FAME biodiesel sales can be calculated via the multiplication of productivity of biodiesel per weight of microalgae (wt biodiesel/wt microalgae), P^{MA}, the microalgae growth productivity, M^{Prod}, and the selling price of FAME biodiesel, C^{FAME} (see Eq(5)). The Monte Carlo simulation was computed using Microsoft Excel software by randomizing the uncertainties (microalgae growth productivity, M^{Prod}, biodiesel selling price, C^{FAME}, microalgae strain purchasing price, C^{MA}, and microalgae FAME biodiesel productivity, P^{MA}) according to their historical statistical data. The model will then perform iterations for 10,000 runs.

3. Illustrative Case Study for Monte Carlo Simulation Model

The purpose of this illustrative case study is to demonstrate the application and results interpretation of the developed stochastic Monte Carlo simulation model. The proposed illustrative MSC is presented in Figure 2. The proposed supply chain is a single product supply chain and the distance between the given processing hub and consumer is 25 km one way. The design of the open pond system is based on the works of Davis et al. (2016) that proposed a design of 50 ponds of 2-acre sizing with a volume of 3,995,082 ft^3. It is worthy to note that, in order to ensure an accurate cost estimation, the cost factors have also been scaled based on the year of operation using Chemical Engineering Plant Cost Index (CEPCI) as a reference indicator. The formulation for CEPCI can be found in the studies conducted by Lo et al. (2021). The current case study proposed for the microalgae cultivation and harvesting to be conducted on site of the FAME biodiesel production hub. Two microalgae species i.e., *Chlorella vulgaris* and *Nannochloropsis sp.* which are widely used for biodiesel production, were considered in this work. The proposed production plant is assumed to have a 20 y total operation lifespan (330 d/y), while the interest rate i is anticipated to be 10 % in the model. As mentioned, the impact of the four supply chain uncertainties (i.e., FAME productivity, selling price of biodiesel, microalgae productivity, and purchasing price of microalgae species) on FAME biodiesel-based supply chain are considered in this work. On the other hand, the fixed parameters adopted in this study are tabulated in Table 3. In the current proposed study, it is assumed that the microalgae-derived FAME produced is entirely sold to consumer (i.e., demand constraint of FAME biodiesel is not considered). Culture crashes and pond downtime is assumed to happen twice a year whereby the culture would require changing (Davis et al., 2016). It is assumed that the probability distribution utilized in this conference paper is normal distribution.

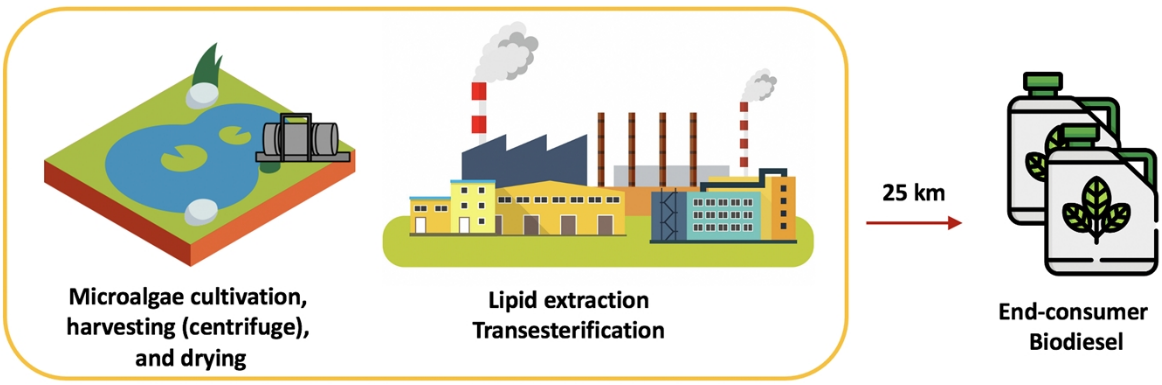

Figure 2: Overview of the supply chain for the current study.

Table 2. Uncertainty Variables.

Variables	Unit	Lower Boundary	Upper Boundary
Chlorella vulgaris Productivity	g/L/d	0.01 (Liang et al., 2009)	0.20 (Rodolfi et al., 2009)
Chlorella vulgaris FAME Productivity	$\%\frac{\text{wt biodiesel (g)}}{\text{wt algal biomass (g)}}$	15.18 (Chu et al., 2013)	17.62 (Chu et al., 2013)
Nannochloropsis sp. Productivity	g/L/d	0.09 (Gouveia and Oliveira, 2009)	0.21 (Rodolfi et al., 2009)
Nannochloropsis sp. FAME Productivity	$\%\frac{\text{wt biodiesel (g)}}{\text{wt algal biomass (g)}}$	14.26 (Das et al., 2011)	15.11 (Das et al., 2011)
FAME Biodiesel Price	USD/t	1,290 (Neste, 2022)	2,600 (Neste, 2022)
Chlorella vulgaris Price	USD	125 (UTEX Culture Collection of Algae, 2022a)	242 (American Type Culture Collection, 2021a)
Nannochloropsis sp. Price	USD	125 (UTEX Culture Collection of Algae, 2022b)	400 (American Type Culture Collection, 2021b)

Table 3. Fixed Parameters for this Study.

Variables	Unit	Value	Remarks
Raw Material Cost			
BG11 culture medium	USD/mL	0.50 (Sigma Aldrich, 2022)	Culture medium for microalgae
Carbon dioxide, CO_2	USD/t dried biomass	91 (Davis et al., 2016)	
Other Operating Expenditure Cost			
Transportation fuel price	USD/L	0.51 (GlobalPetrolPrices.com, 2022)	
Transesterification process	USD	1,160,375 (Heo et al., 2019)	For 1000 kg biomass per h
Capital Investment Cost			
10 acre open pond (inclusive of CO_2 delivery, makeup water delivery, inoculum pond, on-site circulation, and dewatering)	USD	306,256,616.02 (Davis et al., 2016)	Scaled to 2 acre sizing with a scaling factor of 0.6
Transesterification process	USD	392,749.00 (Heo et al., 2019)	
Drum Dryer	USD	293,822.10 (Fasaei et al., 2018)	
Centrifuge	USD	272,057.50 (Fasaei et al., 2018)	

4. Results and discussions

4.1 NPV Distribution

The financial probability curve extracted from the Monte Carlo simulation model is presented in Figure 3. It can be observed that the length of the curve for *Chlorella vulgaris* derived FAME is larger than the length of curve for *Nannochloropsis Sp.* derived FAME. The length of the curve signifies the standard deviation of the NPV distribution. Based on the calculation, the standard deviation for *Chlorella vulgaris*-derived FAME and *Nannochloropsis Sp.*-derived FAME were found to be USD 798.43 x 10^6 and USD 695.90 x 10^6. A larger standard deviation represents a larger potential of risk involved in the investment of supply chain. From Figure 2, it can be observed that both microalgae species derived FAME biodiesel has a possibility to experience losses whereby the NPV value is less than zero. This implies that there is a possibility that the proposed supply chain is unable to payback with the 20 y lifespan. Nevertheless, the mean NPV for *Chlorella vulgaris* derived FAME and *Nannochloropsis Sp.* derived FAME were found to be USD 961.93 x 10^6 and USD 970.48 x 10^6. The 95 % confidence interval for *Chlorella vulgaris* derived FAME and *Nannochloropsis Sp.* derived FAME were calculated to be USD 15.65 x 10^6 and USD 13.64 x 10^6. In other words, the 95 % confidence interval for *Chlorella vulgaris* derived FAME and *Nannochloropsis Sp.* derived FAME are found to be USD 946.28 x 10^6 to USD 977.58 x 10^6 and USD 956.84 x 10^6 to USD 984.12 x 10^6. The above findings are due to the large range of upper and lower boundary of the uncertainties listed. For instance, both microalgae species' productivity has a large difference in their upper and lower boundary that will ultimately result in a greater standard deviation calculated for the uncertainty during data pre-processing stage. This further result in a larger range of simulated NPV as observed.

As a result, a large difference in the amount of biodiesel produced will therefore be experienced, which eventually affects cash in flow during each operating year. Similarly, the FAME biodiesel selling price which has a significant difference between the upper and lower boundary, has therefore, significantly impacted the cash in-flow of the MSC. In comparison between the two microalgae species, *Nannochloropsis sp.* is deemed as a more prominent choice for the biodiesel production process since it is capable of offering a higher mean NPV value (0.89 % higher than *Chlorella vulgaris*) and lower standard deviation (12.8 % lower than *Chlorella vulgaris*). Although both of the microalgae species-derived biodiesel showed great financial profitability in terms of the mean NPV value, there are still other cost factors to be considered besides the ones listed in Table 2 and Table 3 to produce a more realistic result. It is noteworthy that the current results obtained are based on the input data currently available and will be subjected to changes when the input data is altered or more input data is included.

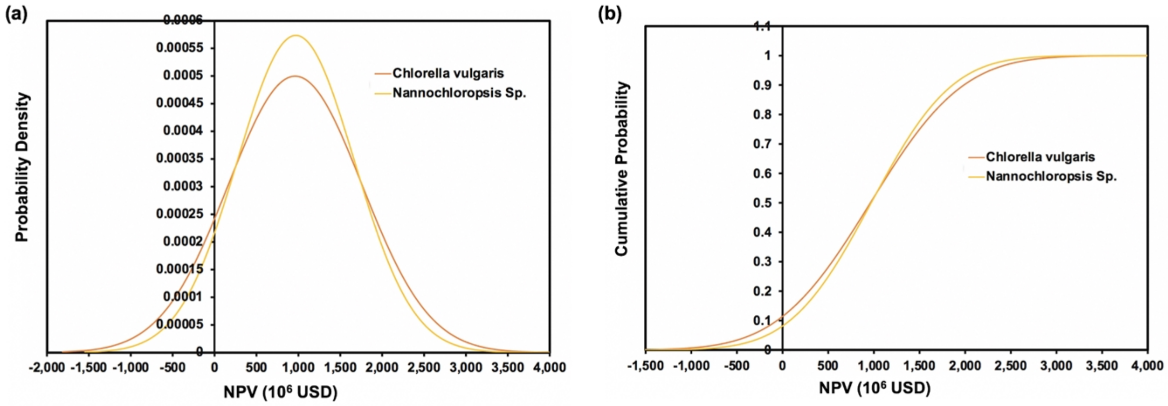

Figure 3: Monte Carlo Simulation Forecast for Microalgae-derived FAME Biodiesel Supply Chain (a) Probability Density; (b) Cumulative Probability.

5. Conclusions

As the global economy continues to grow, alternative feedstock sources that are economically and environmentally sustainable are critical to ensure the sustainability of the present and future generations. The economy is dynamic whereby the current economic situation cannot guarantee the future economic status can be as equally stable or favourable. This paper proposed a Monte Carlo simulation model that presents a financial probability profile for the evaluation of FAME biodiesel-based supply chain. The extracted financial probability profile can be utilized as a guideline in decision-making to evaluate the risk involved in the investment. The findings from the study had found *Nannochloropsis sp.* was a more favourable feedstock compared to *Chlorella vulgaris* with a higher mean NPV value by 0.89 % and lower standard deviation by 12.8 %. Nonetheless, both feedstocks still present a possibility to face losses where the NPV can be less than zero. The limitations to the current case study are that it was assumed all the produced FAME biodiesel can be sold without considering the required demand. Possible extension to this study is the inclusion of product demand as an uncertainty into the currently developed model. When users randomized microalgae productivity and FAME biodiesel demand, the cultivated microalgae may at times exceed amounts of microalgae required to meet FAME biodiesel demand. The scope of the current work can be further enlarged to include selling of excess FAME biodiesel produced to be utilized in other sectors. Another possible extension is incorporating artificial intelligence (AI) model in MSC evaluation to forecast the influence of weather on the microalgae growth productivity. Aside from that, the current study can be performed more in depth to evaluate the influence of each single uncertainty on the economic performance for the same microalgae species.

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