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Optimising Mixture of Agricultural, Municipal and Industrial Solid Wastes for the Production of Alternative Fuel

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The valorisation of waste is often represented through the form of energy recovery, nutrient reclamation and other by-products. Solid Recovered Fuel (SRF) or Refuse Derived Fuel (RDF) as a solid alternative fuel has shown promising results for waste management and enhancing the energy security. The energy recovered is dependent on the quality of the solid fuel, which is evaluated by several parameters, including the calorific value, the moisture content, the density, the oxygen content and the gas emissions. The parameters varied following different types of wastes, which increase the complexity in producing high quality of solid fuel from a mixture of solid waste. This study aims to compare different mixtures of alternative fuel composed of municipal solid waste (MSW), non-hazardous industrial waste and agricultural waste. The selected wastes have high calorific value (2,601-8,657 cal/g), low moisture content (0.06 - 9.86 %), various density (63 - 910 kg/m^3), high carbon (C) of 45 - 67 %, low nitrogen (N) of 0.15 - 2.22 %, low sulphur (S) of 0.01 - 0.80 %, moderate hydrogen (H) of 4.9 - 8.21 % and high oxygen (O) of 25 - 45.5 %. The high C and O content indicated high energy and combustibility, whereas low N and S concentration can reduce the emissions of unwanted gas. The selection of the optimised mixture is based on technical and economic feasibility assessment. The technical score is calculated over seven criteria, including calorific value, moisture content, density, O and gas emissions (CO_x, NO_x, SO_x). Based on the assessment on these parameters, the optimum mixture consists of 23.00 % rice straw, 19.52 % wood, 24.58 % plastics, 18.43 % cotton stalks, and 14.47 % used tires. The optimum mix has a calorific value of 5,272 cal/g, density of 311 kg/m^3, and moisture content of 1.94 %. The analysis demonstrated that mixture with high proportion of plastics, rice, wood and cotton stalk ranked high as preferable alternative fuel. The analysis also showed that the ranking of the alternative fuel decreases following an increase of sludge and olive pomace in the mixture. The proposed selling price of the alternative fuel produced is 135.47 USD/t covering all capital costs and operational and maintenance costs.

1. Introduction

In association with the population growth and development, the energy security for future consumption, typically on the sustainable and renewable energy sources, remain a hot research topic. The consumption of fossil fuel has exerted several disadvantages, such as negative environmental impacts, uneven distribution of resources, undesirable market prices and more (Cepeliogullar et al., 2016). This sparked the search for alternative fuel that is sustainable, renewable and cost effective. Refuse-derived fuel (RDF) or solid-derived fuel (SDF) is an example of alternative fuel which offers high potential of energy and a high valorisation value of waste. The potential of solid waste, such as municipal solid waste (MSW) and agriculture waste, to be used as alternative fuel, has been gaining wide attention due to a win-win situation for combating waste accumulation and ensuring energy security. RDF or SRF is commonly produced from MSW. The production of RDF or SRF is regarded as one of the waste-to-energy (WtE) strategies to solve both waste and energy issue simultaneously in the past

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few decades (Rada and Andreottola, 2012). By processing the MSW into RDFs or SRFs, it can significantly reduce the space requirement and increase energy harvesting from waste (Gug et al., 2015). The MSW that is collected is firstly treated in an industrial plant, such as the mechanical-biological treatment (MBT) plant where the biodegradable portion of the waste is removed or reduced, to minimise the environmental impact when landfilling. The rejected organic fraction including biowaste and paper, can be transformed into RDF (Gallardo et al., 2014).

The utilisation of RDF or SRF as alternative fuel is particularly welcoming in the energy-intensive industries, for example, the cement industries (Samolada and Zabaniotou, 2014) and the power industries (Nithikul et al., 2011). The cement industries accounted for 5 – 8 % of global CO_2 emissions (Nithikul et al., 2011), where the production of 1 t of cement releases 0.65 – 0.95 t of CO_2 (Kara, 2012). The significant GHG emissions and increasing global demand for cement are driving the need for different technological solutions (Kajaste and Hurme, 2016).

Solid waste is characterised by high heterogeneity due to the variation in composition. Such characteristic can lead to diversities in thermal degradation behaviours, thus affecting the quality of SRF as an alternative fuel. Different waste compositions exhibit different characteristics, for example, moisture content, bulk density, particle size, elemental content and more, which can affect its efficiency and suitability as an alternative fuel. A study found that paper, wood and plastics are best suited for recycling, food waste and yard waste are preferable for anaerobic digestion, and textile waste for incineration (Arafat et al., 2013). RDF consists of paper, plastic, textiles and other combustible materials, offers high calorific value fuel (Zhao et al., 2016).

RDF from mechanical-biological treatment plant is usually required to undergone further treatment to remove non-combustible fraction, size reduction and reducing moisture content (Gallardo et al., 2014). RDF with lower moisture content reduces the amount of required start-up energy where homogenous waste leads to stable calorific value (Zhao et al., 2016). The processing of MSW into RDF can significantly increase the typical calorific value where the former recorded a value of 9.1 MJ/ kg and the later having a value of 18 MJ/ kg (Garg et al., 2007). Due to the variation in composition, the energy content of the RDF also varied due to the fluctuation of the quantity of the raw materials, which is the MSW. The proper estimation of the energy content of the RDF is critical for the designing of the processing plant and in selecting different methods to decrease its environmental impact, estimating economic performance and optimising energy performance (Aranda et al., 2012). The quality of the RDF ought to be optimised to maximise the effectiveness of the WtE plants.

Another major concern is the air emission during the combustion of RDF. Proximate and ultimate analysis are frequently carried out to assess the thermal characteristics of RDFs and it was found that such fuel has a low proportion of fixed carbon and high amount of volatile matter than conventional fuels (Akdag et al., 2016). The study reported that the volatile matter among the two RDFs mixes, coal fuel and petroleum coke were 81.8 %, 68.5 %, 29.3 % and 12.1 % whereas for fixed carbon, the fuels recorded a 5.2 %, 16.6 %, 53.5 % and 87.4 %. While some considered that the use of RDF or SDF as alternative fuel and reduce global warming and acidification, others stated the concern over the atmospheric emissions. The N and S concentration in MSW-derived RDF or SRF can lead to the unwanted emission of NOx and SOx, which contributes to global warming and acidification.

The objective of this paper is to investigate several solid wastes, including agricultural waste (rice straw and cotton stalks), MSW (plastics and paper), industrial waste (olive pomace oil, wood, used tires and dried digested sludge) on their characteristics and suitability to be used as alternative fuel. The individual solid wastes and a series of mixtures are evaluated based on technical scores, such as calorific value, moisture content and air emissions, and economic performance.

2. Methods

The three main steps towards the designing of the optimum mixture to produce high quality solid fuels with desired properties are solid waste materials selection, solid waste analysis and solid waste mixes evaluation. The first step is to select the type of solid waste with the desirable characteristics to be used as alternative fuel. The primary selection criteria include availability, sustainability, energy content and cost. The selected wastes include agricultural waste (rice straw and cotton stalks), MSW (plastics and paper), industrial waste (olive pomace oil, wood, used tires and dried digested sludge).

The second step is to further analyse the selected waste on critical parameters including calorific value (CV), moisture content (MC), density and elemental analysis. The elemental analysis includes carbon (C), nitrogen (N), sulphur (S), hydrogen (H) and oxygen (O). The solid wastes are then mixed into different mixes. The analysis of critical parameters on these mixes are performed where each of the parameter is given an optimum target value.

The last step is to rank the individual solid waste and the mixes of solid waste based on the analysis of parameters. The ranking is based on technical evaluation which involves parameters such as CV, MC, density,

oxygen and the emission upon burning (including the release of CO_x, NO_x and SO_x). The waste is further evaluated based on their financial performance based on USD/ t.
Finally, the optimum mix is selected by merging the technical and financial ranking. Different merging ratios are selected for sensitivity analysis. The complete methodology is as shown in Figure 1.

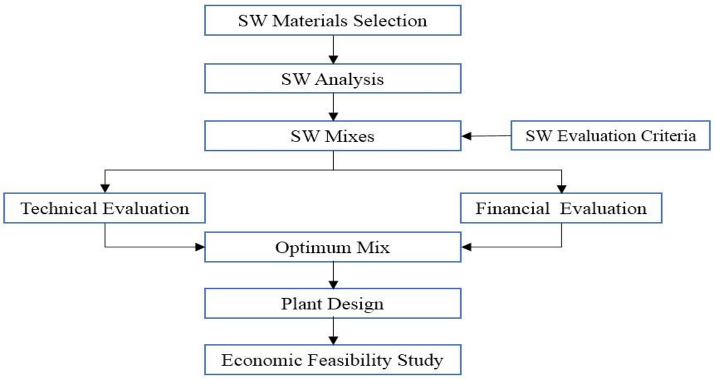

Figure 1: Methodology in determining the optimum mixture of solid waste as alternative fuel.

3. Results and discussions

3.1 Selection of solid waste and mixes

Based on the primary selection criteria, which includes availability, sustainability, energy content and low cost, a total of eight types of solid waste are considered in this study. The selected wastes are rice straw and cotton stalks (agricultural waste), plastics and paper (MSW), olive pomace oil, wood, used tires and dried digested sludge (industrial waste). The selected wastes have high CV (2,601-8,657 cal/g), low MC (0.06-9.86 %), various density (63-910 kg/m^3), high C (45-67 %), low N (0.15-2.22 %), low S (0.01-0.80 %), moderate H (4.9-8.21 %) and high O (25-45.5 %). The high CV, C and O, with low MC, contribute to the combustibility of the alternative fuel whereas the variation in N, S and C, will give rise to the emission of unwanted gas being released upon combustion, thus affecting the quality of the produced fuel. The high C content (32.23 – 92.08 %) and moderate H content (4.19-14.31 %) can indicate a good energy potential (Zhao et al., 2016). After the analysis of solid waste in terms of CV, MC, density, C, N, S, O and H, each parameter is given an optimum target value (based on the analysis results) and proposed weighting factor from 100%. Five trials were conducted with different weighing factors to investigate the sensitivity of the optimum mix selection to weighting factor based on seven criteria, including CV, MC, density, O, CO_x, NO_x and SO_x, with a target value of maximum 8,657 cal/g, minimum 0.06 %, minimum 60 kg/m^3, maximum 45.5 %, minimum 149.7 g CO_x/ g fuel, minimum 0.35 g NO_x /g fuel and minimum 0.09 g SO_x /g fuel. A technical scoring was then performed on the five trials with the consideration that each waste is used alone. The eight selected waste materials were ranked from 1 to 8 to determine its priority in the mixing procedure as shown in table 1. The ranking is to maximise CV, and oxygen and to minimise MC, density, and gas emissions (C, N and S).

Table 1: Scoring and ranking of each selected waste materials.

Trial no.	No mix	Rice straw	Wood	Sludge	Olive pomace oil	Plastics	Paper	Cotton stalk	Tires
1	Score (%)	63	53	27	34	67	45	50	39
	Rank	2	3	8	7	1	5	4	6
2	Score (%)	67	53	24	30	69	46	48	30
	Rank	2	3	8	7	1	5	4	6
3	Score (%)	62	52	31	34	65	47	55	32
	Rank	2	4	8	6	1	5	3	7
4	Score (%)	59	53	29	39	65	44	53	49
	Rank	2	3	8	7	1	6	4	5
5	Score (%)	63	55	22	35	69	43	45	47
	Rank	2	3	8	7	1	6	5	4

The analysis indicated that weighting factor had insignificant impact on the ranking. Among the five trials, plastics is ranked first, followed by rice straw, wood, cotton stalk, paper, tires, olive pomace and sludge. This indicated that waste with high MC such as olive pomace and sludge are not suitable as waste materials for RDF or SRF.

The proportion of such waste should keep at low amount as not to decrease the combustibility of the RDF or SRF produced. As no significant variation was observed following the variation among the weighting factors, trial no 1 is selected for further analysis. A total of eight mixtures are produced under trial 1 where the mixes are further analysed and ranked. Table 2 presented the possible solid mixes under trial 1 and their ranking.

Table 2: Possible mixes of solid waste under Trial no 1.

Rank/ Mix no.	2 Rice straw (%)	3 Wood (%)	8 Sludge (%)	7 Olive pomace oil (%)	1 Plastics (%)	5 Paper (%)	4 Cotton stalk (%)	6 Tires (%)
1	0	0	0	0	100	0	0	0
2	48.34	0	0	0	51.66	0	0	0
3	34.28	29.09	0	0	36.63	0	0	0
4	26.89	22.82	0	0	28.73	0	21.55	0
5	23.00	19.52	0	0	24.58	0	18.43	14.47
6	19.75	16.76	0	0	21.10	14.15	15.82	12.42
7	17.81	15.12	0	9.80	19.03	12.77	14.27	11.21
8	16.55	14.05	7.05	9.11	17.69	11.87	13.27	10.42

It can be seen that mixture with 100 % plastics is ranked first among all mixes. The rank of the mixtures decreases following the decrease in the proportion of plastics in the mix. Similar observation was found for mixtures with high proportion of rice straw, wood and cotton stalk. On the contrary, mixtures with olive pomace and sludge ranked lowest, suggesting the unsuitability for these materials to be processed into RDF or SRF.

3.2 Selection of optimum solid waste mix

To select the optimum solid waste mix as an alternative fuel, the 8 mixes that were ranked in accordance to trial 1 are further evaluated based on their technical and economic feasibility, which are presented in Table 3 and 4. The technical feasibility includes criteria for thermal degradation (CV, MC, density and oxygen) and air emission (CO_x, NO_x and SO_x). The economic feasibility assessment is carried out by ranking the mixtures based on the price of the respective waste in USD/t.

Table 3: Technical evaluation and ranking of possible mixes under Trial no 1.

Mix no.	CV (cal/g)	MC (%)	Density (kg/m^3)	Oxygen (%)	CO_x (g/g fuel)	NO_x (g/g fuel)	SO_x (g/g fuel)	Technical score (%)	Rank
1	5,565	0.08	72	45.50	166.10	0.39	0.16	78	1
2	4,671	0.09	66	44.29	174.43	0.35	0.16	65	2
3	4,709	0.08	178	44.09	177.07	0.44	0.14	72	3
4	4,699	2.19	164	44.05	179.21	0.81	0.11	67	5
5	5,272	1.94	311	37.97	153.28	0.69	0.10	69	4
6	4,959	2.53	276	38.60	154.94	0.68	0.17	63	6
7	4,991	2.32	338	38.18	159.48	1.08	0.17	60	7
8	4,822	2.47	356	37.25	154.70	1.46	0.37	54	8

The eight mixtures under trial 1 were ranked following the technical score over seven criteria, including CV, MC, density, O and gas emissions (CO_x, NO_x, SO_x). In general, the CV ad the MC had an inverse proportional relationship, where higher MC leads to lower CV and vice versa. Density does not show direct impact on the ranking, but it is expected that the mix with high CV, low MC and in addition of low density is preferable due to the ease of transportation and packaging. In terms of gas emissions, NO_x and SO_x showed higher impact on the ranking. Mix no. 8 with the highest NO_x and SO_x achieved a relatively low score, 54 %, among all mixes. These could narrow down the critical parameters in selecting high quality RDF for future work. Further analysis can be performed on the chloro content in MSW as high concentration of chloro can cause severe corrosion in incineration plants and would require additional scrubbing to remove HCl and SO_2 (Zhao et al., 2016). In the cement production, high Cl concentration can weaken the compressive strength of the concrete due to the formation of Cl-alkaline-silica salts that create microcracks within the concrete (Kara, 2012). It is also worth tackling into the analysis of bottom ash composition to investigate the presence of alkali metals that can lead to corrosion, slagging, fouling and ash agglomeration (Akdag et al., 2016). Akdag et al. (2016) compared the proximate analysis among two RDF samples, coals and petroleum coke where the MC contents were 1.6 %, 14.8 %, 4.3 % and 7.0 %. The two RDFs samples had a calorific value of 22.14 kJ/ t and 19.23 kJ/ t.

For tabulating the economic evaluation, the price (USD/ t) of each solid waste materials, including paper, plastics, wood, sludge, olive pomace oil, rice straw, cotton stalk and used tyres, is presented in Table 4. The price per ton of each mix in Trial 1 is further calculated as presented in Table 5 to determine the economic evaluation score and ranking using the lowest mix cost as a target value (Mix No 8 has a minimum cost).

Table 4: Unit price of solid waste materials in USD/ t under Trial no 1.

Solid waste materials	Price (USD/t)
Paper	84.67
Plastics	310.45
Wood	6.77
Sludge	12.42
Olive pomace oil	169.34
Rice straw	33.87
Cotton stalk	28.22
Used tyres	101.60

Table 5: Economic evaluation and ranking for all possible mixes under Trial no 1.

Mix no.	Price (USD/ t)	Economic score (%)	Rank
1	310.45	34	8
2	176.79	60	7
3	136.83	78	6
4	113.46	94	4
5	111.65	96	3
6	107.93	99	2
7	113.91	94	5
8	106.80	100	1

The technical and economic scores are merged to obtain the overall score and then mixture with the highest score is selected as the optimum mix. Different merging ratios are then selected to investigate the sensitivity of optimum mix to merging ratios. The results are presented in Table 6.

Table 6: Overall scores of different mixing ratio under Trial no 1.

Technical (%)	100	90	80	70	60	50	40	30	20	10	0
Economic (%)	0	10	20	30	40	50	60	70	80	90	100
Mix No.					Overall score (%)						
1	77.6	73.2	68.9	64.6	60.2	56.0	51.6	47.3	43.0	38.7	34.4
2	75.3	73.8	72.3	70.8	69.3	67.8	66.4	64.9	63.4	61.9	60.4
3	71.9	72.5	73.1	73.7	74.3	74.9	75.6	76.2	76.8	77.4	78.0
4	66.8	69.5	72.2	75.0	77.7	80.4	83.2	85.9	88.6	91.4	94.1
5	68.7	71.3	74.0	76.7	79.4	82.1	84.8	87.5	90.2	92.9	95.6
6	63.0	66.6	70.2	73.8	77.4	81.0	84.6	88.2	91.8	95.4	98.9
7	59.6	63.0	66.4	69.8	73.2	76.7	80.1	83.5	86.9	90.3	93.7
8	54.2	58.7	63.3	67.9	72.5	77.1	81.7	86.2	90.8	95.4	100.0

The analysis shows that Mix No. 5 is the optimum at merging (T/F) ratios from (80/20) to (40/60). Therefore, Mix No. 5 is selected as the optimum mix. Nevertheless, the energy efficiency of the thermal plant plays a critical role in the energy production efficiency, quality of energy outputs and quality of emissions (Samolada and Zabaniotou et al., 2014).

4. Conclusion

This study aims at the determination of the optimum mix of non-hazardous SW materials to be utilized as AF from selected range of waste. In this study, different waste types were investigated, including rice straw, cotton stalks, plastics, wood, used tires, olive pomace oil, paper, and dried digested sludge. The selection of the optimum mix is based the CV with weighting factor 30 %, density 15 %, MC 15 %, oxygen content 10 %, and gas emissions 30 %, whilst taking into consideration of the cost of the materials. Eight mixes are investigated, and the optimum mix is found to be consisting of 23 % rice straw, 19.52 % wood, 24.58 % plastics, 18.43 % cotton stalks an 14.47 % used tyres. This optimum mix has a CV of 5,272 cal/g, density of 311 kg/m^3, MC of 1.94 %, CO_x of 153.28 (g/g fuel), NO_x of 0.69 (g/g fuel), and SO_x of 0.10 (g/g fuel). With the selected parameters in assessing the environmental, technical and economical performance to produce a high quality fuel, the optimum mix thus offer high potential in securing sustainable energy supply while combating waste accumulation.

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