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Quality Improvement of Refuse-Derived Fuel from Landfill Mining

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ABSTRACT

Refuse-derived fuel (RDF) utilization as an alternative fuel has encountered obstacles in complying with industrial quality standards. This study aimed to improve landfill-mined RDF quality for acceptable calorific values (CV), moisture, volatile, ash, fixed carbon, chlorine, and sulfur contents by the cement industry and coal-fired steam power plant. For eight consecutive working days, a minimum of 100 kg of mined material was sampled randomly from transport trucks. Each sample was separated into three fractions: fine (< 10 mm), medium (10–30 mm), and rough (> 30 mm). RDF ratio of plastic : wood and garden waste, originating from a rough fraction, were set at 20:80 to 80:20 with a 10-point interval, including controls at 0:100 and 100:0. Moisture, CV, volatile solids, ash, and fixed carbon contents of RDF were determined by ASTM codes, while chlorine and sulfur used APHA/AWWA/WEF standard methods. The RDF optimum ratio was 40:60, which produced CV, air-dried moisture, volatile solids, ash, fixed carbon, chlorine, and sulfur contents were 25.23 ± 0.53 MJ kg^{-1}, 26.11 ± 2.84%, 75.20 ± 1.21%, 21.18 ± 0.76%, 3.62 ± 0.63%, 0.129 ± 0.009%, and 0.058 ± 0.004%, respectively. These results met industrial RDF quality standards except for moisture, ash, and fixed carbon contents, which needed process improvements at the RDF processing plant.

Keywords: alternative fuel, calorific value, landfill mining, optimum ratio, quality, RDF.

INTRODUCTION

Landfill mining (LM) is an engineering approach for extending landfill capacity and valorizing landfill-mined materials (LMM) (Márquez et al., 2019; Jagodzińska et al., 2021; Jain et al., 2023). More than 112 LM projects have been operated in 21 countries between 1953 and 2021 (Márquez et al., 2019). LM process separates LMM into soil-like material (SLM), combustible fraction, inert fraction, and remaining material (Kurian et al., 2003; Jain et al., 2023). Some technologies were used in the LM's production line, including screens, shredders, metal separators, wind sifters, and handling equipment (Jain et al., 2023). The classical LM concept focused on LMM reduction and extraction, land reclamation, remediation, gas collection, and metal recovery (Krook et al., 2012). This old concept has been developed into full utilization of LMM, known as enhanced LM. Enhanced LM is a strategy for implementing safe landfill conditioning, excavation, and innovative landfill-mined material valorization while considering rigorous social and environmental criteria (Kurian et al., 2003; Gerven et al., 2010; Jones et al., 2013; López et al., 2018; Jagodzińska et al., 2021).

From an environmental point of view, LM plays a role in global warming (Krook et al., 2018). Each Mg LMM contributes −1550 (savings) to 640 kg CO_2e (burden) (Laner et al., 2019). This discrepancy depends on the extent to which LM contributes to lowering long-term landfill gas emissions and replacing energy and material generation (Krook et al., 2018).

A former study found that LM has limited economic potential (Esguerra et al., 2021). Only 20% of the economic performance modeling of 531,441 LM scenarios in Europe was lucrative. In these scenarios, the most crucial cost elements driving LM's economics were waste-to-energy treatment and mined material disposal (Laner et al., 2019).

The use of MSW as an alternative fuel (AF) in Indonesia has attracted attention since the promulgation of Presidential Regulation No. 35 of 2018 concerning the Acceleration of Construction of Solid Waste Processing Installations into Electrical Energy Based on Environmentally Sustainable Technology (Indonesia Ministry of Law and Human Rights, 2018). However, the implementation of this regulation encountered obstacles due to the high-cost burden on the government in the future. As an alternative, MSW processing is directed to provide AF for the cement industry and coal-fired steam power plants as RDF and solid recovered fuel (Isaac and Bada, 2020; Sharma et al., 2022; Shin et al., 2023). The most popular AFs for cement kilns are waste oils, shredded residues, waste plastics, waste tires, and sewage sludges from conventional and nitrifying-enriched activated sludge (Sepehri and Sarrafzadeh, 2018; Sepehri and Sarrafzadeh, 2019; El-Salamony et al., 2020). The utilization rate of AF in the cement industry in the world, Europe, and Southeast Asia, as evaluated by thermal substitution rate, was 18%, 46%, and 9%, respectively (Sharma et al., 2022), while Indonesia was less than 1% (Jayawati and Taufik, 2021). This circumstance describes a strong chance for landfill-mined RDF to be used as AF in cement plants, substituting coal/petroleum coke in a calciner/kiln. The permissible calorific value (CV) for RDF in a cement kiln in Thailand was 15 MJ kg^{-1} (Prechthai et al., 2008), while in Indonesia was 12.5 MJ kg^{-1} (Paramita et al., 2018). Both standards were lower than the CV of petroleum coke for cement production at 32.6 MJ kg^{-1} (Kara et al., 2010).

Since 2013, the LM concept in Indonesia has been regulated by the Ministerial Regulation of Public Works No. 03/PRT/M/2013 on the Implementation of Infrastructure and Facilities for Handling of Household Solid Waste and Household Solid Waste Alike (Indonesia Ministry of Public Works, 2013). However, the first LM pilot project was not carried out in Indonesia until 2020 at the Jakarta Province-integrated MSW treatment facility (MSWTF) (Prihartanto et al., 2023a). The growing need for landfill-mined RDF as a substitute for coal in the cement industry has driven efforts to develop LM in Indonesia.

The top five Southeast Asian MSW producers, namely Indonesia, Thailand, Vietnam, the Philippines, and Malaysia, used open dumping and controlled-landfill techniques rather than sanitary landfills (Arumdani et al., 2021). The controlled landfill technique is a transition between open dumping and sanitary landfills. The deployment of LM in controlled landfill sites in Indonesia distinguishes it from other LM operations in Southeast Asia, such as Thailand, which used open dumping (Rattanaoudom et al., 2008).

By 2020, at least 20 Indonesian landfills potentially produce RDF for cement kilns AF. In 2022, the LMM recovery potential for RDF production was 26,950 t d^{-1} (Zaenudin, 2023). The Indonesian Cement Group identified at least 21 cement plants in Indonesia that might use RDF as AF in their 34 kilns in 2020 (Jayawati and Taufik, 2021).

The inaugural RDF product in 2020 produced a CV of 9.89–16.07 MJ kg^{-1} that partially met the RDF quality standards for the Indonesian cement industry at 12.5 MJ kg^{-1} (Paramita et al., 2018). Nonetheless, some CVs only met the second and third classes of the Indonesian RDF standards for coal-fired steam powerplants at 10 and 10–15 MJ kg^{-1} (Ismawati et al., 2022; Zaenudin, 2023). Previous study investigated the highest portion of combustible components of LMM was plastic component at 34.36–36.33% (Prihartanto et al., 2023a). This component had a high CV of 20.49–54.39 MJ kg^{-1} (Chiemchaisri et al., 2010; Novita and Damanhuri, 2010; Zhou et al., 2014; Quaghebeur et al., 2018; Cheela et al., 2021) suitable for RDF raw material. However, the presence of high-content chlorine from polyvinyl chloride (PVC) plastic has the potential to produce polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDDs/PCDFs) gases at unsuitable combustion temperatures (Safavi et al., 2021; Kaniowski et al., 2022). The initial RDF product trial in 2019 yielded moisture, chlorine, and ash contents of 38.4–42.55%, 0.2–8.17%, and 17.39–23.80%, respectively, These values partially exceeded the RDF quality standards of 25%, 0.3%, and 15%, respectively (Cahyadi, 2006; Kara et al., 2010;

Ismawati et al., 2022), indicating a suboptimal physical-chemical characteristic of RDF, which required improvement. High ash content in RDF causes increased fouling, slagging, and corrosion at the heat exchanger surfaces of power plant boilers (Kaniowski et al., 2022). Besides, the combustion of a large proportion of chlorine-containing materials at temperatures 200–300 °C produces corrosive HCl (Ma et al., 2020), whereas temperatures 200–800 °C stimulate PCDDs/PCDFs gas generation, causing human health problems (Safavi et al., 2021).

Although the potential use of LMM as an RDF raw material in Southeast Asia has been investigated in several studies (Prechthai et al., 2008; Zhao et al., 2016; Prihartanto et al., 2023a), comprehensive research on optimizing RDF composition and the need for data on the specific factors impacting RDF quality is still lacking. Hypothetically, raw materials re-composition will optimize the CV and physical-chemical contents of the RDF to comply with the cement industry and coal-fired steam power plant's specifications. Hence, the scientific question is to what extent recomposed RDF quality optimization can be achieved to meet both industrial specifications and how it affects the production process, product quality, and environment.

Therefore, the study aimed to improve RDF composition for acceptable CV, moisture, volatile, ash, fixed carbon, chlorine, and sulfur contents by the cement industry and coal-fired steam power plant. Analysis of the possible effects of burning RDF on cement kilns and coal-fired steam power plant boilers focused on the impact on machines and process conditions and product quality produced. The consequences of particulate, PCDDs/PCDFs, and SO_2 emissions on human health and the environment were compared to the likelihood of future increases in ash, chlorine, and sulfur content in RDF.

The results of this research are expected to provide recommendations for the authorities regarding acceptable RDF quality for industries. However, the limitation of this study is that it has not yet tested the combustion performance of RDF under existing conditions in cement kilns and coal-fired power plant boilers. Besides, due to the difficulty of eliminating impurities from the RDF raw material surface, RDF samples were prepared without pre-cleaning, resulting in lower accuracy of CV, volatile solids, and ash content in RDF (Cheela et al., 2021).

MATERIAL AND METHODS

Study area description

In 2022, more than 8.527 t d^{-1} of MSW from six administrative cities in Jakarta Province, namely West Jakarta, Central Jakarta, South Jakarta, East Jakarta, North Jakarta, and Thousand Islands, were transported to the Jakarta landfill in 2022 (Figure 1a) (Indonesia Ministry of Environmental and Forestry, 2020). About 88% (7.543 t d^{-1}) of this MSW was buried in an 81.4 ha landfill site located 51 kilometers southeast of North Jakarta.

The landfill is divided into six zones comprising twelve sub-zones (Figure 1b). Four of these zones (I, II, III, and V) continue to receive fresh MSW, but zones IV and VI have been closed since 2003 and 2006. Zone IV received MSW from 1997 to 2003, with an estimated volume, density, and total waste mass of 21,218.464 m^3, 0.485 t m^{-3}, and 10.29 Mt, respectively.

The unavailability of land for landfill expansion has encouraged the Jakarta Provincial Government to operate LM in 2020. LM was carried out in Sub-Zone IVB, with a landfill area of 1.45 ha and a heap height of 17 m in 2020. This pilot project integrated sequent processes of excavating, transporting, stockpiling, screening, wind sifting, and shredding to produce RDF and SLM (Figure 1c). The RDF has been used as AF in the cement industry, while the SLM has not been used optimally. The average weight of LMM processed was 81.07–150.46 t d^{-1} with an average of 115.25 ± 24.50 t d^{-1} in 2022.

The screening processes using 10 mm and 30 mm trommel screens produced fine, medium, and rough fractions of < 10 mm, 10–30 mm, and > 30 mm, respectively. Fine and medium fractions, dominated by SLM component, were used for non-energy purpose. A rough fraction containing a high content of combustible materials was used for RDF raw material. This fraction was split into heavy and light fractions using a wind sifter. A rough-light fraction was blown to the RDF stockpile and then crushed with a fine shredder until the size was < 3 cm, while the residue was returned to the landfill.

Sample collection and RDF preparation

Samples were collected at the RDF processing plant location for eight consecutive days following the ASTM-D5231-92 (ASTM, 2016).

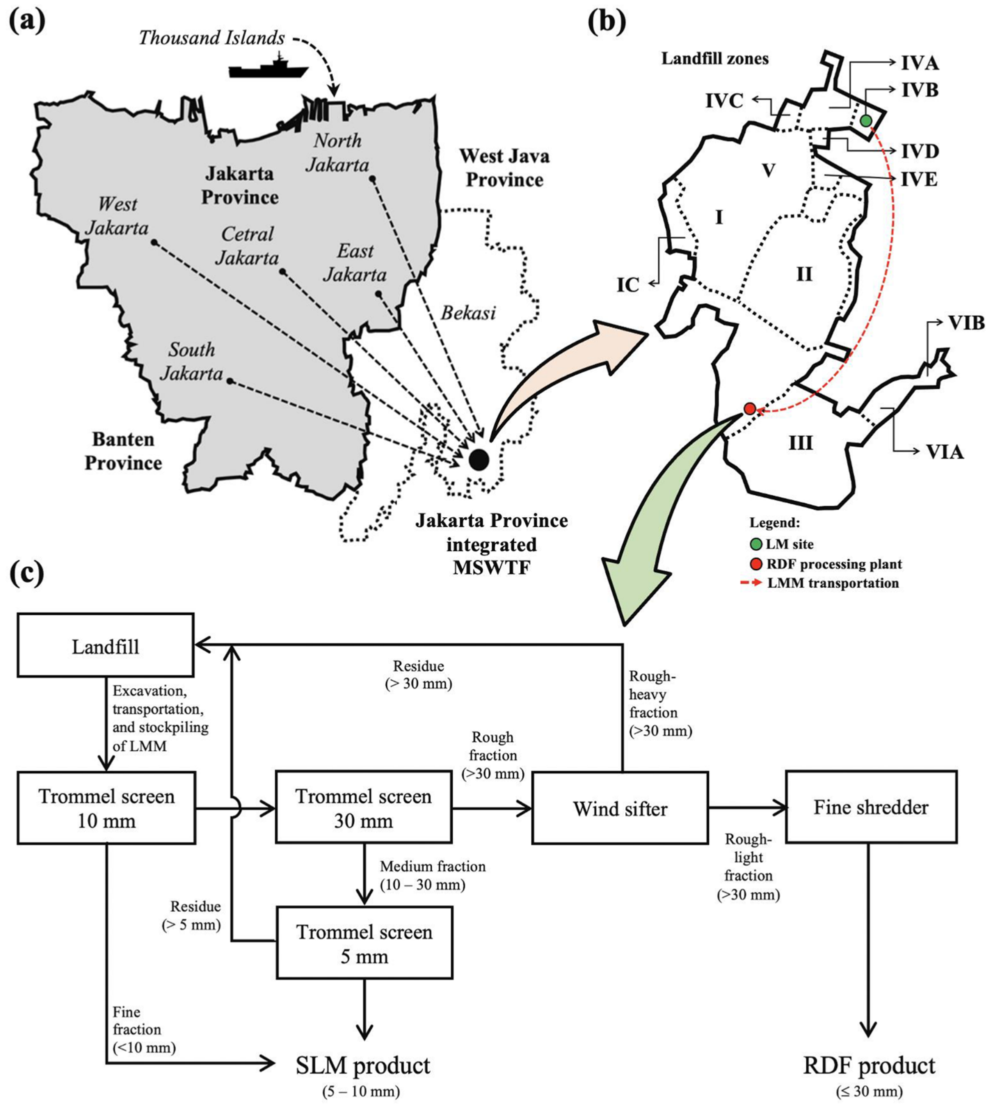

Figure 1. (a) Transport of the Jakarta Province MSW to an integrated MSWTF; (b) landfill zones; (c) process flow of RDF processing plant

The daily sample was analyzed separately every day, and then the values obtained were averaged for each parameter analyzed. Not less than 100 kg of daily LMM samples were taken from randomly selected transport trucks operated at this plant site for the sifting process. Each sample was sifted using 10 mm and 30 mm sieve screens and classified into fine, medium, and rough fractions of < 10 mm, 10–30 mm, and > 30 mm, respectively. Based on rough fraction composition analysis results in a previous study (Prihartanto et al., 2023a), some components were selected as RDF raw materials. The criteria for determining the suitable rough fraction components for RDF raw materials are combustible components with a large portion and a CV above the industrial quality standards of 12.5 MJ kg^{-1}. Using these selection criteria will simplify the RDF raw material sorting and mixing in the production line.

Figure 2 shows that combustible materials in a rough fraction were dominated by plastic, followed by wood and garden waste (W+GW) components of 33.97–34.47% and 16.22–17.11% (Prihartanto et al., 2023a). The CV of plastic was 20.49–54.39 MJ kg^{-1}, while W+GW was 18.20–22.40 MJ kg^{-1} (Rattanaoudom et al., 2008; Chiemchaisri et al., 2010; Quaghebeur et al., 2014; Eriska et al., 2017; Cheela et al., 2021). Therefore, plastic and W+GW components were selected as RDF raw materials.

Both components were shredded by the 0.5 mm cutting mill to get a homogenous RDF mixture (Zhao et al., 2016). An experiment was carried out to determine the optimum CV of nine ratio

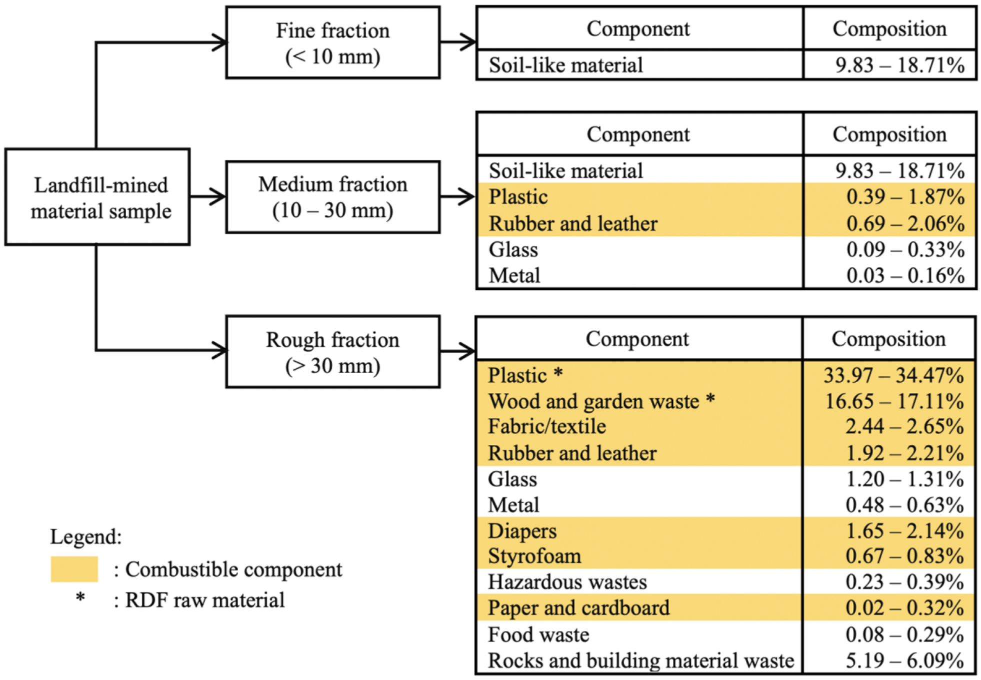

Figure 2. Landfill-mined material categorization based on particle size distribution and component composition (Prihartanto et al., 2023a)

variations of plastic: W + GW components of RDF samples. Ratios of both components were between 20:80 and 80:20. A proportion of 10 points was added for each ratio increment of the plastic component, accompanied by a proportion reduction of 10 points for the W+GW component. Besides, ratios 0:100 and 100:0 were also used as controls.

Calorific value and physical-chemical contents determination

All parameters in Table 1 were analyzed on a dry basis, except for initial moisture content. ASTM-D5865 (ASTM, 2019) determined CV using a bomb calorimeter model PARR 1261. Determination of the initial moisture, which was measured immediately after RDF raw materials were mixed, is critical for evaluating the moisture content reduction potential in open air. RDF sample was dried for two days at room temperature (26–34 °C) before being measured for the air-dried moisture content. RDF samples were dried in an oven at 110 ± 5 °C for 12 hours to measure moisture content, as per ASTM D2216-98 (ASTM, 1998). The volatile solids content was determined by burning the sample at 950 °C for 7 minutes in a crucible with a lid according to ASTM-D3175-07 (ASTM, 2007a). Meanwhile, the ash content was determined using ASTM-D3174-02, which required burning the sample at 600 °C in a muffle furnace (ASTM, 2002). ASTM-D3172-07a defined fixed carbon content as the difference between 100% and the total percentage of moisture, ash, and volatile solids content (ASTM,

Table 1. Standard methods for determining CV and physical-chemical contents of RDF

No.	Parameter	Method	Standard	Reference
1.	Calorific value	Calorimetry	ASTM-D5865	ASTM, 2019
2.	Moisture content *	Gravimetry	ASTM D2216-98	ASTM, 1998
3.	Volatile solids content	Gravimetry	ASTM-D3175-07	ASTM, 2007a
4.	Ash content	Gravimetry	ASTM-D3174-02	ASTM, 2002
5.	Fixed carbon	Gravimetry	ASTM-D3172-07a	ASTM, 2007b
6.	Chlorine	Iodometry	APHA/AWWA/WEF part 4500-Cl-B	APHA/AWWA/WEF, 2018
7.	Sulfur	Spectrophotometry	APHA/AWWA/WEF part 4500-S D	APHA/AWWA/WEF, 2017

Note: *Moisture content was measured on an air-dried basis, except for the initial moisture content on a wet basis.

2007b). Chlorine content was determined using the iodometry method according to APHA/AWWA/WEF part 4500-Cl-B (APHA/AWWA/WEF, 2018), while sulfur content by APHA/AWWA/WEF part 4500-S D (APHA/AWWA/WEF, 2017). For sulfur content analysis, samples were reacted with ferric chloride and dimethyl-p-phenylenediamine to produce methylene blue before being analyzed using a spectrophotometry method at wavelength 664 nm.

RESULTS AND DISCUSSION

Calorific value

At a ratio of plastic : W + GW components of 0:100, RDF produced the lowest CV of 19.18 ± 0.99 MJ kg^{-1} (Table 2). This value met RDF quality standards in the Indonesian cement industry, India, Italy, and the United Kingdom by 10–18.7% MJ kg^{-1} (Saha et al., 2017; Paramita et al., 2018; Pakpahan, 2024). However, it was lower than Thailand's highest standards of 20.71 MJ kg^{-1} (Itsarathorn et al., 2022) and Indonesia's highest standards for coal-fired steam power plants at 20 MJ kg^{-1} (Ismawati et al., 2022). This CV was comparable to a previous study that showed a CV of wood at 18.20–18.30 MJ kg^{-1} (Rattanaoudom et al., 2008; Eriska et al., 2017) and garden waste at 18.7–22.4 MJ kg^{-1} (Duruaku et al., 2016).

Conversely, at a ratio of 100:0, RDF produced the highest CV of 44.82 ± 0.89 MJ kg^{-1}, which met all RDF quality standards. This value was close to previous studies at 41.29–44.75 MJ kg^{-1} (Zhou et al., 2014). In comparison, numerous types of plastic waste in Indonesia, including HDPE, LDPE, PP, PVC, and PS, generated CVs ranging from 41.00 to 51.54 MJ kg^{-1}, whereas PET bottles only 22.81 MJ kg^{-1} (Novita and Damanhuri, 2010). Except for PET, the data confirmed that plastic components had double the CV of W + GM components.

The increase of the plastic component portion, which was coupled with the W + GW component portion reduction, increased rather than decreased the CV of RDF. Therefore, CV optimization of RDF can be achieved by maximizing the plastic component portion while reducing risk to the industrial process, product quality, and the environment. Table 2 shows that a CV of RDF at a ratio of plastic : W + GW components of 40:60 generated a CV of 25.23 ± 0.53 MJ kg^{-1}. This value exceeded the premium RDF quality standards of more than 25 MJ kg^{-1} (Sarc and Lorber, 2013). Meanwhile, with plastic content ranging from 0 to 30%, typical CVs were lower than premium. One factor to consider while adjusting RDF composition is the probability of PCDD/PCDF emissions in the furnace due to improper combustion temperatures (Tomsej et al., 2018). As a result, the proportion of plastic components required to be kept to a minimum while achieving the highest feasible CV. It was expected that the RDF ratio of 40:60 would generate a high CV with a small plastic portion, which is defined as the optimum ratio.

Moisture contents

On an air-dry basis, RDF moisture content ranged from 20.75 ± 0.91% at a ratio of 70:30 to 32.13 ± 1.25% at 30:70 and 26.11 ± 2.84% at the

Table 2. Calorific values, moisture, volatile solids, ash, fixed carbon, chlorine, and sulfur contents of RDF

No.	Composition		RDF Parameter						
	Plastic	W+GW	Calorific values	Moisture	Volatile solids	Ash content	Fixed carbon	Chlorine	Sulfur
	(%)	(%)	(MJ kg^{-1})	(%)	(%)	(%)	(%)	(%)	(%)
1.	0	100	19.18±0.99	23.05±2.05	67.62±1.26	25.94±1.77	6.43±0.72	0.102±0.009	0.047±0.005
2.	20	80	22.04±0.57	27.46±1.00	72.58±3.59	24.05±3.21	3.36±0.39	0.117±0.005	0.039±0.005
3.	30	70	21.19±0.55	32.13±1.25	74.57±1.24	21.63±0.98	3.80±0.36	0.090±0.005	0.040±0.001
4.	40	60	25.23±0.53	26.11±2.84	75.20±1.21	21.18±0.76	3.62±0.63	0.129±0.009	0.058±0.004
5.	50	50	27.14±0.54	22.35±1.40	76.26±1.49	20.55±1.49	3.19±0.59	0.098±0.006	0.059±0.002
6.	60	40	26.51±1.21	23.34±3.77	75.62±4.69	19.98±4.01	4.39±1.24	0.128±0.004	0.060±0.001
7.	70	30	28.43±0.96	20.75±0.91	77.67±1.58	17.85±1.11	4.48±0.77	0.082±0.004	0.042±0.004
8.	80	20	32.84±1.02	25.64±3.25	77.85±0.79	18.00±0.64	4.15±0.55	0.089±0.002	0.059±0.005
9.	100	0	44.82±0.89	24.06±1.97	84.45±0.95	11.25±0.34	4.30±1.06	0.105±0.008	0.050±0.006

Note: Ref.: [a] Pakpahan, 2024; [b] Ismawati et al., 2022; [c] Itsarathorn et al., 2022; [d] Saha et al., 2017; [e] Paramita et al., 2018.

optimum ratio (Table 2). These results partially exceeded RDF quality standards in Indonesia, India, Italy, and the United Kingdom by 7–25% (Saha et al., 2017; Paramita et al., 2018; Ismawati et al., 2022; Pakpahan, 2024) but still meet Thailand's standards of 30–45% (Itsarathorn et al., 2022). This study found a constant moisture content with a narrow range of fluctuation unaffected by changes in the RDF ratio.

RDF had an initial moisture content ranging from 47.86 ± 2.55 to 64.74 ± 23%, exceeding all quality standards. The difference between initial and air-dried moisture contents was required for estimating the possible moisture content reduction in open-air dryers in RDF processing plants. Drying RDF in the open air for two days at 25–35 °C potentially reduces moisture content by one-third to half compared to the initial moisture.

Volatile solids content

The volatile solids content of RDF fluctuated in the range 67.62 ± 1.26% – 84.45 ± 0.95% and at the optimum ratio was 75.20 ± 1.21%. All values met the RDF quality standards of the United Kingdom, and Indonesian coal-fired steam power plants of 65–75% (Paramita et al., 2018; Ismawati et al., 2022). The highest value was close to the volatile solids content of landfill-mined plastic component at the Yingchun landfill, China, at 87.09 ± 0.55% (Zhou et al., 2014), but unburied ordinary plastic waste had 98.5% (Tchobanoglous et al., 2000). Table 2 shows that increasing the proportion of plastic components leads to an increase in RDF's volatile solids content.

The volatile solids content of an LMM decreases with age, but the ash content increases (Sathyanarayanan et al., 2010; Wang et al., 2021). RDF's high volatile solids content was most likely produced by a high amount of combustible plastic and W+GW components at 33.97–34.47% and 16.22–17.11% (Prihartanto et al., 2023a). Previous research found that the volatile solids content in the LMM plastic component was 87.09% (Zhou et al., 2014) and 74.44% in wood (Widyarsana and Tambunan, 2022), similar to the present study.

The high volatile solids content reflects RDF's large proportion of easily ignited combustible components (Larney et al., 2005; Gebreslassie et al., 2020; Widyarsana and Tambunan, 2022). This condition affects the residence time of fuel particles in the combustion chamber.

Ash content

The ash content of RDF varied in the range 11.52 ± 0.34% – 25.94 ± 1.77%, and at the optimum ratio was 21.18±0.76%. Table 2 shows that some countries set RDF quality standards for ash content of 12–25% (Saha et al., 2017; Paramita et al., 2018; Ismawati et al., 2022; Itsarathorn et al., 2022; Pakpahan, 2024), whereas the cement industry in Indonesia has set a maximum ash content for RDF at 15% (Solusi Bangun Indonesia, 2019). At a ratio from 20:80 to 100:0, ash content was 11.25 ± 0.34 – 24.05 ± 3.21%, which met all RDF quality standards, while at a 0:100 ratio was above the standards. At the optimum ratio, the ash content was 21.18 ± 0.78%, meeting the standards. Nevertheless, the ash content in all ratios exceeded the cement industry's specification of 15%.

Table 2 demonstrates that increasing the plastic component portion coupled with decreasing the wood component portion resulted in a decrease in ash content. The ash content of plastic waste in the Yingchun landfill in China was 9.70–12.50% (Zhou et al., 2014), nearly similar to the ash content of RDF at a ratio of 100:0 of 11.25 ± 0.34%. For comparison, regular non-landfilled PE plastic waste contained 1.2% ash (Tchobanoglous et al., 2000). This comparison demonstrated the effect of impurities from the SLM component on the landfilled plastic ash content. The SLM contained a high ash content of 20.97–30.83% (Widyarsana and Tambunan, 2022; Prihartanto et al., 2023b). Previous research showed that several W + GW components had an ash content of 0.10–12.73%. (Duruaku et al., 2016; Eriska et al., 2017; Widyarsana and Tambunan, 2022). Table 2 shows that the ash content at a ratio of 0:100 was 25.94 ± 1.77%, double as high as previous study results. The high ash content was caused by impurities from the SLM and nutrient-plant minerals in the W + GW component (Neina et al., 2020; Smołka-Danielowska and Jabłońska, 2022).

RDF with a high ash content is not preferred because it causes slagging, disrupts the combustion process and affects particulate matter emissions (Sun et al., 2016). Particulate matter is a critical air pollution parameter which requires best removal technology. Its exposure leads to human heart or lung illness, as well as nonfatal heart attacks (US EPA, 2023). As consequence, air pollution control equipment is required to reduce the harmful impact of particulate matter emissions from RDF combustion on the environment (Sun et al., 2016). RDF's high ash content can have an impact on boiler performance. At coal-fired steam power plants, RDF's aggressive ash components, such as potassium, sodium, sulfur, chlorine, and ash agglomeration, cause increased fouling, slagging, and corrosion on boiler heat exchanger surfaces (Kaniowski et al., 2022). Potassium is a key macronutrient for plants produced during the ash phase. Therefore, increasing the quantity of W + GW components in RDF will increase the potassium content of the biomass ash. The potassium in the aerosol phase may be absorbed by the fly ash or directly condense on the cooler surfaces of the heat exchangers, resulting in a low melting deposit. The accumulation of these deposit reduces boiler efficiency by decreasing the heat transfer coefficient (Kaniowski et al., 2022).). The presence of high potassium content in soluble salt forms such as Kl, K_2CO_3, or K_2SO_4 increases the risk of corrosion in metal boilers at 600 °C (Pettersson et al., 2011; Kaniowski et al., 2022).

The ash content, which exceeded the industrial RDF standards of 15%, remains an issue in Indonesia, India, and China (Cheela et al., 2021; Jain et al., 2023; Prihartanto et al., 2023a). Consequently, it is necessary to remove SLM containing high ash content attached to RDF raw materials using the best available pre-cleaning techniques, such as sorting, cleaning, drying, and washing (Zhou et al., 2014; Jain et al., 2023). Although the washing procedure could not enhance the CV of landfill-mined plastic components, it did reduce ash content by up to 10.84±1.19% (Zhou et al., 2014). For comparison, the ash content of non-cleaned landfill-mined plastic components ranged between 20% and 35% (Quaghebeur et al., 2014). The ash content of landfill-mined plastic component was predicted to match cement industry specification of 15% through the washing process.

Fixed carbon content

The fixed carbon content of RDF fluctuated in the range 3.19 ± 0.59% – 6.43 ± 0.72%, and at the optimum ratio was 3.62 ± 0.63%. At a ratio of 0:100, the fixed carbon content was 6.43 ± 0.72%, meeting the lowest RDF quality standards for coal-fired steam power plants of 5 – 15% (Ismawati et al., 2022). Meanwhile, fixed carbon contents were below the standards in other ratios. A previous study found a highly significant relationship between the amount of lignin in biomass and the percentage of fixed carbon (Demirbaş, 2003). Therefore, the fixed carbon content of RDF should decrease in line with the reduction in the W + GW component. However, Table 2 shows that the fluctuation of fixed carbon content exhibited no particular trend.

The plastic-dominated RDF, at a ratio of 100:0, had a fixed carbon content of 4.30 ± 1.06%. These values were higher than the study at the Yingchun landfill, China, at 2.07% (Zhou et al., 2014). In contrast, non-landfilled regular PE plastic waste had a constant solid composition of less than 0.1% (Tchobanoglous et al., 2000). Therefore, the high fixed carbon content of landfilled plastic components could be attributed to a lignin-containing impurity given by LMM biomass. A biomass proportion in the form of the W+GW component of the LMM at 16.91– 19.17% in this study (Prihartanto et al., 2023a) was higher than in Yingchun at 2.43% (Zhou et al., 2014), potentially contributing to the higher fixed carbon contents than in Yingchun.

Table 2 shows that increasing the W + GW component portion approaching 100% will increase a fixed carbon content to above the RDF quality standards of 5%. However, this effort will escalate the ash content to above RDF quality standards of 25% and reduce the CV approaching the minimum value. Therefore, the optimum ratio was set at 40:60 to achieve the highest CV while complying with RDF quality standards for ash and fixed carbon contents.

Despite being affected by the LMM's age and composition, raising fixed carbon content remains a challenge for improving RDF quality in the future. Higher fixed carbon content results in longer combustion retention times, resulting in a rapid and more intense thermal response (Mboowa et al., 2017; Nasiri et al., 2023). The fixed carbon content of RDF in present study, India, China, and Iran were 3.19–6.43%, 3.1–8.1%, 2.10%, and 2.85%, respectively (Cheela et al., 2021; Nasiri et al., 2023), some of which were categorized as low-quality RDF below 5% and needed improvement. The addition of zeolite to RDF pellets has been proven to increase the fixed carbon content by 2.85% to 3.70% (Nasiri et al., 2023).

Chlorine content

The chlorine content of RDF slightly fluctuated in the range 0.082 ± 0.004–0.129 ± 0.009%, and at the optimum ratio was 0.129 ± 0.009%, meeting all RDF quality standards of 0.2–1% (Saha et al., 2017; Paramita et al., 2018; Ismawati et al., 2022; Itsarathorn et al., 2022; Pakpahan, 2024). RDF quality standards for the cement industry and coal-fired steam power plant are aligned with chlorine content. The RDF chlorine content standards for the Indonesian cement industry is 0.8% (Solusi Bangun Indonesia, 2019), while coal-fired power plants use 0.2–1% (Ismawati et al., 2022). Therefore, the results of this study complied with both industrial quality standards.

Previous research has identified plastic, specifically PVC, as a primary source of chlorine in MSW (Ma et al., 2020). Therefore, the high plastic content should contribute to the high chlorine content in RDF. However, Table 2 shows the low and constant chlorine content without any particular trend. A low chlorine content below the standards indicates a small portion of PVC in the composition of plastic components. A narrow fluctuation was probably caused by the uneven distribution of samples collected during the study.

The combustion of an excessive chlorine content in kiln or boiler at a temperature of 200–800 °C potentially generates PCDDs/PCDFs (Zhang et al., 2015; Safavi et al., 2021; Kaniowski et al., 2022). PCDDs/PCDFs are categorized as persistent, bio-accumulative, and toxic pollutants that cause human health problems (Picone et al., 2020). These pollutants exposures to human cause obesity, skin diseases, immune and nervous system disorders, negative effects on reproduction, teratogenicity, endocrine disruption, and a predisposition to cancer (Loganathan and Masunaga, 2009). Therefore, low chlorine contents of RDF in this study indicated a minimum risk of PCDDs/PCDFs emissions produced during the combustion of RDF in the cement kiln and coal-fired steam power plant's boiler. However, when the chlorine concentration raised exceeding the quality standards, air supply and temperature adjustment during combustion is required to lower the PCDDs/PCDFs formation (Ma et al., 2020). A thermochemical reaction of the high chlorine content of fuels and cement raw materials at a temperature of 200–300 °C potential to form HCl, which is corrosive to metal constructions of power plant boilers and rotary kiln (Zhang et al., 2015; Ma et al., 2020; Kaniowski et al., 2022)

Using high-ash RDF with cement raw materials during the clinker formation process results in crude clinker (Dahliar et al., 2014). The primary chemical reaction in a cement kiln converts calcium oxide and silicate oxide into calcium silicate (Horkoss, 2008). Excessive chlorine input to the cement kiln will damage cement quality due to the reaction between chlorine and CaO from raw materials, which produces $CaCl_2$. This combination creates an excess of chlorine ions in the cement, resulting in concrete freeze-thaw and steel reinforcement corrosion. This condition will eventually impact the service life and safety of the concrete structure (Wang et al., 2019). Besides, the salt compound formed from the reaction between chlorine and alkali-silica generates microcracks, causing compressive strength degradation of concrete (Kara et al., 2009). A reaction between chlorine and alkali metals or their oxides in the cement kiln creates NaCl and KCl, which causes the formation of low-temperature melt and crusts, generating different levels of blockage in the rotary kiln. (Wang et al., 2019).

The higher the kiln temperature, the greater the chlorine content in flue gas and fly ash. The chlorine was primarily found in flue gas and residual solids, with fly ash content of less than 3.5% (Wang et al., 2019; Ma et al., 2020). At a cement kiln temperature of 1100 °C, increasing the chlorine concentration above 0.50% causes an increase in chlorine in flue gas, followed by a decrease in residual solids due to the decrease in Ca/Cl and CaO de-chlorination efficiency in the cement kiln. Besides, the chlorine content in flue gas and fly ash escalates as retention time increases from 0 to 30 minutes, then stabilizes after 30 minutes due to the termination of chlorine release (Wang et al., 2019).

Sulfur content

Table 2 shows that sulfur content of RDF fluctuated in the range 0.039 ± 0.005% – 0.060 ± 0.001%, and at the optimum ratio was 0.058 ± 0.004%, meeting all RDF quality standards of 0.1–1.5% (Saha et al., 2017; Paramita et al., 2018; Ismawati et al., 2022; Itsarathorn et al., 2022; Pakpahan, 2024). RDF sulfur contents were nearly similar for all ratios, with no particular trend. A narrow fluctuation of sulfur contents was most likely due to the uneven distribution of samples during the study. The primary sources of sulfur in LMM include food waste, paper, and wastewater treatment plant sludge (Ko et al., 2015), as well as from cover soil material.

The sulfur content of RDF was predicted to emit SO_2 content below the emission quality standards for coal-fired steam power plants. However, it was necessary to anticipate sulfur contents increasing possibility, correlated to SO_2 increment, exceeding quality standards in the future. High emission of SO_2 may contributes to acid rain formation, causing disserved impacts on soil and water quality due to acidification.

The primary source of sulfur at the cement kiln comes from cement raw materials and fuels. Combustion of sulfur from both sources potentially produces SO_2. In the rotary kiln, the SO_2 reacts with CaO, K_2O, and Na_2O (in cement raw materials mix), reacts with the intermediate and final crystals of clinker, or leaves a kiln as flue gas. Besides, another undesirable possibility appears when sulfur is retained in the kiln system as deposits, resulting in kiln system blockage (Horkoss, 2008).

Process improvements of the RDF processing plant

Table 2 shows that moisture, ash, and fixed carbon contents partially exceed the RDF quality standards in Indonesia, Thailand, India, Italy, and United Kingdom. Meanwhile CV, volatile solids, chlorine, and sulfur contents meet these standards. These results indicate the need for process improvements at the RDF processing plant to improve product quality. This improvement was designed based on the physical and chemical characteristics of RDF. The need for process improvement is to ensure that RDF quality meets the cement industry and coal-fired steam power plant standards, particularly for CV, moisture, ash, chlorine, and sulfur contents. The process flow was modified to obtain the optimum ratio of RDF without significantly altering the current initial process (Figure 1).

Figure 3 shows that the proportion of rough fraction to LMM reached 66.25% or 99.37 t d^{-1} of the RDF processing plant's full capacity of 150 t d^{-1} (Prihartanto et al., 2023a). The wind sifter separated 99.37 t d^{-1} of rough fraction into a rough-heavy fraction of 40.01 t d^{-1} and a rough-light fraction of 59.36 t d^{-1}. Based on a ratio of 40:60, about 16.66 t d^{-1} of plastic component was taken from a rough-light fraction, while 24.99 t d^{-1} of crushed W+GW component was from a rough-heavy fraction. Both plastic and W + GW components were mixed using a mechanical mixer to produce type 1 RDF. The remaining plastic components from a rough-light fraction of 34.66 t d^{-1} were mixed with non-plastic components from a rough-light fraction of 8.04% to produce type 2 RDF. The type 2 RDF analysis was not discussed in this study. The residue of non-W+GW components at 15.02 t d^{-1} was returned to the landfill.

Figure 3 identifies additional equipment required for process improvement, including manual sorting equipment, crusher, mixer, dryer, and excavator. According to an earlier study, 12 operators could manually sort 40.01 t d^{-1} rough-heavy fraction to obtain the W+GW component on a conveyor belt (Nafi'ah and Fadilah, 2023). A single hydraulic excavator is sufficient for handling RDF raw materials. For comparison, handling 150 t d^{-1} LMM at ISWTF requires one excavator. Because the shredder's used capacity was still less than 10% of its maximum capacity of 150 t d^{-1}, it is possible to use the remaining capacity to crush W+GW components. With a production capacity of 41.65 t d^{-1} and a working time of 8 hours per day, a spiral mixer with a capacity of ± 5 t h^{-1} was recommended for mixing RDF raw materials.

Additionally, the high moisture content of RDF needs further drying to meet quality standards. Therefore, the proposed process improvement includes the use of appropriate drying technology. Previous research concluded that solar dryers are the most cost-effective option and suited for tropical regions (Ismail et al., 2020; Tun and Juchelková, 2018). Although thermal dryers have the quickest drying time, they are recommended for use with external heat sources or waste heat from power plants (Tun and Juchelková, 2018). RDF drying experiments with conventional and greenhouse solar dryers reduced RDF moisture content from 30% to 21.58% and 16.25–17%, respectively (Arifianti et al., 2019). Therefore, solar dryers are feasible to use for reducing RDF moisture content.

During the production process, it is necessary to carry out a careful production sorting process at LMM to obtain the composition of RDF raw materials with low chlorine and sulfur content. Particular efforts to monitor RDF quality are required to ensure RDF composition supports optimum CV. In relation to environmental concerns, setting a stable temperature above 800 °C in the combustion zone of a furnace or boiler is essential to reduce the environmental risks of burning RDF. In addition, sufficient air supply for the RDF combustion process is necessary to

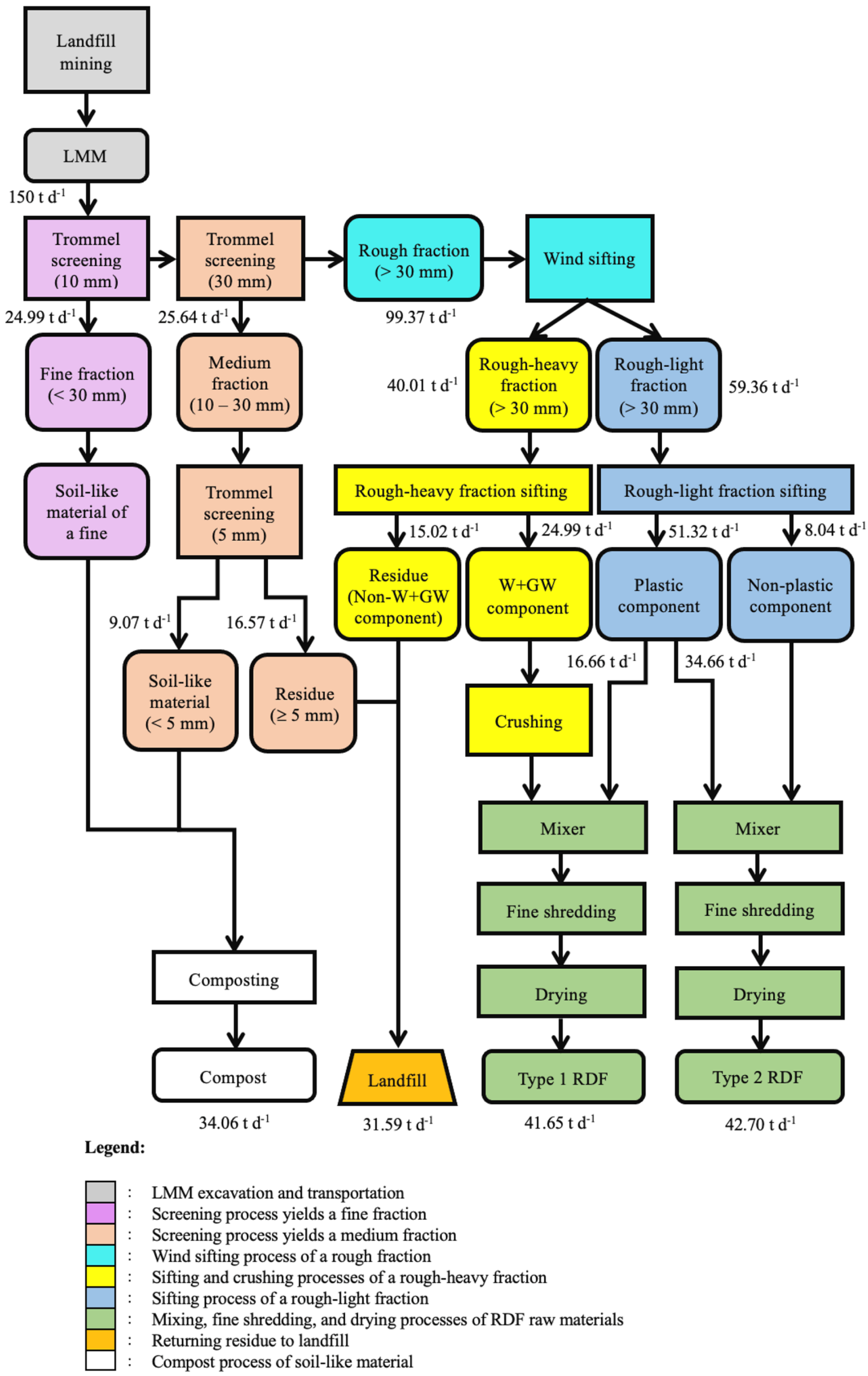

Figure 3. Proposed process improvement and mass balance of RDF processing plant

produce more HCL and less Cl_2. In addition, the use of scrubbers to control SO_2 emissions is crucial to reduce the impact on human health and the environment.

A previous study identified that of the 11 Southeast Asia countries, only Indonesia and Thailand conducted LM for energy recovery (Márquez et al., 2019). Both countries still produce low-quality RDF (Suknark et al., 2022; Prihartanto et al., 2023a). This study addresses quality improvement of the RDF by adjustment of raw material composition to increase the CV and decrease moisture, ash, fixed carbon, chlorine and sulfur contents.

CONCLUSIONS

The optimum ratio of plastic : wood and garden waste components for the RDF is 40:60. At this ratio, the CV, initial moisture, air-dried moisture, volatile solids, ash, fixed carbon, chlorine, and sulfur contents was 25.23 MJ kg^{-1}, 60.16%, 26.11%, 75.20%, 21.18%, 3.62%, 0.129%, and 0.058%, respectively. These results were close to their average values of 19.18 MJ kg^{-1}, 57.80%, 24.98%, 75.76%, 20.05%, 4.19%, 0.104%, and 0.050%, respectively. All values met the RDF quality standards, except for moisture content. This condition requires an additional drying unit in the RDF processing plant to reduce moisture content.

Process improvements at the RDF processing plant are required to accommodate the proposed RDF optimization at a ratio of 40:60. Sifting and mixing processes adjustment, either in a sorted rough or light fraction of LMM in the RDF processing plant, is required to obtain an optimum ratio. By this improvement, about 16.66 t d^{-1} plastic component was mixed with 24.99 t d^{-1} crushed W+GW component to produce 41.65 t d^{-1} RDF.

Chlorine and sulfur contents of RDF met the quality standards. However, anticipation of possibilities of increasing chlorine and sulfur contents exceeding standards needs concern, especially when using a large extent of RDF. Burning high chlorine and sulfur content RDF in furnaces and boilers at unsuitable temperature increases risks to the production process, product quality, and the environment.

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REFERENCES

1. APHA/AWWA/WEF. 2018. APHA/AWWA/WEF Method 4500-CL: Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington.
2. APHA/AWWA/WEF. 2017. APHA/AWWA/WEF Method 4500-S D: Methylene Blue Method, 23rd ed. American Public Health Association, Washington.
3. Arifianti, Q.A.M.O., Abidin, M.R., Nugrahani, E.F., Ummatin, K.K. 2019. Experimental Investigation of a Solar Greenhouse Dryer Using Fiber Plastic Cover to Reduce the Moisture Content of Refuse Derived Fuel in an Indonesian Cement Industry. In: International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE), Phuket, Thailand, 2018. https://doi.org/10.23919/ICUE-GESD.2018.8635723
4. Arumdani, I.S., Puspita, A.S., Budihardjo, M.A. 2021. MSW handling of top 5 leading waste-producing countries in Southeast Asia. In: IOP Conference Series – Earth Environmental Science, 896, 012003. https://doi.org/10.1088/1755-1315/896/1/012003
5. ASTM. 2019. D5865 Standard Test Method for Gross Calorific Value of Coal and Coke. American Society for Testing and Materials International, West Conshohocken.
6. ASTM. 2016. D5231–92 Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste. American Society for Testing and Materials International, West Conshohocken.
7. ASTM. 2007a. D3175–07 Standard Test Method for Volatile Matter in the Analysis Sample of Coal and Coke. American Society for Testing and Materials International, West Conshohocken.
8. ASTM. 2007b. D3172–07a Standard Practice for Proximate Analysis of Coal and Coke. American Society for Testing and Materials International, West Conshohocken.
9. ASTM. 2002. D3174–02 Standard Test Method for Ash in the Analysis Sample of Coal and Coke from Coal. American Society for Testing and Materials International, West Conshohocken.
10. ASTM, 1998. D2216–98 Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. American Society for Testing and Materials International, West Conshohocken.
11. Cahyadi. 2006. Strategy to reduce SO_2 emissions in coal-fired power plants that do not have desulfurization. Jurnal Ilmiah Teknologi Energi, 1, 41–53.
12. Cheela, V.R.S., John, M., Dubey, B. 2021. Quantitative determination of energy potential of refuse derived fuel from the waste recovered from Indian landfill. Sustainable Environment Research, 31(24). https://doi.org/10.1186/s42834-021-00097-5
13. Chiemchaisri, C., Charnnok, B., Visvanathan, C. 2010. Recovery of plastic wastes from dumpsite as refuse-derived fuel and its utilization in small gasification system. Bioresource Technology, 101(5), 1522–1527. https://doi.org/10.1016/j.biortech.2009.08.061

14. Dahliar, N., Widodo, S., Tonggiroh, A. 2014. The influence of coal ash composition on the quality of portland cement clinker at PT. Tonasa Cement unit III. Geosains, 10, 58–67.
15. Demirbaş, A. 2003. Relationships between lignin contents and fixed carbon contents of biomass samples. Energy Convertion and Management, 44(9), 1481–1486. https://doi.org/10.1016/S0196-8904(02)00168-1
16. Duruaku, J.I., Ajiwe, V.I.E., Okoye, N.H., Arinze, R.U. 2016. An Evaluation of the calorific values of the branches and stems of 11 tropical trees. Journal of Sustainable Bioenergy Systems, 6(2), 44–54. https://doi.org/10.4236/jsbs.2016.62005
17. El-Salamony, A.R., Mahmoud, H.M., Shehata, N. 2020. Enhancing the efficiency of a cement plant kiln using modified alternative fuel. Environmental Nanotechnology, Monitoring and Management, 14, 100310. https://doi.org/10.1016/j.enmm.2020.100310
18. Eriska, H., Dewi, K., Pasek, A.D., Damanhuri, E. 2017. Hydrothermal carbonization of biomass waste by using a stirred reactor: An initial experimental results. Reaktor, 16(4), 212–217. https://doi.org/10.14710/reaktor.16.4.212-217
19. Esguerra, J.L., Laner, D., Svensson, N., Krook, J. 2021. Landfill mining in Europe: Assessing the economic potential of value creation from generated combustibles and fines residue. Waste Management, 126, 221–230. https://doi.org/10.1016/j.wasman.2021.03.013
20. European Commission-Directorate General Environment. 2003. Refuse Derived Fuel, Current Practice, and Perspectives: Quality Standards for Solid Recovered Fuel. European Commission-Directorate General Environment, Brussels.
21. Gebreslassie, M.G., Gebreyesus, H.B., Gebretsadik, M.T., Bahta, S.T., Birkie, S.E. 2020. Characterization of municipal solid waste's potential for power generation at Mekelle City as a waste minimisation strategy. International Journal of Sustainable Engineering, 13(1), 68–75. https://doi.org/10.1080/19397038.2019.1645757
22. Gerven, T.V., Geysen, D., Pontikes, Y., Cizer, Ö., Mertens, G., Elsen, J., Balen, K.V., Jones, P.T. 2010. An integrated materials valorisation scheme for enhanced landfill mining.
23. Horkoss, S., 2008. Reducing the SO_2 emission from a cement kiln. Internastional Journal of Natural and Social Science, 1, 7–15.
24. Indonesia Ministry of Law and Human Rights. 2018. Presidential Regulation no. 35 of 2018 concerning the Acceleration of Construction of Solid Waste Processing Installations into Electrical Energy Based on Environmentally Sustainable Technology.
25. Indonesia Ministry of Environmental and Forestry. 2020. National Solid Waste Management Information System. Available from: https://sipsn.menlhk.go.id/sipsn/
26. Indonesia Ministry of Public Works. 2013. Ministerial Regulation of Public Works no. 03/PRT/M/2013 on Implementation of Infrastructure and Facilities for Handling of Household Solid Waste and Household Solid Waste Alike.
27. Isaac, K., Bada, S.O. 2020. The co-combustion performance and reaction kinetics of refuse derived fuels with South African high ash coal. Heliyon, 6(1), e03309. https://doi.org/10.1016/j.heliyon.2020.e03309
28. Ismawati, Y., Proboretno, N., Septiono, M.A., Zaki, K. 2022. Refuse-Derived Fuel in Indonesia. Nexus3 Foundation/IPEN.
29. Ismail, T.M., Ramzy, K., Sherif, H. 2020. Drying of refuse-derived fuel (RDF) using solar tunnel dryer integrated with flat-plate solar collector: An experimental approach. Detritus, 13, 140–147. https://doi.org/10.31025/2611-4135/2020.14028
30. Itsarathorn, T., Towprayoon, S., Chiemchaisri, C., Patumsawad, S., Wangyao, K., Phongphipat, A. 2022. The Situation of RDF Utilization in the Cement Industry in Thailand. ICUE 2022 on Energy, Environment, and Climate Change.
31. Jagodzińska, K., Lopez, C.G., Yang, W., Jönsson, P.G., Pretz, T., Raulf, K. 2021. Characterisation of excavated landfill waste fractions to evaluate the energy recovery potential using Py-GC/MS and ICP techniques. Resources, Conservation and Recycling, 168, 105446. https://doi.org/10.1016/j.resconrec.2021.105446
32. Jain, M., Kumar, A., Kumar, A. 2023. Landfill mining: A review on material recovery and its utilization challenges. Process Safety and Environmental Protection, 169, 948–958. https://doi.org/10.1016/j.psep.2022.11.049
33. Jayawati, D., Taufik, A. 2021. Supply and demand analysis of refuse derived fuel (RDF) for the cement industry in Indonesia. In: 2nd National Seminar on Industrial and Supply Chain Management, 196–202.
34. Jones, P.T., Geysen, D., Tielemans, Y., Passel, S.V., Pontikes, Y., Blanpain, B., Quaghebeur, M., Hoekstra, N. 2013. Enhanced Landfill Mining in view of multiple resource recovery: a critical review. Journal of Cleaner Production, 55, 45–55. https://doi.org/10.1016/j.jclepro.2012.05.021
35. Kaniowski, W., Taler, J., Wang, X., Kalemba-Rec, I., Gajek, M., Mlonka-Mędrala, A., Nowak-Woźny, D., Magdziarz, A. 2022. Investigation of biomass, RDF and coal ash-related problems: Impact on metallic heat exchanger surfaces of boilers. Fuel, 326, 125122. https://doi.org/10.1016/j.fuel.2022.125122
36. Kara, M., Günay, E., Tabak, Y., Durgut, U., Yıldız, Ş., Enç, V. 2010. Development of refuse derived fuel for cement factories in Turkey. Combustion Science

and Technology, 183(3), 203–219. https://doi.org/10.1080/00102202.2010.512580

37. Kara, M., Günay, E., Tabak, Y., Yıldız, Ş. 2009. Perspectives for pilot scale study of RDF in Istanbul, Turkey. Waste Management, 29(12), 2976–2982. https://doi.org/10.1016/j.wasman.2009.07.014
38. Ko, J.H., Xu, Q., Jang, Y.C. 2015. Emissions and control of hydrogen sulfide at landfills: A Review. Critical Reviews in Environmental Science and Technology, 45(19), 2043–2083. https://doi.org/10.1080/10643389.2015.1010427
39. Krook, J., Svensson, N., Eklund, M. 2012. Landfill mining: A critical review of two decades of research. Waste Management, 32(3), 513–520. https://doi.org/10.1016/j.wasman.2011.10.015
40. Krook, J., Svensson, N., Passel, S.V., Acker, K.V. 2018. How to evaluate (enhanced) landfill mining: A critical review of recent environmental and economic assessments. In: Proceedings of the 4th International Symposium on Enhanced Landfill Mining, 317–332.
41. Kurian, J., Esakku, S., Palanivelu, K., Selvam, A. 2003. Studies on landfill mining at solid waste dumpsites in India.
42. Laner, D., Esguerra, J.L., Krook, J., Horttanainen, M., Kriipsalu, M., Rosendal, R.M., Stanisavljević, N. 2019. Systematic assessment of critical factors for the economic performance of landfill mining in Europe: What drives the economy of landfill mining? Waste Management, 95, 674–686. https://doi.org/10.1016/j.wasman.2019.07.007
43. Larney, F.J., Ellert, B.H., Olson, A.F. 2005. Carbon, ash and organic matter relationships for feedlot manures and composts. Canadian Journal of Soil Science, 85(2), 261–264. https://doi.org/10.4141/S04-060
44. Loganathan, B.G., Masunaga, S. 2009. PCBs, dioxins, and furans: Human exposure and health effects, in: Handbook of Toxicology of Chemical Warfare Agents. Academic Press, pp. 245–253.
45. López, C.G., Küppers, B., Clausen, A., Pretz, T. 2018. Landfill mining: A case study regarding sampling, processing and characterization of excavated waste from an Austrian landfill. Detritus, 2, 29–45. https://doi.org/10.31025/2611-4135/2018.13664
46. Ma, W., Terrence, W., Flemming, J.F., Beibei, Y., Guanyi, C. 2020. The fate of chlorine during MSW incineration: Vaporization, transformation, deposition, corrosion and remedies. Progress in Energy and Combustion Science, 76, 100789. https://doi.org/10.1016/j.pecs.2019.100789
47. Mboowa, D., Quereshi, S., Bhattacharjee, C., Tonny, K., Dutta, S. 2017. Qualitative determination of energy potential and methane generation from municipal solid waste (MSW) in Dhanbad (India). Energy, 123, 386–391. https://doi.org/10.1016/j.energy.2017.02.009
48. Nafi'ah, C.F., Fadilah, K. 2023. Planning for the development of an integrated waste processing site at the Banjarbakula regional final disposal site, South Kalimantan. Jurnal Teknik Sipil dan Lingkungan, 8, 37–46. https://doi.org/10.29244/jsil.8.1.37-46
49. Widyarsana, I.M.W., Tambunan, S.A. 2022. Analysis of potential utilization of landfill materials (case study: Sumur Batu landfill, Bekasi). In: IOP Conference Series – Earth Environmental Science, 999, 012021. https://doi.org/10.1088/1755-1315/999/1/012021
50. Márquez, A.J.C., Filho, P.C.C, Rutkowski, E.W., Isaac, R.D. 2019. Landfill mining as a strategic tool towards global sustainable development. Journal of Cleaner Production, 226, 1102–1115. https://doi.org/10.1016/j.jclepro.2019.04.057
51. Nasiri, S., Hajinezhad, A., Kianmehr, M.H., Tajik, S. 2023. Enhancing municipal solid waste efficiency through Refuse Derived Fuel pellets: Additive analysis, die retention time, and temperature impact. Energy Reports, 10, 941–957. https://doi.org/10.1016/j.egyr.2023.07.039
52. Neina, D., Faust, S., Joergensen, R.G. 2020. Characterization of charcoal and firewood ash for use in African peri-urban agriculture. Chemical and Biological Technologies in Agriculture, 7, 2–10. https://doi.org/10.1186/s40538-019-0171-2
53. Novita, D.M., Damanhuri, E. 2010. Heating value based on composition and characteristics of municipal solid waste in indonesia in waste to energy concept. Jurnal Teknik Lingkungan, 16, 103–114.
54. Paramita, W., Hartono, D.M., Soesilo, T.E.B. 2018. Sustainability of refuse derived fuel potential from municipal solid waste for cement's alternative fuel in Indonesia (a case at Jeruklegi landfill, in Cilacap). In: IOP Conference Series – Earth Environmental Science, 159, 012027. https://doi.org/10.1088/1755-1315/159/1/012027
55. Pettersson, J., Folkeson, N., Johansson, L.G., Svensson, J.E. 2011. The effects of KCl, K2SO4 and K2CO3 on the high temperature corrosion of a 304-type austenitic stainless steel. Oxidation of Metals, 76, 93–109. https://doi.org/10.1007/s11085-011-9240-z
56. Picone, M., Delaney, E., Tagliapietra, D., Guarneri, I., Ghirardini, A.V. 2020. Bioaccumulation of polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) in Hediste diversicolor (Polychaeta: Nereididae). Frontiers in Ecology and Evolution, 8, 235. https://doi.org/10.3389/fevo.2020.00235
57. Prechthai, T., Padmasri, M., Visvanathan, C. 2008. Quality assessment of mined MSW from an open dumpsite for recycling potential. Resources, Conservation and Recycling, 53, 70–78. https://doi.org/10.1016/j.resconrec.2008.09.002

58. Prihartanto, P., Trihadiningrum, Y., Kholiq, M.A., Bagastyo, A.Y., Warmadewanthi, I.D.A.A. 2023a. Characterization of landfill-mined materials as a waste-to-energy source at integrated solid waste treatment facilities of Jakarta Province, Indonesia. Journal of Material Cycles Waste Management, 25, 3872–3884. https://doi.org/10.1007/s10163-023-01810-9
59. Prihartanto, Putri, V.M., Trihadiningrum, Y., Kholiq, M.A., Bagastyo, A.Y., Warmadewanthi, I.D.A.A. 2023b. Characteristics of humate soil from landfill mining in Bantargebang integrated solid waste treatment facility, Indonesia. In: IOP Conference Series – Earth Environmental Science, 1201, 012002. https://doi.org/10.1088/1755-1315/1201/1/012002
60. Quaghebeur, M., Laenen, B., Nielsen, P., Geysen, D. 2018. Valorisation of materials within enhanced landfill mining: What is feasible?
61. Quaghebeur, M., Laenen, L., Geysen, D., Nielsen, P., Pontikes, Y., Gerven, T.V., Spooren, J. 2013. Characterization of landfilled materials: Screening of the enhanced landfill mining potential. Journal of Cleaner Production, 55, 72–83. https://doi.org/10.1016/j.jclepro.2012.06.012
62. Rattanaoudom, R., Juanga, J.P., Visvanathan, C. 2008. Dumpsite toxicty assessment and potential for rehabilitation: A case study at Maung Pathum dumpsite, Thailand.
63. Rotheut, M., Quicker, P. 2017. Energetic utilisation of refuse derived fuels from landfill mining. Waste Management, 62, 101–117. https://doi.org/10.1016/j.wasman.2017.02.002
64. Safavi, S.M., Richter, C., Unnthorsson, R. 2021. Dioxin and Furan Emissions from Gasification. In: V. Silva, C.E. Tuna (Eds.), Gasification. IntechOpen. https://doi.org/10.5772/intechopen.95475
65. Sarc, R., Lorber, K.E. 2013. Production, quality and quality assurance of refuse derived fuels (RDFs). Waste Management, 33(9), 1825–1834. https://doi.org/10.1016/j.wasman.2013.05.004
66. Sathyanarayanan, S.S., Karthikeyan, O.P., Joseph, K. 2010. Biological stability of municipal solid waste from simulated landfills under tropical environment. Bioresource Technology, 101, 845–852. https://doi.org/10.1016/j.biortech.2009.08.104
67. Sepehri, A., Sarrafzadeh, M.H. 2019. Activity enhancement of ammonia-oxidizing bacteria and nitrite-oxidizing bacteria in activated sludge process: metabolite reduction and CO_2 mitigation intensification process. Applied Water Science, 9(131). https://doi.org/10.1007/s13201-019-1017-6
68. Sepehri, A., Sarrafzadeh, M.H. 2018. Effect of nitrifiers community on fouling mitigation and nitrification efficiency in a membrane bioreactor. Chemical Engineering and Processing - Process Intensification, 128, 10–18. https://doi.org/10.1016/j.cep.2018.04.006
69. Sharma, P., Sheth, P.N., Mohapatra, B.N. 2022. Recent progress in refuse derived fuel (RDF) co-processing in cement production: Direct firing in kiln/calciner vs process integration of RDF gasification. Waste Biomass Valorization, 13, 4347–4374. https://doi.org/10.1007/s12649-022-01840-8
70. Shin, J.S., Shun, D., Cho, C.H., Bae, D.H. 2023. A study on the co-combustion characteristics of coal and bio-SRF in CFBC. Energies, 16, 1981. https://doi.org/10.3390/en16041981
71. Smołka-Danielowska, D., Jabłońska, M. 2022. Chemical and mineral composition of ashes from wood biomass combustion in domestic wood-fired furnaces. International Journal of Environmental Science and Technology, 19, 5359–5372. https://doi.org/10.1007/s13762-021-03506-9
72. Solusi Bangun Indonesia. 2019. Production of Refuse-Derived Fuel (RDF) as Alternative Fuel in Cement Kiln.
73. Suknark, P., Buddhawong, S., Towprayoon, S., Vinitnantharat, S., Phongphiphat, A., Jirajariyavech, I., Wangyao, K. 2022. Assessment of refuse-derived fuel production from a thin-layer landfill.
74. Sun, R., Ismail, T.M., Ren, X., El-Salam, M.A. 2016. Effect of ash content on the combustion process of simulated MSW in the fixed bed. Waste Management, 48, 236–249. https://doi.org/10.1016/j.wasman.2015.10.007
75. Tchobanoglous, G., Theisen, H., Vigil, S. 2000. Integrated Solid Waste Management Engineering Principles and Management Issues, first. ed. McGraw-Hill, New York.
76. Tomsej, T., Horak, J., Tomsejova, S., Krpec, K., Klanova, J., Dej, M., Hopan, F. 2018. The impact of co-combustion of polyethylene plastics and wood in a small residential boiler on emissions of gaseous pollutants, particulate matter, PAHs and 1,3,5-triphenylbenzene. Chemosphere, 196, 18–24. https://doi.org/10.1016/j.chemosphere.2017.12.127
77. Tun, M.M., Juchelková, D., 2018. Drying methods for municipal solid waste quality improvement in the developed and developing countries: A review. Environmental Engineering Research, 24(4), 529–542. https://doi.org/10.4491/eer.2018.327
78. US EPA. 2023. Health and Environmental Effects of Particulate Matter (PM). United State Environmental Protection Agency. Available from: https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm#:~:text=Health%20Effects&text=Exposure%20to%20such%20particles%20can,nonfatal%20heart%20attacks
79. Wang, Y., Lu, X., Fei, X. 2021. Property changes of conventional plastic waste mixed with municipal solid waste after 10-year degradation experiments simulating landfill conditions. Journal of Hazardous

Materials Letters, 2, 1–7. https://doi.org/10.1016/j.hazl.2021.100047

80. Wang, Y., Zhu, H., Jiang, X., Lv, G., Yan, J. 2019. Study on the evolution and transformation of Cl during co-incineration of a mixture of rectification residue and raw meal of a cement kiln. Waste Management, 84, 112–118. https://doi.org/10.1016/j.wasman.2018.11.036
81. Zaenudin, A. 2023. Towards the Red and White RDF Plant.
82. Zhang, M., Buekens, A., Jiang, X., Li, X. 2015. Dioxins and polyvinylchloride in combustion and fires. Waste Management Research., 33(7), 630–643. https://doi.org/10.1177/0734242X15590651
83. Zhao, L., Giannis, A., Lam, W.Y., Lin, S.X., Yin, K. Yuan, G.A., Wang, J.Y. 2016. Characterization of Singapore RDF resources and analysis of their heating value. Sustainable Environment Research, 26(1), 51–54. https://doi.org/10.1016/j.serj.2015.09.003
84. Zhou, C., Fang, W., Xu, W., Cao, A., Wang, R. 2014. Characteristics and the recovery potential of plastic wastes obtained from landfill mining. Journal of Cleaner Production, 80, 80–86. https://doi.org/10.1016/j.jclepro.2014.05.083