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Circular Sustainability Optimisation Model for Diverse Oil Crops Feedstock System via Element Targeting Approach

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Need of oil crops for bio-diesel production has been increasing due to its sustainable characteristic as compared to fossil fuel. Nonetheless, effort to ensure sustainable practise along bio-diesel production is essential to prevent back-fire from sustainable development. Each oil crop production and plantation activities are unique, leading to various in sustainability profile. In such context, systematic process optimisation for oil crop utilisation and selection is critical to ensure highest overall sustainable performance in the diverse oil crop system. This research adapts concept of element targeting in multi biomass selection to determine best diverse oil crop utilisation strategic. Various sustainable indexes are considered such as land used, carbon footprint, deforestation, water usage and fertiliser usage are considered. Cost calculation including transportation and production cost is incorporated in the study, while concept of circular economy is incorporated into the model by considering circular carbon element within the system. Demonstration case study is discussed to evaluate the performance of the model. The result shows that rapeseed oil is favourable in highest sustainability case, soybean provide lower cost and sunflower promote less carbon release.

1. Introduction

There is an increasing demand for bio-diesel due to its sustainability characteristic as a renewable resource compared to the traditional fossil fuel. However, there have been various debates on the sustainability of oil crop plantations, such as deforestation of oil palm plantation in South East Asia regions. This has led to initiation of activities to ban palm oil utilisation in some Europe countries, disregard of the advantages of oil palm sustainable performance. The initiation has resulting major economy impact to the palm oil exporting countries in South East Asia. With the increasing demand for bio-diesel, diversification of bio-diesel source from various crops plantation is important to ensure sustainable, secure and consistent supply. Apart from that, different oil crops have dissimilar plantation activities and practises, leading to different sustainability profile in land usage, carbon footprint, deforestation, water usage and fertiliser usage. Thus, diversifying and mixing different oil crops in bio-diesel utilisation may help to improve overall sustainability profile for the industry.

In December 2015, Paris Agreement was signed by 195 nations to reduce the global greenhouse gas emissions in order to keep global temperatures “well below 2 °C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C (United Nations Framework Convention on Climate Change, 2015). Circular economy is a promising concept to evaluate and minimise carbon release from bio-diesel production based on regenerative and restorative of carbon footprint in plantation. High carbon release materials are problematic because removing carbon from environment required huge amount of investment and not sustainable. Recently, the Dutch government’s allocated 150 million euros for the construction of industrial-scale biodigesters to capture and valorise methane emissions from cow manure, which is expected to dent the country’s agricultural

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emissions (Boztas, 2016). Similarly, carbon released from crop processing, transportation, cultivation and carbon fixation from plantation is critical to evaluate the sustainability of bio-diesel production. Complexity of sustainable bio-diesel production has led to development of various optimisation methods, such as an input-output model was suggested for sustainable oil palm plantation development by Foong et al. (2019). In logistic, Li and Zhao (2018) researched on the optimisation of chemical transportation using linear programming model. Whereas swarm particle optimisation was used by Wu et al. (2018) to optimise chemical productions. Nonetheless, none of the researcher has explored into development of sustainable bio-diesel development via feed diversification. In this research, a systematic oil crop utilisation model for process supply chain optimisation is proposed to consider the sustainability profile, production cost and circular carbon element in bio-diesel utilisation system. From the inspiration of multi-biomass selection model in Lim et al. (2018), Element Targeting approach is used in this study to consider multiple sustainability profile of various oil crops including fertiliser usage, land usage, water usage, carbon footprint and deforestation. Based on the acceptable range of each sustainable profile, a diverse oil crops utilisation system for bio-diesel production can be designed with optimum sustainability, cost and circular carbon element performance. In this study, land and sea transportation cost of bio-diesel produced from various oil crop is considered to determine the minimum requirement for production cost. With the concept of circular economy, carbon emission is determined based on carbon release and fixation from plantation activities-to-processing-to-product to identify circular sustainability of the system in terms of circular carbon element. With consideration of three aspects, i) oil crop sustainability profile, ii) production cost, and iii) circular carbon element, the proposed optimisation model can be used in oil crops management and development strategy to create a diverse bio-diesel utilisation system.

2. Methodology

In order to obtain a diverse oil crop system with optimum sustainable characteristic, a two-step optimisation process is adapted to achieve an optimum performance of the system in terms of sustainability profile, production cost and circular element. Thus, the model proposed in this study includes multiple objectives/criteria, *m* optimisation that considered various oil crops, *i* and their respective sustainability indexes, *j*. The model also considered the supply chain network for oil crop distribution from respective resources location, *r* to respective process plant, *p*. Firstly, the proposed model is used to optimise each three criteria, *m* individually by i) maximising the sustainability profile, ii) minimising the total cost and iii) minimising the circular carbon element emission. By using the extreme cases of each aspect obtained from the first step, the overall performance can be evaluated in the second stage by maximising the overall performance score.

2.1 Sustainability profile criteria

Sustainability score, S_{ij} for each oil crop, *i* is evaluated based on each sustainable aspect, *j* including land usage, carbon footprint, deforestation, water usage and fertiliser usage. The sustainability indexes, SI_{ij} are calculated based on Eq(1) by comparing the sustainability score of each sustainable aspects, *j* with the maximum, S_max_{ij} and minimum S_min_{ij} value among the considered oil crops, *i*. For example, score of 100 % is assigned to oil palm in land usage aspect due to highest oil yield per unit land. In contrast, 0 % is assigned in deforestation due to highest deforestation activity.

$$SI_{ij} = 100\ \% \times \frac{S_{ij} - S\_Min_{ij}}{S\_Max_{ij} - S\_Min_{ij}} \qquad \forall\ i,j \in I,J \qquad (1)$$

Sustainable indexes of oil crops mixture, SI_Mix_{ij} is determined based on the individual indexes, SI_{ij} of each oil crop i and sustainability aspect *j*, and the respective utilisation ratio of each crops, X_i.as shown in Eq(2). The summation of utilisation ratio of each oil crops is always equal to one as per Eq(3). To ensure the proposed mixture of oil crop utilisation fulfilled the requirement of each sustainability aspect, *j*, a constraint is introduced such that the sustainability indexes of the proposed oil crop utilisation is higher than the minimum sustainability profile, SI_min_j requirement as shown in Eq(4). An overall sustainability index, *Overall_SI* in introduced to evaluate the performance of the oil crop utilisation mixture as shown in E(5). This equation is used as objective function for first step optimisation to maximise sustainability profile criteria. Priority factor W_j for each sustainability aspect *j* is introduced to improve the model flexibility to handle different scenarios. For example, higher priority factor value for carbon footprint index is set to ensure the result provides the best strategy to utilise mixture of bio-diesel to minimise carbon footprint.

$$SI\_Mix_j = \sum_{i=1}^{I} \left[X_i \times SI_{ij} \right] \qquad \forall\ j \in J \qquad (2)$$

$$\sum_{i=1}^{I} X_i = 1 \tag{3}$$

$$SI\_Mix_j \geq \text{SI\_Min}_j \qquad \forall\, j \in J \tag{4}$$

$$Overall\_SI = \frac{\sum_{j=1}^{J}\left[\, SI\_Mix_j \times \text{w}_j \right]}{\sum_{j=1}^{J} \text{w}_j} \tag{5}$$

2.2 Cost criteria

Total production cost for each oil crop utilisation is also considered in this model. Transportation cost, *Transport_cost* is determined by using Eq(6), where Demand represents the demand of bio-diesel at bio-diesel mixing plant; $d_{r\,i\,p}$ represents truck travelled distance to deliver oil crops, *i* from resource *r* to plant *p* with road freight rate of RFR. Second term of the right-hand-side of Eq(6) covers transportation by sea. Sea freight rate, SFR is calculated based on Tanker World Scale Index as per Eq(7) (Muruganand, n.d.). Total production cost of bio-diesel, *Production_cost* is calculated based on production cost per unit of bio-diesel, P_i from each oil crops, *i* is calculated using Eq(8) and total cost of the system governed by Eq(9). This equation is used as the objective function to minimise the total cost, *TC* for cost criteria consideration.

$$Transport\_cost = \sum_{r,i,p=1}^{R,I,P} \left(\text{Demand} \times X_i \times \text{RFR} \times \text{d}_{r\,i\,p}\right) + \sum_{i=1}^{I} \left(\text{Demand} \times X_i \times \text{SFR}\right) \tag{6}$$

$$\text{SFR} = \frac{\text{Daily hire + Port Cost + Fuel cost + Canal dues}}{\text{Cargo Quantity}} \tag{7}$$

$$Production\_cost = \sum_{i=1}^{I} \left(\text{Demand} \times X_i \times \text{P}_i\right) \tag{8}$$

$$TC = Transport\_cost + Production\_cost \tag{9}$$

2.3 Circular Carbon Element criteria

The overall circular carbon element, C_i for each oil crops, *i* is evaluated based on carbon emission per land used, C_emit_i and carbon fixation, C_fix_i per land used as per Eq(10). Eq(11) shows calculation of total circular carbon element score, *TCCE*, where Y_i is refers to oil yield per unit of land used for each corps, *i* to determine total land usage for plantation for net carbon emission calculation. This equation is used as objective function to minimise the net carbon emission of the system during circular carbon element criteria consideration.

$$\text{C}_i = \text{C\_emit}_i - \text{Carbon\_fix}_i \qquad \forall\, i \in I \tag{10}$$

$$TCCE = \sum_{i=\text{i}}^{I} \left(\frac{\text{Demand} \times X_i}{\text{Y}_i} \times \text{C}_i\right) \tag{11}$$

2.4 Overall Performance Score of Oil Crop Mixture

In order to obtain an overall performance score of the system based on the listed criteria, *m*, (sustainable index, cost, and circular carbon element), three extreme cases are generated to i) maximising Eq(5), ii) minimising Eq(9), and iii) minimising Eq(11). Similar to Eq(1), Eq(12) shows calculation of criteria index, CI_m which is used to determine the level of satisfaction of each criteria score CS_m with respect to the maximum criteria score, CS_max_m and minimum criteria score, CS_min_m in the extreme cases. An overall performance of the system across all three criteria can be optimised as per Eq(13). Another priority factor, F_m is introduced to provide model flexibility to prioritise each criteria, *m* in different scenario or application. This equation is used as the objective function in second stage optimisation to maximise the overall performance, *OP* of the system.

$$CI_m = 100\ \% \times \frac{CS_m - \text{CS\_min}_m}{\text{CS\_max}_m - \text{CS\_min}_m} \qquad \forall\, m \in M \tag{12}$$

$$OP = \frac{\sum_{m=1}^{M}[\ CI_m \times F_m]}{\sum_{m=1}^{M} F_m} \quad (13)$$

3. Case Study

A demonstration case study is constructed to show the performance of the proposed model. Processing plant for bio-diesel mixing and utilisation is set to be in Germany, and the bio-diesel is obtained from various region, namely oil palm from Malaysia, rapeseed from Rostock, Germany, soybean from Verona, Italy and sunflower from Toulouse, France. The location of resources is determined based on the total production percentage in European Union (USDA, 2014). The proposed model is used to determine the optimum oil crop utilisation ratio based on sustainable index, cost and circular carbon element. Table 1 shows the data for sustainable index for each oil crops based on Eq(1). Five indexes were considered, namely deforestation, oil yield, fertiliser, carbon footprint, and water usage. The minimum score of each sustainable index of the oil crop mixture is set to be 40 % as per Eq(4). The individual oil crop deforestation percentage was determined based on ratio of total deforestation area and total plantation area from European Commission (2013) and Lima et al. (2011). The land usage data was extracted by considering the oil yield in gal/ acre extracted from Kurki et al. (2010) to estimate plantation land needed. Besides, the fertiliser emission of oil palm was extracted from Saswattecha et al. (2015), fertiliser emission of soybean was extracted from Zortea et al. (2018), while fertiliser emission of rapeseed and sunflower was extracted from Forleo et al. (2018). Moreover, the data for water usage of oil crops were extracted from Mekonnen and Hoekstra (2010) and sources for carbon footprint were obtained from Muñoz et al. (2014). The bio-diesel demand was estimated at 13.9 million tones and Table 2 shows the transportation distance (estimated from Google Map) from respective resource location to the process plant via truck with a fix transportation cost, RFR of \$ 0.0807 /t.km. Noted that additional shipment transport of palm oil from Malaysia to German via sea freight was considered with the distance of 15,864 km at the rate, SFR of \$ 0.0526 /kg bio-diesel. Production cost of bio-diesel from respective oil crops is also summarised in Table 2 with consideration of raw material cost and operating cost. Table 3 shows the calculation of carbon emission for each oil crops.

Table 1: Sustainable indexes data for each oil crop

	Oil Palm		Soybean Oil		Rapeseed Oil		Sunflower Seed Oil	
	Score	SI (%)	Score	SI (%)	Score	SI (%)	Score	SI (%)
Land deforestation percentage (%)	23.10	0	14.90	36	0.40	100	3.10	88
Oil yield (gal oil/ acre)	610	100	46	0	122	14	98	9
Fertiliser emission (kg)	0.4035	63	0.0983	100	0.8830	4	0.9159	0
Carbon footprint(kg)	2,024	0	2,024	0	262	100	760	72
Water Usage (m3/ton)	1,098	100	2,271	54	2,145	48	3,366	0

Table 2: Land transportation distance of each bio-diesel to processing plant and its respective production cost

	Oil Palm	Soybean Oil	Rapeseed Oil	Sunflower Seed Oil
Land distance (km)	175	1,112	154	1,723
Production cost (\$ /kg bio-diesel)	0.72 (Ong et al., 2012)	0.61 (Haas et al., 2006)	1.07 (El-Enin et. al., 2013)	1.06 (Adhikari & Illukpitiya, 2017)

Table 3: Carbon released and fixation by each oil crop

	Oil Palm	Soybean Oil	Rapeseed Oil	Sunflower Seed Oil
Emission from cultivation (kg CO_2/t of oil)	101.0	535.5	151.0	321.2
Emission from transportation (kg CO_2/t of oil)	212.25	2.80	4.90	6.70
Emission from processing (kg CO_2/t of oil)	51.00	293.30	450.55	140.00
Yield (t/ha/y)	4.5	2.2	3.1	2.5
Total emission (kg CO_2/t/ha)	1,639.13	1,829.52	1,880.00	1,169.75
Carbon fixation (kg CO_2/ha/y)	-2,497.5	-2,098.0	-2,449.8	-2,084.0
Net emission, C_i (kg CO_2/ha/y)	-858.37	-268.48	-569.80	-914.25

The model was solved using General Algebraic Modelling System (GAMS). Result from the first stage optimisation of each extreme cases (maximising *Overall_SI*, minimising *TC* and minimising *TCCE*) are tabulated in Table 4. All priority factors were set to be one to reflect equal importance of each sustainable index. In each case, optimum oil crops usage ratio, X_i were suggested for difference objective functions. The result shows approximately 46 % of bio-diesel from rapeseed oil, 43 % from oil palm and 11 % from soybean should be used in order to obtain maximum sustainable rating at 51.16 %. In other case, soybean oil crop utilisation should be prioritised in order to obtain lowest total cost. Likewise, sunflower should be utilised more to achieve minimum circular carbon element or carbon release. Based on the first stage optimisation, second stage optimisation was conducted to obtain the highest overall sustainable performance score. Priority factors, F_m were assumed to be one for equal priority of each aspect where the result shows an optimum overall performance of 57.2 %. The oil crop utilisation ratio for the suggested optimum result was found to be identical to the case of maximising *Overall_SI* in Table 4. In this optimum result, the sustainability criteria was achieved 100 %, cost criteria was achieved only 54 % and circular carbon element criteria was achieved the lowest at 18 % as show in Table 5. The individual sustainability index also tabulated in Table 5.

Table 4: Result after optimising one of the aspects (1st step optimisation)

CI_m	MAX *Overall_SI*	MIN *TC*	MIN *TCCE*
Sustainable Rating of Mixture (%)	51.16	47.10	39.56
Total Cost ($ m)	12,659.7	11,920.8	13,515.5
Circular carbon element (t CO_2/ t of oil)	-2,493,590	-2,240,940	-3,642,950
X_i			
Oil Palm	0.4273	0.2515	0.2534
Rapeseed	0.4589	0.3596	0.0000
Soybean	0.1138	0.3888	0.2412
Sunflower	0.0000	0.0000	0.5054

Table 5: Each criteria fulfilment and mixture sustainability indexes for optimum overall performance case

	MAX *Overall_SI*	MIN *TC*	MIN *TCCE*		
CI_m	100 %	54 %	18 %		
	Fertiliser (%)	Carbon Footprint (%)	Land usage (%)	Deforestation (%)	Water usage (%)
SI_Mix_i	40.00	45.89	48.92	50.00	71.00

The mixture sustainable index SI_Mix_j was calculated using Eq (2). The result shows fertiliser index fulfilled the minimum requirement of 40 % while water usage index achieved highest score at 71 %. Based on the result, the optimum oil crops ratio is favorable towards rapeseed oil and palm oil due to both oil crops have relatively higher sustainability score shown in Table 1. Thus, increase utilisation of both oil crops will provides better overall sustainable index performance. In contrast, soybean oil has lower utilisation fraction due to lack of performance in carbon footprint and land usage. This shows a significant improvement opportunity for soybean stakeholders to enhance overall carbon footprint and efficiency of land usage. Similarly, land and water usage should also be a concern in sunflower plantation to compete with other oil crop in term of sustainability. However, in the event where cost is the priority and value of 2 is assigned in cost criteria factor, new optimum solution was obtained. Utilisation of bio-diesel from oil palm was suggested as 0.2515, rapeseed as 0.3596, soybean as 0.3888, sunflower seed as 0, while the overall performance of system increases to 66.24 %. Similarly, when assigned circular carbon element as priority, the optimum crop utilisation fraction changes to oil palm as 0.3116, rapeseed as 0, soybean as 0.2047, sunflower seed as 0.4837, while the overall performance of system was 52.64 %. With the flexibility of the proposed model, utilisation strategic of each oil crop for bio-diesel production can be generated based on the priority of each sustainability index and criteria. Ultimately, this model can be used as a guideline to produce a diverse agriculture development, such as to strategise amount of plantation of each oil crop based on the proposed ratio to achieve better sustainable practises in bio-diesel production.

4. Conclusions

In conclusion, this research proposed an optimisation model to determine multi oil crop utilisation in bio-diesel production with consideration of sustainability index, cost and circular carbon element. A demonstration case study was illustrated in this paper to determine oil crop utilisation strategy in bio-diesel production. Priority factor was used to enhance model flexibility for various scenarios, such as providing strategy to focus on cost saving instead of sustainability profile. This provides flexibility to accommodate different stakeholders and their respective optimisation intention. Future improvement of model is possible by considering fluctuation of process performance based on differences in oil crop and bio-diesel properties. In addition, consideration of food supply chain in parallel with energy supply chain also will provide insightful oil crop plantation and development strategy.

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