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An Optimum Biomass Supply Network Synthesis Using the Elemental Targeting Approach

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Malaysia has been relying on fossil fuels as the major source of energy despite the global trend in transitioning towards using renewable energy. It is crucial for the country to execute energy transformation to reduce its reliance on fossil fuels. Malaysia with its agriculture industries as one key economy sector, generates abundant biomass from the agriculture activities. The biomass has been underutilised despite the country's policy to promote waste-to-wealth strategy. This work aims to trigger the industrial energy transition in the country and tackling climate protection through the adoption of local and underutilised biomass energy. In this work, an optimal biomass fuel formulation is developed using the elemental targeting approach. The modelling approach blends multiple species of underutilised biomass in the country for biofuel production to achieve feedstock security while maintaining acceptable biofuel properties. A conceptual biofuel product which could be fed into the existing energy extraction technology for consumption is targeted. The underutilized biomass wastes in Malaysia are first reviewed and their respective element characteristics are studied. Then, the underutilised biomass is integrated into the biomass supply chain and an optimum biofuel formulation is evaluated using the element targeting approach. The modelling result indicates that hemicellulose, cellulose and volatile matter are the major limiting characteristics that constrain the supply of biomass to the gasification plants and biomass of low cost is preferred in the biomass supply network.

1. Introduction

1.1 Biomass as fuel

In Malaysia, approximately 168 Mt of biomass waste is being generated annually, which mainly constitutes of oil palm waste, wood residues, rice husks, and coconut trunk. Stich et al. (2017) estimated the available biomass energy in Malaysia as shown in Table 1.

Table 1. Available energy by solid waste residues in Malaysia (Stich et al., 2017)

Biomass	Total available energy (GWh)	Biomass	Total available energy (GWh)
Paddy waste	6,295.17	Coconut	1,224.42
Corn waste	182.99	Coffee	39.58
Sugarcane	140.49	Groundnut	3.04
Oil palm waste	33,578.52	Forestry residues	17,372.47
Cassava	13.82		

Pelletization technology has been used for a long time and is gaining popularity among Asian countries. The increasing demand for wood pellet has inspired the research toward alternative biomasses that have been overlooked in the past. However, the variation of quantity and quality of biomass supplied is difficult to predict due to various external factors, such as seasonal availability, weather, soil condition, etc. The fluctuation of

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biomass feedstock supply would directly affect the quality of biofuel product as well as creating inconsistent energy supply to downstream biofuel users. This poses challenge to biomass utilisation.

Biomass generally requires the pre-treatment and densification processes to remove impurities, minerals, and moisture before it is ready to be converted. The challenges faced in biomass energy plant are the high capital and operating costs for biomass drying, chemical pre-treatment, grinding, pelletizing and wastewater treatment. Typically, plants with higher production capacity benefit from lower capital cost. However, inconsistent supply of biomass and high transportation cost has limited the establishment of higher capacity bioenergy plant. Diversification of biomass feedstock is one solution to reduce the risk of supply disruption as more biomass feedstock are integrated into the supply chain. Additional feedstock choices do not only provide flexibility in biomass pellet production but also creates a buffering effect when there is fluctuation in biomass supply. The blending of different biomasses has the potential to reduce transportation cost through the integration of local underutilized biomass in the supply chain. The cost-saving from the integration of local biomass into the supply chain is especially remarkable for large scale pellet producers considering local underutilized biomass is cheaper and has lower transportation costs.

1.2 Integrated biomass fuel

The growing interest for cheap yet effective biomass pellet as biofuel has created market demands for alternatives sources of biomass pellet. However, the supply and quality of biomass feedstock have been fluctuating due to weather, cultivation, harvesting method and soil condition (Yancey et al., 2013). Integrating multiple species of biomass feedstock into the biomass pellet supply chain may even out the inconsistency of biomass supply and characteristics. Through this strategy, the desirable characteristics of different biomass are combined to result in a feedstock that is more suitable for biofuel production. Biomass with a longer period of seasonal harvest or waste generated during replantation of crops requires larger storage capacity to accommodate the huge quantity at once. Through the diversification of biomass input, the storage size can be reduced. This could add versatility and economic advantage to high capacity biofuel processing plant and allow unpopular biomass to be blended into the supply chain. Wattana et al. (2017) studied the characteristics of mixed biomass pellet made from oil palm frond (OPF) and rubber tree residues and observed an improvement in the density of pellet from 935 kg/m^3 to 1,023 kg/m^3. Various researchers have conducted elemental analyses on different biomass wastes by performing proximate analysis to study the moisture content, ash content, volatile matter, and fixed carbon of biomass as well as ultimate analyses to investigate the carbon, hydrogen, nitrogen, oxygen and sulphur contents in the biomass. Yancey et al. (2013) demonstrated the benefits of mixed biomass by using biomass pellet made of switchgrass, eucalyptus, corn stover and lodgepole pine.

1.3 Elemental targeting approach

The Elemental Targeting Approach was first introduced by Lim and Lam (2014a) as a tool to predict the applicability of biofuel made of different biomass species in commercial application. Through this method, biomasses are categorised according to their elemental characteristics. Lim et al. (2016) found a linear relationship between the feedstock element characteristics with the element characteristics of the pyrolysis product which becomes the basis of the elemental targeting approach to predict the element characteristics of mixed biomass feedstock. The elements such as ash content, fixed carbon (FC), volatile matter (VM), moisture (MC), heating value (HV), cellulose (Cel), hemicellulose (Hcell) and lignin (Lig) were found to be the key elements in determining the quality of biofuel products (Lim and Lam, 2016). This work aims to integrate as much as possible the different types of local underutilized biomass into the biomass supply chain to maximize resource utilization using the elemental targeting approach. There were existing studies which integrate different types of biomass into the biomass supply chain to optimise the supply chain performance. However, most of the studies considered only the economic and sustainability performances of the supply chain and less focus has been made on the practicability of the integration and the technological constraint to accommodate the change of feedstock in the biomass supply chain. In this work, the technological feasibility which is constrained by the biomass's elemental composition is considered as one main element for biomass supply chain synthesis. An optimum biofuel formulation made of multiple biomass feedstock is targeted in this work, which potentially and conceptually forms the basis for biofuel composition design using local and underutilised biomass.

2. Model formulation and case study

The integrated biofuel product can be made of a combination of biomass, such as palm kernel shell (PKS), palm mesocarp fiber (PMF), rice husk (RH), rice straw (RS), oil palm trunk (OPT), oil palm frond (OPF), wood residue (Wood) and empty fruit bunch (EFB). The compositions of biomass feedstock are then determined from the model using the element acceptance range (EAR). The following objective function and equations are developed to constrain the model.

The typical mass balance formulation applies to constrain the biomass availability and mass flow from its source point to the pre-treatment facilities and along the biomass supply chain. These general equations can be found elsewhere in the published documents such as Ng et al. (2015) for biomass allocation and cost calculations. The amount of biomass's element that enters the pre-treatment facility ($Elemass_{m,e,p}^{bm}$) is equal to the product of the mass of biomass ($M_{m,p}^{bm,in}$) and the biomass's elemental composition ($E_{m,e}^{bm}$).

$$Elemass_{m,e,p}^{bm} = M_{m,p}^{bm,in} \times E_{m,e}^{bm} \qquad \forall\, m \in M, e \in E, p \in P \tag{1}$$

where m is the types of biomass, e is the characteristics of the biomass and p is the pre-treatment facility. Biomass requires pre-treatment such as leaching and drying. During the process, biomass experiences change in elemental composition. Eq.2 accounts for the elemental composition changes and mass loss by using yield factor. The element mass flow of processed biomass ($Elemass_{m,e,p}^{pbm}$) is calculated as the product of the element mass flow of raw biomass and their respective yield factor ($Yield_{m,e}^{PT}$) listed in Table 3.

$$Elemass_{m,e,p}^{pbm} = Elemass_{m,e,p}^{bm} \times Yield_{m,e}^{PT} \qquad \forall\, m \in M, e \in E, p \in P \tag{2}$$

In the processing hub, the yield factors used for biomass pellet and syngas production ($M_j^{product}$) are 1 t/t feed and 1,940 Nm^3/t feed.

$$M_{j,p}^{product} = M_{j,p}^{Feed} \times Yield_{j,p}^{P} \quad j \in J, p \in P \tag{3}$$

where j is the types of biomass products in the processing plant.
The pellet and syngas produced are used for electricity generation. The capacity of the power plant is limited at the working capacity of 90 %. The costs involved in pre-treatment, processing technology vary for different biomass and pre-treatment processes. The processing cost of biomass consists of the installation cost of the power plant, the annual fixed cost and variable cost. The total processing cost equals to the sum of processing cost in each processing hubs.
The total profit of the system which involves the raw material cost ($Ctot_c^{rawmat}$), pre-treatment cost ($Ctot_c^{pretreat}$), processing cost ($Ctot_c^{process}$) and transportation cost ($Ctot_c^{Trans}$) is to be maximised.

$$Max.\ Profit = \sum_{j=1}^{J} \left(Revenue_j - Ctot_j^{rawmat} - Ctot_j^{pretreat} - Ctot_j^{process} - Ctot_j^{Trans}\right) \tag{4}$$

A case study was performed to integrate the major biomass in one of the states in Malaysia to investigate the biomass integration potential using the element targeting approach. A Mixed Integer Linear Program (MILP) model was constructed to conceptually formulate the composition of an integrated biomass fuel produced using local underutilized biomasses. The model generated is solved using General Algebraic Modelling System (GAMS). As shown in Figure 1, the system model consists of 5 major sections: biomass originated from a resource point is transferred into pre-treatment facilities. After pre-treatment, biomass is evaluated based on their element characteristics that is capable to fit into the biofuel consumption technology. The integrated biomass fuel with composition that satisfies the element acceptance of the corresponding processing technology is produced for electricity generation in the biomass power plant. The model aims to obtain an optimal composition of biomass to produce solid biofuel from pelletization process and syngas from the gasification process. To conduct this modelling, parameters such as production cost, technology conversion yield and biomass element characteristics (Table 2) were obtained from the literature.

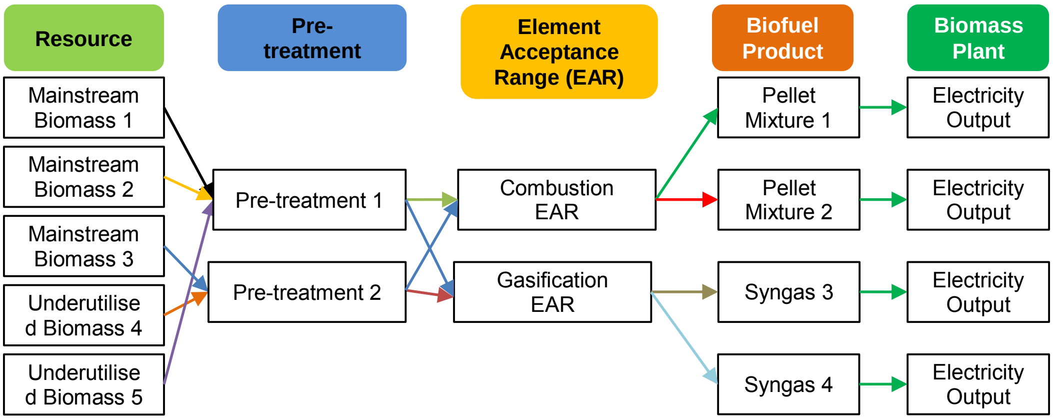
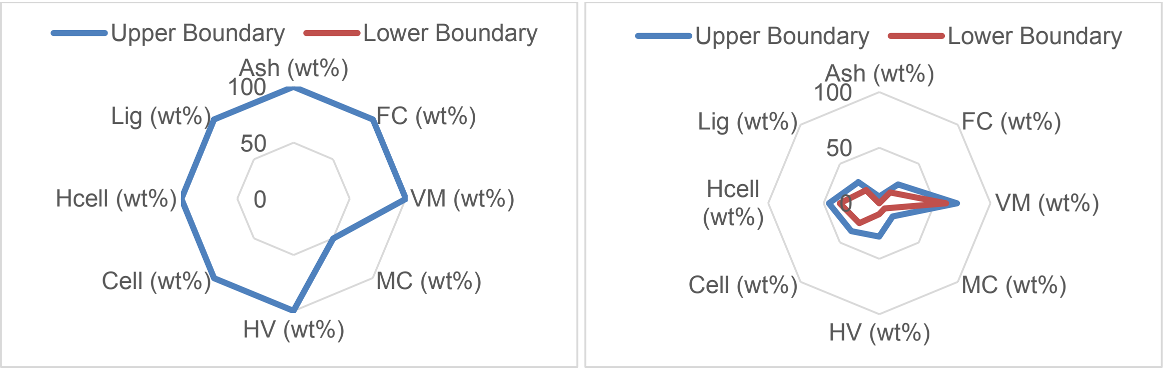


Figure 1: The model structure for integrated biofuel production

Table 2: Element characteristics (weight fraction) of different types of biomass

Material	Cel	Hcell	Lig	MC	Ash	VM	FC	HV (MJ/kg)	Reference
PKS	0.2092	0.2293	0.5123	0.0613	0.0173	0.7216	0.1998	20.09	Soh et al. (2019)
PMF	0.389	0.1936	0.3311	0.0678	0.0303	0.6959	0.2061	19.06	Soh et al. (2019)
EFB	0.3907	0.3527	0.2284	0.0785	0.0221	0.7167	0.1826	18.88	Soh et al. (2019)
OPF	0.304	0.404	0.217	0.1600	0.0109	0.7014	0.1277	17.28	Guangul et al. (2012)
RH	0.286	0.286	0.243	0.1171	0.1162	0.6381	0.1286	16.56	Lim et al. (2016)
RS	0.32	0.357	0.223	0.0740	0.1699	0.6945	0.0616	14.7	Calvo et al. (2012)
OPT	0.4581	0.1774	0.2449	0.0869	0.0323	0.6810	0.1998	17.47	Soh et al. (2019)
Wood	0.4	0.275	0.285	0.2000	0.0080	0.6560	0.1360	20.48	McKendry. (2002)

Lim and Lam (2014b) constructed the element acceptance range based on the key elements of the processing technology as a constraint in developing the mixed biomass feedstock. These key elements are used as the determining factors to constrain the quality of biofuel.



(a) (b)

Figure 2: (a) EAR of combustion (Lim and Lam, 2014b) and (b) EAR of gasification (Lim and Lam, 2014b)

Upon entering the processing hubs, the biomass undergoes pretreatment processes such as grinding, leaching and drying. The cost of raw biomass and elemental yield (in terms of fraction of its original value) of the pretreatment process are tabulated in Table 3.

Table 3: Elemental yield of biomass pre-treatment process and raw biomass cost

	MC	Ash	VM	FC	HV	Reference	Cost (MYR/t)	Reference
PKS	1.00	1.00	1.00	1.00	1.00	-	130	AIM (2013)
PMF	1.00	1.00	1.00	1.00	1.00	-	40	AIM (2013)
EFB	0.9425	0.22	0.9425	0.9425	0.9425	Chin et al. (2015)	36	Malek et al. (2017)
OPF	1.00	1.00	1.00	1.00	1.00	-	60	AIM (2013)
RH	0.8	0.1	0.8	0.8	0.8	Bazargan et al. (2015)	400	MiGHT (2013)
RS	0.95	0.1	0.95	0.95	0.95	Liu et al. (2013)	62.67	Shafie et al. (2013)
OPT	0.991	0.6	0.991	0.991	0.991	Chin et al. (2015)	13.5	MiGHT (2013)
Wood	0.6	1	1	1	1	-	50	Malek et al. (2017)

In this case study, a total of 26 resource points of oil palm and paddy biomass and 18 resource points of woody biomass in Sabah, Malaysia are considered to supply the biomass feedstock. The planted area of oil palm and paddy in different districts in 2016 was obtained from Department of Agriculture Sabah (2016) and the annual volume of logs production from timber industry was obtained from the Sabah Forestry Department (2017). These values form the biomass source points and availabilities of the case study. The model is solved to look for the supply of biomass required to produce the biomass pellet and syngas that fulfils the EAR of the biomass fuel consumption technologies. The biofuel is to be consumed in four pre-selected power plants (P1-P4) in the district. P1 and P3 are combustion plants, whilst P2 and P4 are gasification plants.

3. Result and discussion

Through element targeting approach, the element characteristics of the mixed biomass feedstock of plants P1, P2, P3 and P4 were calculated by the model as shown in Figure 3a-3d (green lines). Comparing the EAR of the combustion plant and gasification plant, the gasification plant has a more stringent requirement on the biomass element characteristics. The biofuel compositions in terms of element characteristics that are specific to each of the processing plant are developed as shown in Figure 3a-3d. As shown in Figure 3b and Figure 3d, the hemicellulose content of mixed biomass lies on the lower boundary of the EAR, while the cellulose content of the mixed biomass lies on the upper boundary of element acceptance range. This shows that the hemicellulose, cellulose and volatile matter are the major limiting characteristics for the gasification plant in this case study.

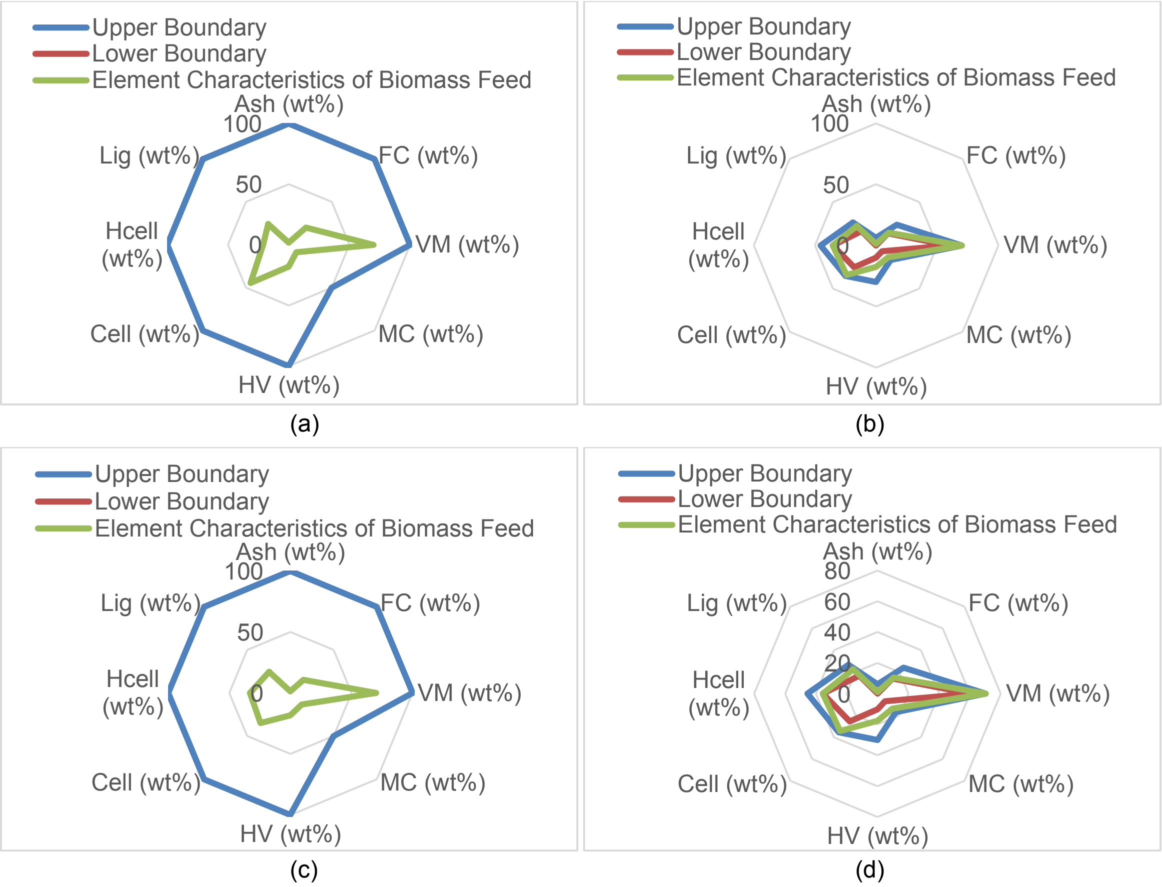


Figure 3: (a) element characteristics of feed in P1, (b) element characteristics of feed in P2, (c) element characteristics of feed in P3, and (d) element characteristics of feed in P4

Table 4 shows the biomass feedstock requirement in the power plants. The results indicated that the biomass selectivity were significantly affected by the market value of the biomass. Conventionally, palm kernel shell, rice husk, and wood residues are the popular biomass feedstock for biomass power plant. However, in this study, the utilization of these biomasses are low due to their higher costs. The model tends to select the cheaper underutilized biomass to maximize profit as long as their element characteristics fit the EAR of the technologies.

Table 4: Biomass received in power plants

	P1	P2	P3	P4
PKS (t/d)			8.00	
PMF (t/d)			20.88	
EFB (t/d)	66.06	39.279	20.14	51.10
OPF (t/d)		298.67	170.56	290.20
OPT (t/d)	252.92	86.164	45.41	83.63
Wood (t/d)			44.14	
Total (t/d)	318.98	424.11	309.13	424.93
Profit (MYR/d)	33,315.86	13,181.50	20,556.78	12,969.01

4. Conclusions

The element targeting approach was introduced to integrate to underutilized biomass for combustion plant and gasification plant. The element acceptance range comprises cellulose, hemicellulose, lignin, moisture, fixed carbon content, volatile matter and heating value of biomass. The model integrates low cost and underutilized biomass in the biomass supply chain instead selecting the mainstream biomasses, as long as the element characteristics of the mixed biomass feedstock fulfil the EAR of the technologies. The approach can be applied to other regional scenario that biomass product is to be produced without undergoing chemical reaction. Future work will investigate the effect of the approach on the seasonal availability of biomass feedstock. More studies could be performed to analyse the energy cost and energy density of the biomass that may affect the selection of the biomass in the system.

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