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# Synthesis of A Sustainable Sago-Based Value Chain via Fuzzy Optimisation Approach

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**Abstract.** Sago starch is one of the staple foods for human, especially in Asia's Region. It can be produced via sago starch extraction process (SSEP). During the SSEP, several types of sago wastes are generated such as sago fiber (SF), sago bark (SB) and sago wastewater (SW). With the increase in production of existing factories and sago mills, the sago industrial practice in waste disposal management is gaining more attention, thus implementation of effective waste management is vital. One of the promising ways to have effective waste management is to create value out of the sago wastes. In a recent study, sago-based refinery, which is a facility to convert sago wastes into value-added products (e.g., bio-ethanol and energy) was found feasible. However, the conversion of other value added products from sago wastes while considering the environmental impact has not been considered in sago value chain. Therefore, an optimum sago value chain, which involved conversion activities of sago wastes into value-added products, is aimed to be synthesised in this work. The optimum sago value chain will be evaluated based on profit and carbon emissions using fuzzy-based optimisation approach via a commercial optimisation software, Lingo 16.0. To illustrate the the developed approach, an industrial case study has been solved in this work.

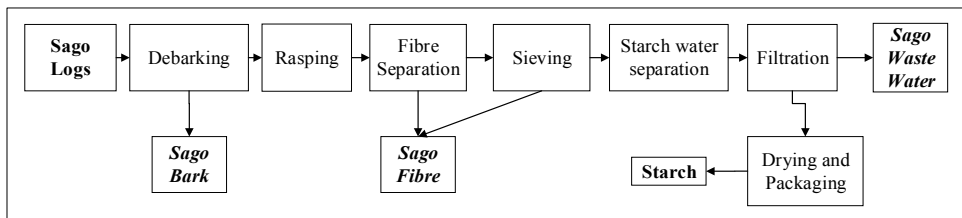
## 1 Introduction

Sago palm (*Metroxylan Sagu*) is one of the underutilised crops that can potentially produce staple food for human, especially in Asia's Region. The sago palm produces sago starch which contains high carbohydrates that can be obtained from the trunks of sago palm. Such palm is an excellent crop for sustainable agriculture due to its ability to thrive in most soil conditions and it requires only one time planting that has the ability of self-sustain by producing its young tree, also known as suckers or tillers [1]. It can also be served as an income for poverty alleviation as it is commonly planted in rural areas [2]. Karim et al. [3] states that, under optimal farming practices, up to 25 metric tonnes of sago starch per hectare annually can be achieved, which is roughly 3 - 4 times the starch yield of staple crops such as rice (6 tonnes/ha/yr) or wheat (5 tonnes/ha/yr) [2], [4]. Sago starch can be produced via sago starch extraction process (SSEP) as shown in Figure 1. As shown, there

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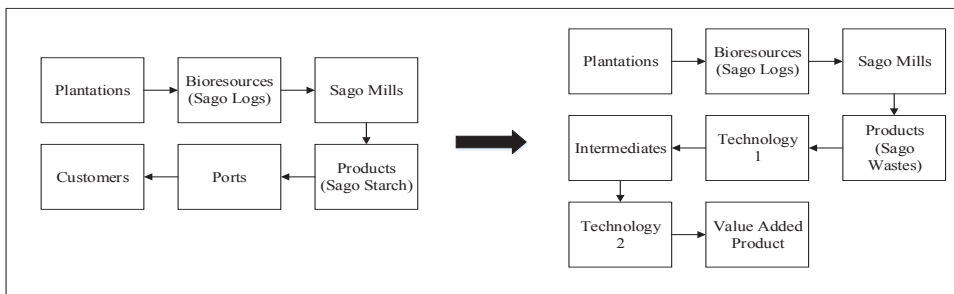
are several types of sago wastes that are generated during the process, namely sago fiber (SF), sago bark (SB) and sago wastewater (SW)[4].



**Fig. 1.** Block Flow Diagram of SSEP

In current industrial practices, SB is used as timber fuel for firing or will be disposed around the mills to be used as flooring material [4]. SF is used as animal feed, otherwise, it will be released into nearby streams along with SW. According to Adeni et al. [5], SW, combined with SF, represents high organic materials, chemical oxygen demand (COD) and biochemical oxygen demand (BOD), which does not comply to the discharged regulations set in Environmental Quality Act, 1974. The installation of pollution control devices can be costly, approximately 20-50% of the total investment for a large scale production mill, which is not preferred by producers in this relatively low value commodity industry [5]. SF and SB, which are lignocellulosic waste (LCW), contains residue starch which can be converted into value added products such as glucose, which can be further refined to higher value product such as bio-fuels.

To address the aforementioned issues, a viable alternative is to create value out of the sago wastes to improve the current performance of sago value chain. As mentioned, SF and SB could be utilised for the production of value added products (i.e., ethanol, organic acids, enzymes and others)[6]. However, the idea of converting sago wastes into valuable products is still in its infancy. In most recently, Wan et al. [7] studied the feasibility of a sago-based refinery, which is a facility to convert sago wastes into value-added products (e.g., bio-ethanol and energy). The study results showed that it is feasible to convert sago wastes (SB and SF) into bioethanol and energy in sago-based refinery. In addition, Wan and her co-authors [8] also conducted a value chain analysis for sago industry to determine the optimum value chain pathway for sago industry. Value chain is a set of activities that are done to design, produce, market, deliver and support the product created by a party [9]. First proposed by Michael Porter, value chain divides break down a chain of activities into individual parts to scrutinise the dynamics of activities in order to reveal its strength and weaknesses, thus identifying value creation opportunities. Application of value chain in the sago industry has been pioneered by a study done by Wan et al. [8], whom developed a value chain to improve the sustainability of the industry to identify value creation opportunities. However, the conversion of sago wastes into value-added products had not been considered in the sago value chain. Therefore, in order to further improve the economic and environmental performance of the sago value chain, this study aims to expand the previous work done by Wan et al [8], by introducing alternatives towards utilisation of sago wastes to create value added products while considering the environmental impact done to the sago value chain. Figure 2 showed the sago value chain done by Wan et al. [8] and the sago value chain has been expanded in this work by considering value added product conversion technologies (i.e., technology 1, intermediates products, technology 2, and value-added products).



**Fig. 2.** Proposed Value Chain of Sago Industry in this Study

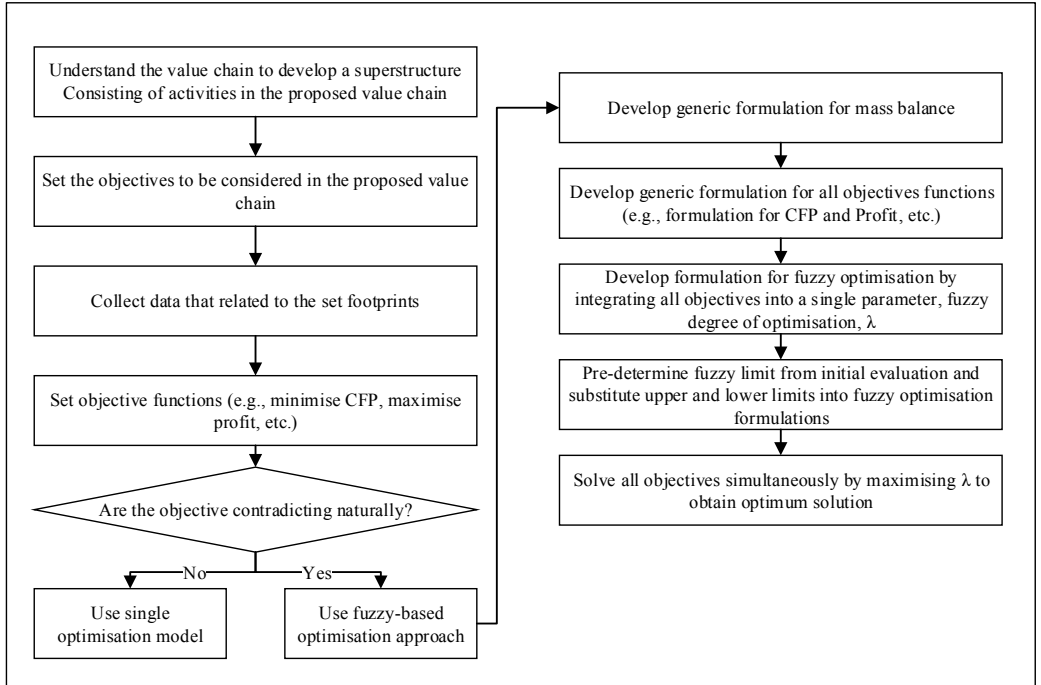
Douglas et al. [10] adapted fuzzy-based optimisation approach based on ‘max-min’ aggregation to synthesis of a sustainable integrated bio-refinery. The author’s study did not identify the optimal value chain in the sago industry. However, the author has proven that fuzzy-based optimisation approach can be used to obtain an optimal pathway from a superstructure, while considering the economic and environmental impact. Therefore, in order to further improve the economic and environmental performance of the sago value chain, this study aims to expand the previous work done by Wan et al. [8], by introducing alternatives towards utilisation of sago wastes to create value added products to maximise profit, while minimising environmental impact done of the sago value chain. To determine the optimum pathway in this, a fuzzy-based optimisation approach will be developed in this work to find an optimal solution to the multi-objective model in this study. To illustrate the application of proposed model, a real industrial case study has been solved.

## 2 Methodology

A generic wastewater treatment superstructure is first developed to show all possible pathway to treat wastewater as shown in Figure 1. Based on this generic superstructure, MFCA-based approach has been developed by formulating mathematical equations for each treatment in WWTP as shown in following sections. These equations included mass balance equation, contaminant equation, and cost computation equations. To demonstrate the developed approach, an industry case study, organic wastewater treatment plant is solved.

### 2.1 Generic superstructure of wastewater treatment

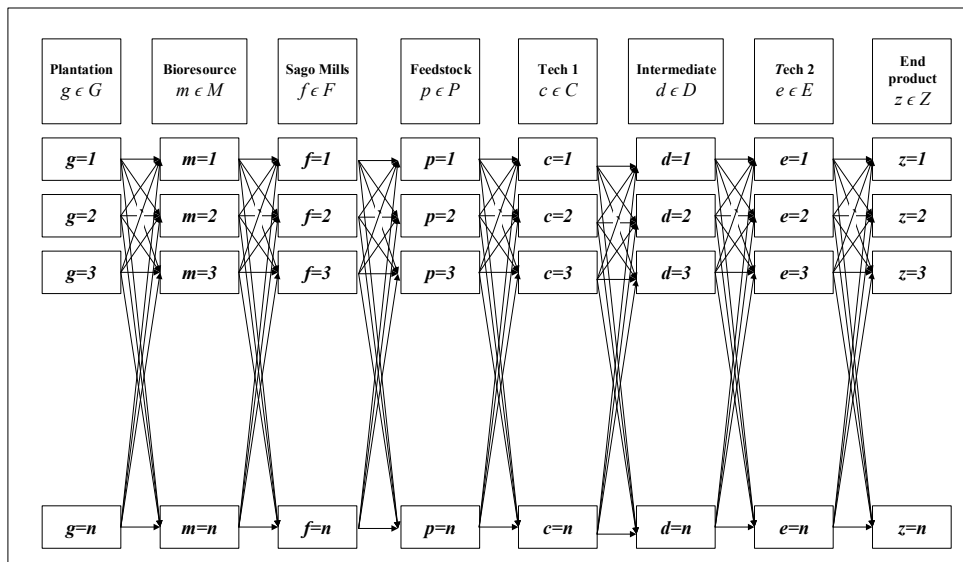
Fig. 3 illustrates the methodology using the fuzzy-based optimisation approach. First step is to determine the superstructure based on the layers of activities from the proposed value chain in this study. Then, the objectives of the study have to be set and relevant data needs to be collected based on the objective set. In this study, the objective of maximising profit and minimising CFP of the sago value chain is set for synthesis of an optimal value chain for sago waste conversion. Profit and CFP objectives are contradictory. Therefore, a fuzzy-based optimisation approach has to be developed. Douglas et al. [10] Following the fuzzy-based optimization approach, the mass balance has to be formulated, as well as the formulation of equations necessary for all objective functions, which in this case, is the profit and CFP equations. The developed formulations are then solved using a commercial optimization software Lingo V.16.



**Fig. 3.** Methodology Flow Chart for Fuzzy-Based Optimisation Approach

To illustrate the alternatives stages of the value chain, superstructure is first developed. As shown in Figure 4, the superstructure illustrates the seven layers of activities that is considered in the value chain proposed in this study. With reference to the approach used by Wan et al. [8], the activity starts from the harvesting palms from a set of plantation  $g \in G$  with annual available palm  $F_g^{av}$ , processed and converted to a set of bio-resource  $m \in M$ , which is limited to only sago logs in this study. The sago logs are then sent to a set of sago mill  $f \in F$  with starch production capability  $F_f^{starch.lim}$ . The sago mill  $f$  turns the bio-resource  $m$  into a set product  $p \in P$  based on the amount of starch produced from the sago mill, which in the case of this study, represents the sago wastes. In the study of Wan et al. [8], the product considered in the author's study is just sago starch in the product  $p$  layer. However, in this study, sago starch would not be focused, unlike as shown in the works of Wan et al. [8]. Sago wastes (e.g., SB, SF, SW) will be considered in this study instead.

The sago waste is then sent to a set of conversion technologies  $1 c \in C$  to produce a set of Intermediate product  $d \in D$ . Intermediate product  $d$  is then sent for further processing in a set of technology  $2 e \in E$  to produce a set of end product  $z \in Z$ . To model this superstructure, mathematical equations have been formulated in following sections.



**Fig. 4.** Generic Superstructure

### 2.1 Mass Balance Equations

The mass balance for the first four layers of activities illustrated by the value chain in this study is adopted from the work done by Wan et al [8]. The total number of palms harvested  $F_g^{out}$  (palm/y) from plantation  $g$  has to be less than available palms to ensure a sustainable harvesting process, as:

$$F_g^{av} > F_g^{out} \quad \forall g \tag{1}$$

Harvested sago palms from plantation  $g$  are then converted into bio-resource  $m$  before its sent to sago mill  $f$ . Currently, the only bio-resource  $m$  sent to sago mills are sago logs. Therefore, given the conversion of palms to sago logs  $X_{g,log}$ , the total amount of sago logs sent to sago mill  $f$ ,  $F_{g,log}^{in}$  (log/y) can be determined via:

$$F_{g,log,f}^{in} = F_{g,f}^{out} X_{g,log} \quad \forall g \tag{2}$$

The total sago logs transported to sago mill  $f$  is the determined via:

$$F_f^{in} = \sum_{g=1}^G F_{g,log,f}^{in} \quad \forall f \tag{3}$$

It is noted that sago logs can be transported via roads or river. However, only road transportation is considered in this study, similar to the study done by Wan et al.[8]. Given a lorry capacity  $C_{weightlim}^{lorry}$  (t/trip) and weight per log  $W_{log}$  (t/log), the number of trips needed to transport the sago logs from plantation  $g$  to sago mill  $f$   $n_{g,f}^{trip}$  (trip) is determined via

$$n_{g,f}^{trip} \geq \frac{F_{g,\log,f}^{in} W_{\log}}{C_{weight\ lim}^{lorry}} \quad \forall g \forall f \quad (4)$$

In sago mill  $f$ , the sago logs are converted into sago starch, producing sago wastes as by-products, labelled as product  $p$  in this study. To calculate the amount of starch produced from sago mill  $f$   $Starch^f$  (t/y), Equation (5) is formulated.

$$Starch^f = \sum_{g=1}^G F_{g,\log,f}^{in} X_{g,\log,starch} \quad \forall f \quad (5)$$

Given that each sago mill  $f$  has a production capacity  $F_{Starch}^{av}$  (t/y) which cannot be exceeded, hence, the equation below is included in the model

$$Starch^f < F_{Starch}^{av} \quad \forall f \quad (6)$$

To satisfy sago demand,  $StarchDemand$  (t/y) which is set at 32,000 t/y in this study, the Equation (7) is added into the model.

$$StarchDemand = \sum_{f=1}^F starch^f \quad (7)$$

The amount of product  $p$  produced from sago mill  $f$  from SSEP  $F_{f,p}^{out}$  is calculated via:

$$F_{f,p}^{out} = Starch^f X_{starch,p} \quad \forall f \forall p \quad (8)$$

Hence, the amount of product  $p$  produced  $F_p^{in}$  (t/y) from all sago mills is calculated as:

$$F_p^{in} = \sum_{f=1}^F F_{f,p}^{out} \quad \forall p \quad (9)$$

Product  $p$  is then sent to technology 1  $c$  to be converted into intermediate  $d$ . The amount of product  $p$  sent to technology 1  $c$   $F_c^{in}$  (t/y) is as

$$F_c^{in} = \sum_{p=1}^P F_{p,c}^{in} \quad \forall c \quad (10)$$

In technology 1, the amount of intermediate  $d$  produced from product  $p$  is dependent on the conversion  $X_{p,b}^c$ , as:

$$F_{c,d}^{out} = F_c^{in} X_{p,d}^c \quad \forall c \forall d \quad (11)$$

Given the conversion  $X_{p,b}^c$ , the amount of intermediate  $d$  produced  $F_d^{in}$  (t/y) can be calculated via:

$$F_d^{in} = \sum_{c=1}^C F_{c,d}^{out} \quad \forall d \quad (12)$$

Next, intermediate  $d$  is the distributed to technology 2  $e$  via:

$$F_d^{out} = \sum_{e=1}^E F_{d,e}^{out} \quad \forall d \tag{13}$$

Between these 2 layers of activities, conversion of Intermediate  $d$  into suitable unit for Technology 2  $e$   $X_{d,e}^{unit}$  might be needed (e.g., conversion of syngas to power unit GJ in for CHP in technology 2  $e$ ). Therefore, the flow into technology 2  $e$  is calculated via:

$$F_{d,e}^{in} = F_{d,e}^{out} X_{d,e}^{unit} \quad \forall d \forall e \tag{14}$$

Hence, the amount received in technology 2  $e$   $F_e^{in}$  (unit/y) can be calculated via:

$$F_e^{in} = \sum_{d=1}^D F_{d,e}^{in} \quad \forall e \tag{15}$$

Similar to technology 1  $c$ , the amount produced from technology 2  $e$  is dependent on the conversion  $X_{d,z}^e$

$$F_{e,z}^{out} = F_{e,z}^{out} X_{d,z}^e \quad \forall e \forall z \tag{16}$$

Given the conversion  $X_{d,z}^e$ , the amount of end product  $z$  produced  $F_z^{in}$  (unit/y) can be calculated via:

$$F_z^{in} = \sum_{e=1}^E F_{e,z}^{out} \quad \forall d \tag{171}$$

## 2.2 Economic Performance Evaluation Equations

The economics performance of each activities is evaluated to determine the economic performance of the proposed value chain as a whole. In this study, the economic performance is defined as the difference between revenue obtained from production of end product  $z$  and the cost associated with the production of end product  $z$ . Similar to mass balance formulation at section 2.4, the economic performance of the first four layers of activities in the value chain is formulated with reference to the approach taken by Wan et al in [8]. At plantation  $g$ , the cost considered is the harvesting cost, as well as the transportation of bio resource  $m$  (sago logs) to sago mill  $f$ . the total cost of harvesting  $Tot\ cost_g^{Harvest}$  (USD/y), as well as total cost of transportation  $Tot\ cost^{Transportation}$  (USD/y) is calculated via:

$$Tot\ cost_g^{Harvest} = \sum_{g=1}^G U\ cost_g^{Harvest} F_g^{out} \tag{18}$$

$$Tot\ cost^{Transportation} = \sum_{f=1}^F \sum_{g=1}^G U\ cost^{km} d_{g,f}^{trip} n_{g,f}^{trip} \tag{19}$$

where  $U\ cost_g^{Harvest}$  is the cost of harvesting at plantation  $g$ ,  $U\ cost^{km}$  (USD/palm) is cost of transportation per km (USD/km) and  $d_{g,f}^{trip}$  (km) is the distance between plantation  $g$  and sago mill  $f$ . Hence the total cost incurred by all plantations  $Tot\ cost^{Plantation}$  (USD/y) is as:



$$Tot\ cost^{Plantation} = Tot\ cost_g^{Harvest} + Tot\ cost_g^{Transportation} \quad (20)$$

In sago mill  $f$ , the cost considered is the cost of process  $Tot\ cost_f^{Process}$  (e.g., electricity, water consumption) as well as raw material cost  $Tot\ cost_f^{Material}$  for the production of sago starch. In this study, sago wastes are assumed to be produced from SSEP without cost. The cost of transportation to refinery site for conversion via technology 1  $c$  is also not considered in this study. Therefore, the total cost of the sago mill is calculated by summing the cost of process and raw materials as showed in Equations (21) – (23):

$$Tot\ cost_f^{Material} = \sum_{f=1}^F U\ cost_f^{Material} Starch^f \quad (21)$$

$$Tot\ cost_f^{Process} = \sum_{f=1}^F U\ cost_f^{Process} Starch^f \quad (22)$$

$$Tot\ cost^{mill} = Tot\ cost^{material} + Tot\ cost^{process} \quad (23)$$

where  $U\ cost_f^{Material}$  (USD/t) and  $U\ cost_f^{Process}$  (USD/t) is the process and raw material unit cost to produce one tonne of sago starch in sago mill  $f$ . The total cost of production  $Tot\ cost^{Prod}$  (USD/y) is the calculated via:

$$Tot\ cost^{Prod} = Tot\ cost^{plantation} + Tot\ cost^{mill} \quad (24)$$

Next, the cost of the product  $p$   $Tot\ cost_p$  (USD/y) is considered in this study via:

$$Tot\ cost_p = \sum_{p=1}^P UCost_p F_p^{in} \quad (25)$$

where  $UCost_p$  is unit cost of product  $p$  (USD/t). In order to produce intermediate  $d$  from Technology 1  $c$ , there will be cost associated, which is calculated via:

$$Tot\ cost_b = \sum_{b=1}^B UCost_b F_b^{out} \quad (26)$$

where  $UCost_b$  (USD/t) is the unit cost of converting product  $p$  to intermediate  $d$ . Similarly, the cost to produce end product  $z$  via Technology 2  $e$  is calculated via:

$$Tot\ cost_e = \sum_{e=1}^E \sum_{z=1}^Z UCost_e F_e^{in} \quad (27)$$

where  $UCost_e$  (USD/t) is the unit cost of converting Intermediate  $d$  into End Product  $Z$  via technology 2  $e$ . Lastly, the total cost of the value chain  $Tot\ Cost^{Overall}$  (USD/y) is calculated via:

$$Tot\ Cost^{Overall} = Tot\ cost_{production} + Tot\ cost_b + Tot\ cost_c + Tot\ cost_d + Tot\ cost_e \quad (28)$$

Next, the revenue from the proposed value chain  $Tot Rev_z$  (USD/y) can be calculated via:

$$Tot Rev_z = \sum_{z=1}^Z Price_z F_z^{in} \tag{29}$$

where  $Price_z$  is the unit price for the End Product  $z$  produced. Therefore, in order to evaluate the economic performance of the proposed value chain, the overall profit  $Tot Profit^{Overall}$  (USD/y) is calculated via:

$$Tot Profit^{Overall} = Tot Rev_z - Tot Cost^{Overall} \tag{30}$$

### 2.3 Carbon Footprint (CFP) Computation Equations

The formulation of CFP is done with reference to CFP formulation done by Wan et al. [8]. The author considered the land use change (LUC) emission from the commercialisation of land for plantation. Given that the yearly emission per metre square from LUC  $UCFP_g^{LUC}$  (kg/m<sup>2</sup>.y) is 2.33 as reported by Fargione et al. [11]. The total land use change carbon footprint from plantation  $g$   $TotCFP^{LUC}$  (kg CO<sup>2</sup>/y) can be calculated via:

$$TotCFP_{plantation}^{LUC} = \sum_{g=1}^G A_g UCFP_g^{LUC} \tag{31}$$

$$TotCFP_{plantation}^{Fuel} = \sum_{f=1}^F UCFP_{km}^{fuel} n_{g,f}^{trip} d_{g,f}^{trip} \tag{32}$$

$$TotCFP_{plantation}^{total} = TotCFP_{plantation}^{LUC} + TotCFP_{plantation}^{Fuel} \tag{33}$$

Next, the total amount of power and fuel consumed in sago mill  $f$  is determined in order to calculate the CFP emission from sago mill  $f$ . The CFP from power consumption and fuel consumption is calculated via:

$$TotCFP_{mill} = \sum_{f=1}^F UCFP_{KWh}^{Power} E_{f, starch} Starch^f \tag{34}$$

Thus the total CFP emission from production process can be calculated via:

$$TotCFP^{Production} = TotCFP_{mill}^{Power} + TotCFP_{plantation}^{total} \tag{35}$$

Considering that product  $p$  in this study represents the sago waste produced from SSEP, the CFP emission for production of product  $p$  is assumed to be zero. However, the CFP emission from conversion of product  $p$  to intermediate  $d$  via technology  $c$  is considered in this study as:

$$TotCFP_b^{Total} = \sum_{b=1}^B UCFP_b F_b^{out} \tag{36}$$

Next, the CFP emission from conversion of intermediate  $d$  to end product  $z$  via technology  $2 e$  is the sum of the base CFP emission from processing intermediate  $d$  and also the specific power consumption of producing end product  $z$  via technology  $2 e$ .

$$TotCFP_e^{Base} = \sum_{e=1}^E UCFP_e^{base} F_e^{in} \quad (37)$$

$$TotCFP_e^{Specific} = \sum_{z=1}^Z \sum_{e=1}^E UCFP_{e,z}^{specific} F_{e,z}^{out} \quad (38)$$

$$TotCFP_e^{Total} = TotCFP_e^{Base} + TotCFP_e^{Specific} \quad (39)$$

The total overall CFP  $TotCFP^{Overall}$  (kg CO<sup>2</sup>/y) is calculated via:

$$TotCFP^{Overall} = TotCFP_{plantation}^{total} + TotCFP_{mill} + TotCFP_b^{Total} + TotCFP_e^{Total} \quad (40)$$

## 2.4 Fuzzy-Based Optimization Approach Equations

Cost and Environmental objectives are often contradictory, a fuzzy-based optimisation approach is adopted in this study to select the optimum pathway for conversion of sago waste to value –added products. Using the ‘min-max’ aggregation concept in fuzzy optimisation, the optimum pathway can be obtained by maximising the least satisfied constraints. Fuzzy optimisation combines multiple objectives into a single variable,  $\lambda$ , having a range of 0 to 1. In this study, the objectives are integrated into  $\lambda$  as shown in the equations below:

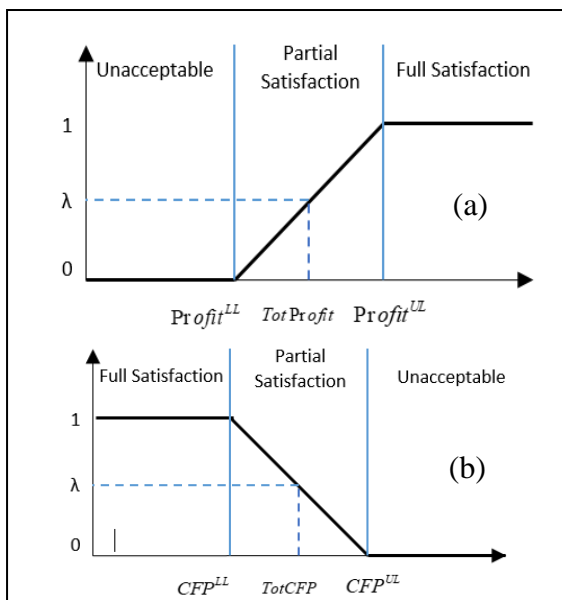
$$\frac{CFP^{UL} - TotCFP}{CFP^{UL} - CFP^{LL}} \geq \lambda \quad (41)$$

$$\frac{Tot\ Profit - Profit^{LL}}{Profit^{UL} - Profit^{LL}} \geq \lambda \quad (42)$$

where  $TotCFP$  and  $Tot\ Profit$ , are the carbon footprint and profit generated by utilizing the optimum pathway for conversion of sago wastes. Meanwhile,  $CFP^{LL}$  and  $CFP^{UL}$  are the pre-determined lower and upper limit of the carbon footprint generated, same goes for  $Profit^{UL}$  and  $Profit^{LL}$  for profit generated. These upper and lower limit are determined by extracting data from evaluation results of the model at different objectives.

It is noted that each objective has a predetermined fuzzy range, represented by a linear function within the lower and upper limit, as shown in Fig 2.

Fig. 2 (a) illustrates the maximization case, where  $\lambda$  approaches 1 when the objective,  $Tot\ Profit$  approaches the upper limit,  $Profit^{UL}$  of the fuzzy approach. On the contrary, Fig. 2 (b) demonstrates the minimization case, where  $\lambda$  approaches 1 when the objective,  $TotCFP$  approaches the lower limit,  $CFP^{LL}$ .



**Fig. 2.** The Concept of Fuzzy

In order to generate an optimum pathway for the conversion of sago waste while maximizing profit and minimizing carbon footprint, Eq. (40) and (41) are included in the optimization model, and solved simultaneously by maximising the degree of satisfaction,  $\lambda$ . This mixed integer linear programming (MILP) model is solved via Lingo v17.0 in a Lenovo Ideapad 700 with Intel Core i7-6700HQ (2.6 GHz) and 8GB ram running on 64-bit operating system.

### 3 Case Study

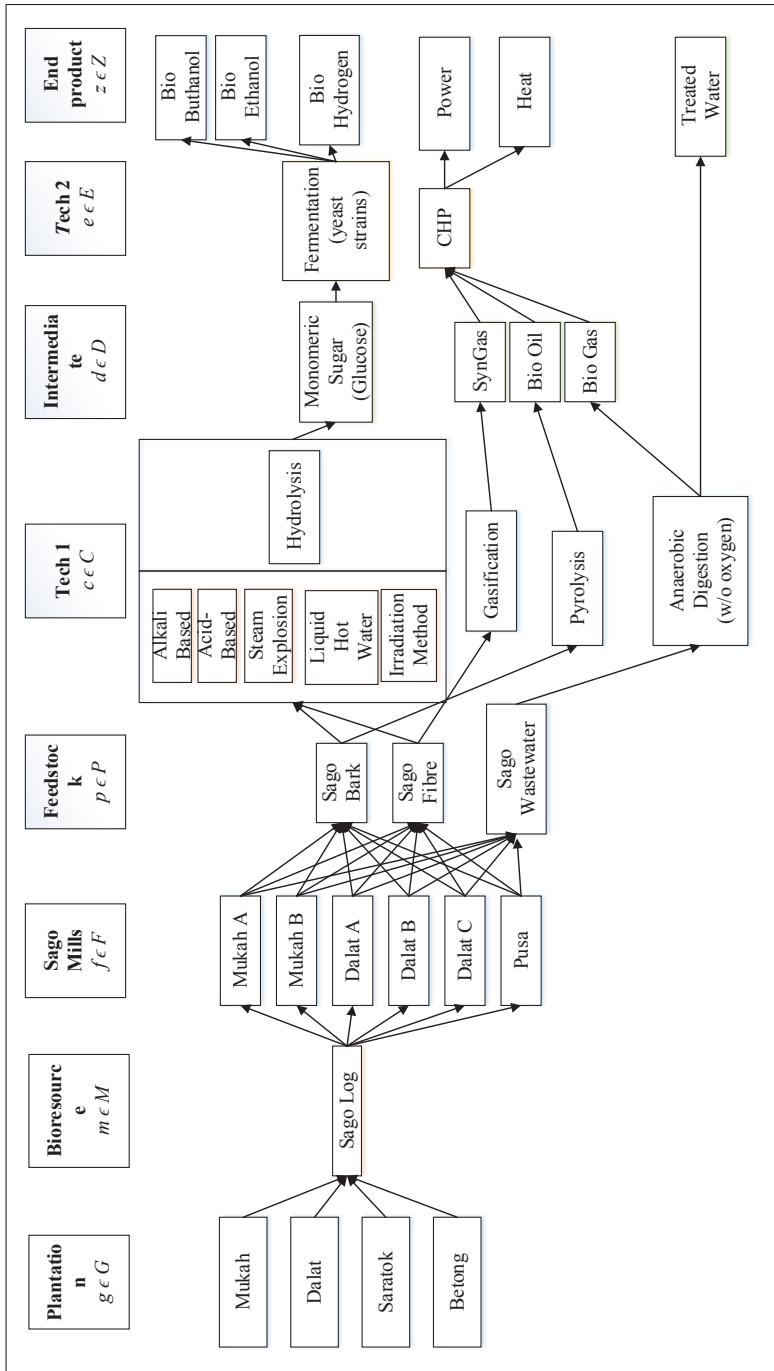
Fig 6 shows the case study superstructure that with all the possible pathways of activities from the proposed value chain in this study. In this case study, plantations from Mukah, Dalat, Saratok and Betong are considered, with sago logs as the only bio-resource produced from the considered sago plantations. The sago mills considered in this study are the ones located around the plantations.

The sago mills products considered in this study are the sago fibers, sago wastes, and sago wastewater, which are produced simultaneously in the sago mill during SSEP. In this study, eight different conversion technology are considered in technology 1 that produces primarily four different intermediates, which will be sent to technology 2 considered in this study. The end product considered in this study consists of high value product from agriculture biomass that has been intensively studied recently. Data from superstructure, such as amount of palms available annually, capacities of sago mill and distance between sago mill and plantation can be found is taken from data reported by Wan et al. [8]. For this study, the conversion rate of palm to sago log  $X_{g,log}$  are taken as 10 logs/palm, the weight of log  $W_{log}$  is taken as 0.05t/log. Different plantation  $g$  produces palms with different starch content due to different soil conditions, which can also be found in [8]. To determine the economic and environmental performance of the value chain proposed in this study, unit costs and CFP emission of producing intermediate  $d$  and end product  $z$  via

technology 1 *c* and technology 2 *e* are estimated from literature and summarized in Table 1 [12]–[18].

**Table 1.** Conversion, Cost and CFP data

	<i>Feed Type</i>	<i>Product Type</i>	<i>Conversion (product/feed)</i>	<i>Cost (USD/Tonne Product)</i>	<i>CFP (kg CO<sub>2</sub>/tonne Product)</i>
<b>Alkali Based</b>	Sago Fiber	Glucose	0.4828	650	467.48
	Sago Bark	Glucose	0.16401		
<b>Acid Based</b>	Sago Fiber	Glucose	0.5440	420	503.44
	Sago Bark	Glucose	0.1848		
<b>Steam Explosion</b>	Sago Fiber	Glucose	0.6120	430	521.42
	Sago Bark	Glucose	0.2079		
<b>Liquid Hot Water</b>	Sago Fiber	Glucose	0.6120	790	467.48
	Sago Bark	Glucose	0.2079		
<b>Irradiation Method</b>	Sago Fiber	Glucose	0.2244	370.58	317.15
	Sago Bark	Glucose	0.0762		
<b>Gasification</b>	Sago Fiber	Syngas	0.2271	45,200	2,200
	Sago Bark	Syngas	0.2220		
<b>Pyrolysis</b>	Sago Fiber	Bio-Oil	0.3200	89,630	1,727
	Sago Bark	Bio-Oil	0.3200		
<b>Anaerobic Digestion</b>	Sago Waste Water	Bio Gas	1.7250	4,400	0
<b>Fermentation</b>	Glucose	Butanol	0.0857	1,370	12,652.53
	Glucose	Ethanol	0.2910	874.52	5,977.79
	Glucose	Hydrogen	0.0111	5400	13,055.82
<b>CHP</b>	GJ	Power(GJ)	0.2222	1.55	0
	GJ	Heat(GJ)	0.8000	16.95	0



**Fig. 6.** Case Study Superstructure

### 3.1 Results and Discussion

To solve the case study, the upper and lower fuzzy limit is pre-determined by solving the objectives individually (e.g., maximize profit, minimize CFP emission) without mutual interaction between objectives. The single objective optimization results are shown in Table 2. Based on the results on, the upper and lower fuzzy limits is coded into the model and solved via Lingo 16.0 in a Lenovo Ideapad 700 with Intel Core i7-6700HQ (2.6 GHz) and 8GB ram running on 64-bit operating system. The CPU time to obtain the maximum global optimal solution for degree of satisfaction  $\lambda$  is approximately within 5s. In addition, Table 3-6 illustrate the flow rate between layers at different objectives.

**Table 2.** Total Profit and CFP in multiple objectives

<i>Objective Functions</i>	<i>Total Profit (Million USD/y)</i>	<i>Total CFP (tonne CO2/y)</i>
<b>Max Total Profit</b>	342.90	779,803.00
<b>Min Total CFP</b>	-4.30	768,777.90

**Table 3.** Mass Flowrates of logs from plantations to sago mills with objective function minimize  $TotCFP^{Overall}$ , maximize  $Tot Profit^{Overall}$  and maximize  $\lambda$ .

<b>Flow Rate from sago plantation to sago mill (log/y)</b>						
minimize $TotCFP^{Overall}$						
	Mukah A	Mukah B	Dalat A	Dalat B	Dalat C	Pusa
<b>Mukah</b>	0	375,000	0	0	200	0
<b>Dalat</b>	0	0	302,400	317,400	204,600	0
<b>Saratok</b>	0	0	0	0	0	220,000
<b>Betong</b>	0	0	0	0	0	0
maximize $Tot Profit^{Overall}$						
	Mukah A	Mukah B	Dalat A	Dalat B	Dalat C	Pusa
<b>Mukah</b>	0	374,200	0	0	0	0
<b>Dalat</b>	0	600	302,400	343,600	178,800	0
<b>Saratok</b>	0	0	0	0	0	220,000
<b>Betong</b>	0	0	0	0	0	0
maximize $\lambda$						
	Mukah A	Mukah B	Dalat A	Dalat B	Dalat C	Pusa
<b>Mukah</b>	0	0	0	0	0	0
<b>Dalat</b>	200	343,600	302,400	343,600	343,600	0
<b>Saratok</b>	0	0	0	0	0	0
<b>Betong</b>	0	0	0	0	0	0

**Table 4.** Mass Flow Rate of Sago Wastes from sago mills with objective function minimize  $TotCFP^{Overall}$ , maximize  $Tot Profit^{Overall}$  and maximize  $\lambda$ .

<i>Production of Sago wastes from Sago mills.</i>									
Objective s	minimize $TotCFP^{Overall}$			maximize $Tot Profit^{Overall}$			maximize $\lambda$		
	SF	SB	SW	SF	SB	SW	SF	SB	SW
Mukah A	0	0	0	0	0	0	4.8	19.2	96
Mukah B	8,25	33,00	165,00	8,24	32,98	164,93	9,24	32,98	164,92
Dalat A	7,25	29,03	145,15	7,25	29,03	145,15	7,25	29030	145,15
Dalat B	7,61	30,47	152,35	8,24	32,98	164,92	8,24	3,295	164,92
Dalat C	4,91	19,65	98,296	4,29	17,16	85,824	8,24	3,295	164,92
Pusa	3,96	15840	79,200	3,96	1,584	79,200	0	0	0
	0			0					

**Table 5.** Mass Flow Rate of intermediate  $d$  into technology 1 with objective function minimize  $TotCFP^{Overall}$ , maximize  $Tot Profit^{Overall}$  and maximize  $\lambda$ .

	minimize $TotCFP^{Overall}$			maximize $Tot Profit^{Overall}$			maximize $\lambda$		
	SF	SB	SW	SF	SB	SW	SF	SB	SW
<b>Irradiation Method</b>	0	128,000	0	0	0	0	0	128,006	0
<b>Gasification</b>	0	0	0	0	0	0	3,068	0	0
<b>Pyrolysis</b>	32,000	0	0	32,002	128,008	0	28,933	0	0
<b>Anerobic Digestion</b>	0	0	640,000	0	0	640,040	0	0	640,032

**Table 6.** Amount of Intermediate  $d$  and End Product  $z$  produced

	minimize $TotCFP^{Overall}$	maximize $Tot Profit^{Overall}$	maximize $\lambda$
<b>Butanol</b>	0	0	0
<b>Ethanol</b>	2,839	0	2,839.
<b>Hydrogen</b>	0	0	0
<b>Power</b>	8,480,067	8,716,897	8,523,204
<b>Heat</b>	0	0	0

An optimum sustainable sago value chain with degree of satisfaction,  $\lambda$  of 0.8596, a total profit of 294.2 million USD/y and CFP emission of 770.32 ton CO<sub>2</sub>/y is obtained as shown in Table . Furthermore, Table also shows the flow rate between activities in the optimum sago value chain at optimised solution.



Based on the optimised result, only palms from Dalat is harvested, which is first processed into sago logs before sending into sago mill Dalat A, Dalat B, Dalat C and Pusa SSEP process. The SSEP process then produces sago waste SF, SB and SW. SF is then sent into gasification and pyrolysis to produce syngas and bio-oil respectively, while SB is sent for microwave irradiation pre-treatment, followed by hydrolysis to produce monomeric sugars such as glucose. SW is sent to for anaerobic digestion to produce biogas. The intermediates are then sent for further processing. Glucose undergoes fermentation to produce ethanol, while syngas, bio-oil and bio gas are sent to CHP to generate power. The amount of final products produced in this optimised sago value chain is 2,839.611 t/y of ethanol and 8,523,204 GJ/y of power.

**Table 7.** Mass Flow Rate of Optimized Sago Value chain

<i>Pathways</i>	<i>Amount</i>	<i>Pathways</i>	<i>Amount</i>
Dalat - Sago Log	133,340	SF- Gasification	3,068
Sago Log - Dalat A	343,600	SF - Pyrolysis	28,933
Sago Log - Dalat B	302,400	SB- Irradiation Method	128,005
Sago Log - Dalat C	343,600	SW- Anaerobic Digestion	640,032
Sago Log - Pusa	343,600	Irradiation Method - Glucose	9,758
Dalat A - SF	8,246	Gasification - Syngas	696

**Table 8.** Mass Flow Rate of Optimized Sago Value chain (Continued)

<i>Pathways</i>	<i>Amount</i>	<i>Pathways</i>	<i>Amount</i>
Dalat A - SB	32,985	Pyrolysis - Bio Oil	9,258
Dalat A - SW	164,928	Anaerobic Digestion - Bio Gas	1,104,055
Dalat B - SF	7,257	Glucose - Fermentation	9,758
Dalat B - SB	29,030	Syngas - CHP	696
Dalat B - SW	145,152	Bio Oil - CHP	9,258
Dalat C - SF	8,246	Bio Gas - CHP	1,104,055
Dalat C - SB	32,985	Fermentation - Bio Ethanol	2,839
Dalat C - SW	164,928	CHP - Power	8,523,204
Pusa - SF	8,246		
Pusa - SB	32,985	Total CFP	770,324,800
Pusa - SW	164,928	Total Profit	294,206,200



### 3 Conclusions

A fuzzy-based optimisation model approach that considers economic and environmental performance of the proposed sago value chain simultaneously is developed in this study. This model can be used as an analysis tool that aids decision making in selecting the most optimal pathway for conversion of sago waste to value added product while considering the environmental and economic impacts.

This model developed in this study is requires intensive data and is customized for sago industry in this study; however, with some modification, it can be applied in different agriculture industry to evaluate conversion pathways of agriculture biomass into value-added products. Note that data such as yield, cost and CFP of crops might not be readily available and is subjected to the magnitude of attention and research on that specific agriculture industry. Sensitivity to uncertainties or changes in data is not considered in this study via robust optimization, which can be considered in the future.

The limitation of this study is that it only considers the sago wastes produced from the SSEP process in the sago mill, which can also be considered in future researches.

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