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Characterization of Singapore RDF resources and analysis of their heating value

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A B S T R A C T

Refuse Derived Fuel (RDF) was formulated from several municipal waste components in Singapore in order to maximize energy efficiency and minimize the environmental impacts. At first, the physico-chemical properties (proximate and ultimate analysis, chloro, heavy metals) and the heating values of waste components were analyzed to assess their thermal behaviour. Three RDF prototypes were formulated by combining individual waste type in various fractions with respect to their properties and heating values. Landfill mining material and chicken manure were also involved in the RDF formation as alternative fuel sources. Optimum RDF was formulated consisting of 42% plastics, 41% paper/cardboard, 7% textile and 10% horticultural waste, based on the existing Singapore waste composition. This RDF had a lower heating value of 23.7 MJ kg^{-1}, which was less than mineral fuel but it could meet the fuel requirements given in the European standards. The addition of chicken manure and landfill mining material in RDF lowered the heating value and increased heavy metal concentration, but they are considered good alternative fuel. It is believed that power plants or dedicated incinerators could be potential end-users of RDF in Singapore.

1. Introduction

Municipal solid waste (MSW) management is one of the most eminent environmental problems arising from rapid industrialization, increasing population and economic development. 130 Mt of MSW are incinerated each year in the 600 Waste-to-Energy (WTE) plants worldwide [1]. The WTE plants provide a good alternative to relieve the environmental burdens coming from landfilling. For land-scarce Singapore, incineration is an effective approach to extend the service life span of the one and only landfill [2].

Energy recovery through WTE plants is a beneficial solution in face of the rising energy prices. The high calorific value fuel, which is produced after the removal of non-combustible materials such as ferrous materials, glass, grit etc., is termed refuse-derived fuel (RDF). RDF typically consists of paper, plastic, textiles and other combustible materials. It presents several advantages as a fuel compared to raw MSW such as higher heating value, more homogeneous physicochemical composition, ease of storage, handling and transportation, lower pollutant emissions and reduced excess air requirement during combustion. For example, the raw MSW has a typical calorific value of 9.1 MJ kg^{-1} while the processed RDF pellets have a typical calorific value of 18 MJ kg^{-1} [3].

Current regulations set high quality standards for RDF so that it can be readily accepted as a substitute fuel in most combustion systems without major modifications. However, the production of high calorific value RDF requires complex production lines with a greater number of separation steps, leading to a higher production costs which reduce the market prospect of the product [4–6]. In order to obtain relatively stable RDF production, the waste streams need to be dried, sorted and homogenous [3]. Dried feedstock reduces the amount of required start-up energy. Homogenous waste produces stable calorific value. Using these approaches, the quality of RDF is regulated for maximizing the effectiveness of WTE plants.

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The aim of this paper was to produce a high quality RDF by sorting materials from several waste streams in Singapore. It was analyzed the physiochemical properties and energy content of several components of MSW to determine their suitability for RDF production. It was further identified the components with high heavy metals and Cl concentration, and eliminated from the waste stream. Considering these factors, three different RDF mixtures were formulated to determine the optimal quality in terms of high calorific value and low environmental impacts.

2. Materials and methods

2.1. Materials

Several waste components were collected for this study such as plastics, paper/cardboard, textile, horticulture and food waste. Landfill mining materials and chicken manure from poultry farm were also included in RDF mixture. Landfill mining provides the opportunity to recover combustible materials that could otherwise be used to generate electricity in WTE plants. The feasibility of using landfill mining materials and chicken manure in RDF production was evaluated in the present study, thereby reducing the volume occupied by these materials and extending the service time of existing disposal and landfill sites. Fig. 1 presents the amount of MSW disposed in Singapore in 2014.

2.2. Proximate and elemental analysis

Before proximate and elemental analysis, the waste components materials were shredded in a cutting mill using a 0.5 mm sieve. Proximate analysis was conducted according to ASTM Standard D5142 [7]. Several parameters were determined including moisture, ash and volatile matter content. Elemental analysis (CHNOS) was conducted using Elemental analyser (Germany).

2.3. Calorific value determination

The calorific value was tested using a bomb calorimeter (IKA, Germany). The analysis was duplicated. The bomb calorimeter provided Higher Heating Value (HHV). The Lower Heating Value (LHV) was determined by using the HHV obtained from the bomb calorimeter including the hydrogen content and moisture of the waste components [8]. Equations (1) and (2) were used to determine the LHV of the waste samples:

Fig. 1. Amount of waste disposed in Singapore (2014).

$$LHV_{dry} = HHV_{dry} - 2441.8 \times \frac{9H_{dry}}{100} \tag{1}$$

$$LHV_{wet} = LHV_{dry} \times \frac{100 - W}{100} - 24.42W \tag{2}$$

where: HHV_{dry} is the HHV of a dry sample (kJ kg^{-1}), LHV_{dry} is the LHV of a dry sample (kJ kg^{-1}), H_{dry} is the weight percentage of hydrogen, LHV_{wet} is the LHV of a wet sample and W is the percentage of moisture in sample. Heat energy for vaporisation of water is 2442 kJ kg^{-1}.

2.4. Cl determination

Chloro content in waste component was analysed using a combination of High Pressure Decomposition Device (HPDD) Method with Ion Chromatography (IC) according to ASTM Standard D808 [9]. This method uses a Bomb Calorimeter to perform HPDD Method. 0.8 g of sample was used, while 5 mL of sodium carbonate (50 g L^{-1}) solution was added to absorb chlorine gas produced during combustion. The solution in the bomb was collected in a beaker by rinsing the interior of the bomb, the sample cup and the lid with deionised water. The collected solution was filtrated through a 0.45 μm filter paper, then brought up to 50 mL with deionized water and tested for chloride content using an IC analyser (Dionex ICS-1100, USA).

2.5. Heavy metals analysis

The metal concentrations in the samples were measured through by microwave digestion. The microwave digestion was carried out by dissolving 0.1 g of sample in concentrated nitric acid. The samples were subjected to controlled pressure and temperature for 3 h. Triplicates were carried out for each waste type. Afterwards, the samples were diluted to 25 mL and analyzed in Inductively Coupled Plasma spectrometry.

3. Results and discussion

3.1. Waste characterisation

3.1.1. Proximate analysis
Table 1 shows the results of the proximate analysis for the individual waste component. Moisture, ash content and volatile matter (wt%) could provide a good indication of the combustibility of the MSW [10]. The LHV values were calculated on wet basis. Results shows that plastics (i.e., Polypropylene/polyethylene (PP/PE), polyethylene terephthalate (PET) and polystyrene (PS)) contained higher percentage of volatile matter and higher LHV$_{wet}$

Table 1
Proximate analysis of waste components.

Sample	Moisture (%)	Ash content (%)	Volatile matter (%)	LHV (MJ kg^{-1})
PP/PE	0.06	0.03	99.4	43.2
PS	0.12	0.02	99.8	39.9
PET	0.5	0.1	94.6	21.9
Textile	5.4	0.9	93.6	16.6
Landfill mining materials	21.2	8.1	63.3	14.1
Paper	7.1	17.1	75.6	12.1
Horticulture	45.3	2.7	46.5	8.9
Chicken manure	16.3	34.3	51.4	7.8
Biomass waste	73.8	1.1	21.4	4.1
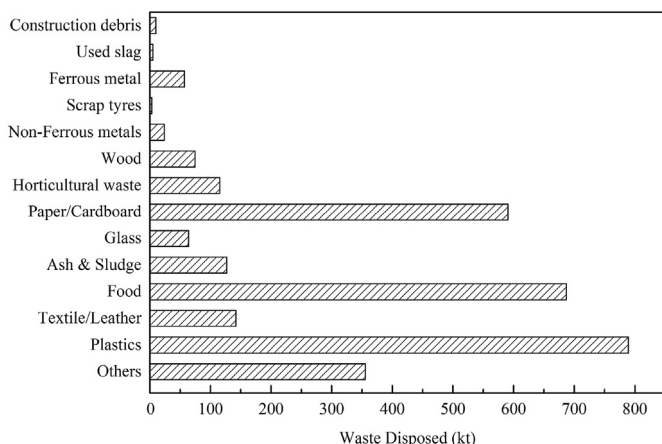
Table 2
Elemental analysis on waste components.

Sample	C (%)	H (%)	N (%)	O (%)	Cl (%)
PP/PE	85.31	14.31	0.01	0.08	0.00
PET	61.65	4.19	0.00	31.57	0.00
PS	92.08	7.83	0.00	0.00	0.00
Paper	37.81	5.51	0.07	44.74	0.10
Textile	48.51	5.86	0.24	44.84	0.01
Landfill mining materials	57.93	5.62	2.11	36.21	0.06
Horticulture	46.58	6.34	0.65	47.12	0.08
Chicken manure	32.23	4.79	1.99	38.85	0.21
Biomass waste	45.36	7.40	1.83	49.35	0.80

Table 4
Formulation of RDF prototypes.

RDF type	Composition
SGRDF	42.1% plastics
	41.2% paper/cardboard; 7.0% textile; 9.6% horticulture waste
SGCM	24.0% plastics (16.8% PP/PE, 3.6% PET, 3.6% PS)
	23.5% paper/cardboard; 4.0% textile; 5.5% horticulture waste
	19.5% biomass waste; 23.5% chicken manure
SGLF	24.0% plastics
	23.5% paper/cardboard; 4.0% textile; 5.5% horticulture waste
	19.5% biomass waste; 23.5% landfill mining materials

values than other types of waste. This was mainly due to relative high water content present in other wastes and the nature of the plastic materials.

3.1.2. Elemental analysis

The results of elemental analysis are shown in Table 2. The waste component generally had high carbon content and moderate hydrogen content, indicating a good energy potential. The high nitrogen content in landfill mining materials and food waste could cause a concern as it could contribute to NO_x emissions. The chloro content was lower than 1% for all types of wastes.

The high chloro content in MSW could cause severe corrosion in the incineration plants. A high concentration of chloro during combustion stimulates the formation of eutectics in fly ashes with a relatively low melting point, which would then condense on the super heaters to induce corrosion. Above 450 °C, super heater pipes become sensitive to such corrosion and lead to unscheduled shutdown of the entire system. Furthermore, sulphation in the combustion chamber facilitates accumulation of HCl and vaporised salts. As a result, more reagents would be demanded for excessive HCl and SO_2 introduction in the subsequent scrubber process increasing the operational cost.

3.1.3. Metal content analysis

The heavy metal contents of the solid waste components are summarised in Table 3. Referring to the standard [11], the values marked with "*" indicate metal content that exceeds the limit, while those marked with "#" indicate metal content that are relatively higher as compared to other waste types, yet not exceeding the standard.

Paper was found to contain high concentration of copper while landfill materials and chicken manure displayed various metals: higher levels of copper, manganese, lead and zinc in landfill materials whereas copper, manganese and zinc were elevated in chicken manure.

Table 5
Physico-chemical properties of RDF prototypes.

	Moisture content (%)	Ash content (%)	LHV (MJ kg^{-1})
SGRDF	7.8	7.4	23.7
SGCM	22.7	12.5	16.1
SGLF	23.8	6.3	17.6
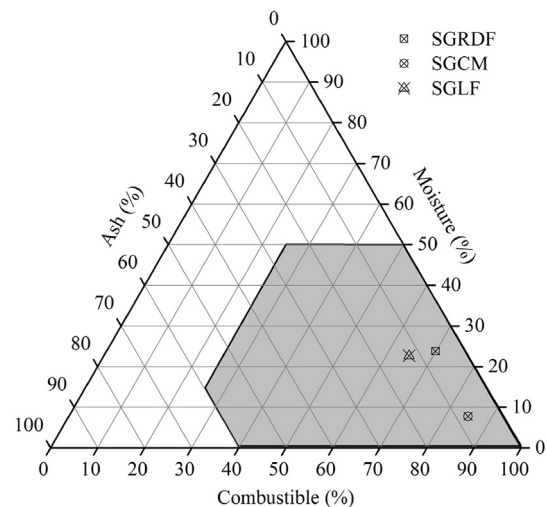
Fig. 2. Tanner triangle for determining combustibility of waste components.

3.2. RDF formulation

Based on the above data (proximate, ultimate, Cl, heavy metals content) of the waste components, three RDF were formulated. The primary RDF formula was based on the waste component distribution in Singapore, named as Singapore RDF (SGRDF). The other two RDFs were accordingly derived by the addition of Chicken

Table 3
Metal content of the individual waste components.

Sample	Cd (ppm)	Cr (ppm)	Cu (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)	Ni (ppm)
PP	0.02	1.2	0.6	0.7	3.8	NA	2.9
PET	NA	2.0	NA	0.7	3.6	NA	0.4
LDPE	5.6	3.2	8.0	6.2	19	96	4.0
HDPE	3.9	1.6	2.0	2.0	11.5	17.3	2.7
PS	NA	2.5	NA	0.7	4.9	61	3.0
Paper	0.1	4.0	54#	14	6.1	23	2.3
Textile	0.1	2.5	4.5	2.6	4.2	25	3.7
Landfill mining	NA	9.2	62#	46#	43#	230	3.4
Horticulture	NA	1.3	4.1	10	4.9	29	1.0
Biomass waste	0.01	0.5	1.4	7.2	2.8	24	0.8
Chicken manure	NA	3.9	53#	429*	4.2	415#	0.1
Limits	5	100	300	400	200	500	40

*Value exceeds the limit of the standard; #Value is relatively high.

Table 6
Metal content of RDF prototypes.

Sample	Cd (ppm)	Cr (ppm)	Cu (ppm)	Mn (ppm)	Pb (ppm)	Zn (ppm)	Ni (ppm)
SGRDF	0.05	2.6	23	7	4.9	18	2.4
SGCM	0.03	2.5	26	106	4.3	112	1.6
SGLF	0.03	3.7	28	16	13	69	2.3
Limits	5	100	300	400	200	500	40

Manure and landfill mining materials in SGRDF, named Singapore Chicken Manure (SGCM) and Singapore Landfill (SGLF), respectively. The compositions of the three RDFs are shown in Table 4.

Based on the results of different waste components, the physicochemical properties of three RDFs were calculated (Table 5). LHV provides useful information about the theoretical energy release that can be obtained from the combustion since the latent heat of water vaporisation during combustion has been subtracted. The LHVs of the RDFs are comparable to commercial fuel. The compositions used for the RDF prototypes were therefore deemed feasible for real application. In addition, the actual moisture content of RDF products can be lowered by mechanical pre-treatment.

Fig. 2 shows the Tanner triangle for assessment of RDFs, based on the three main quality standards (moisture content (M), ash content (A) and combustible (C)) [11]. The waste is theoretically feasible for combustion without auxiliary fuel when M < 50%, A < 60%, and C > 25%. It can be seen that all RDF prototypes fall within the limits in the Tanner triangle, indicating a suitable fuel for combustion. The metal content of various RDF prototypes was determined as shown in Table 6. It shows that the heavy metal contents were below the limits set by European countries (i.e., Finland, Italy, France and Netherlands) for the RDF emission [12]. RDF calorific value and heavy metal content were defined as the two main indexes for evaluation of RDF quality. The chicken manure RDF exceeded allowable limits for ash content, LHV, and Mn. Hence, the percentage of chicken manure in SGCM needs to satisfy the following criteria:

$$Ash_{SGRDF} \times (100 - CM)\% + Ash_{chicken\ manure} \times CM\% \leq 20\% \quad (3)$$

$$LHV_{SGRDF} \times (100 - CM)\% + LHV_{chicken\ manure} \times CM\% \geq 15\ MJ\ kg^{-1} \quad (4)$$

$$Mn_{SGRDF} \times (100 - CM)\% + Mn_{chicken\ manure} \times CM\% \leq 400\ ppm \quad (5)$$

According to the calculation, the proportion of chicken manure should be lower than 33.7wt% by weight. As for landfill mining materials, only LHV exceeded the limit, thus percentage of landfill in SGLF needs to satisfy the following criteria:

$$LHV_{SGRDF} \times (100 - landfill)\% + LHV_{chicken\ manure} \\ \times landfill\% \geq 15\ MJ\ kg^{-1} \quad (6)$$

Accordingly the proportion of landfill mining should be lower than 80 wt%.

4. Conclusions

Physicochemical analysis of different waste components could optimize RDF formulation. Involvement of landfill mining materials and chicken manure offers an environmentally friendly strategy to reuse the misplaced resource. This study included proximate and elemental analysis for RDF formulation. Three types (SGRDF, SGCM and SGLF) were recommended in Singapore. Formulations were made according to LHV, elemental and heavy metal emissions with maximum loading of chicken manure and landfill mining materials in SGCM and SGLF being 33.7 and 80%, respectively. Considering thermal stability and environment impacts for local incinerators, 20% of chicken manure and 60% of landfill mining materials are recommended for SGCM and SGLF, respectively.

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