Contents list available at IJRED website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.undip.ac.id

Research Article

Solid waste management by RDF production from landfilled waste to renewable fuel of Nonthaburi

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Abstract. A worldwide increase in waste production and energy demand as the world's population grows and consumes more resources: therefore, sustainable waste management strategies are important. The goal of this work is to research the guidelines for the appropriate RDF production and landfill waste management of the Nonthaburi province, Thailand. Refuse Derived Fuel (RDF) produced from landfilled Waste (LW) in Nonthaburi was investigated the physicochemical. The following procedure has implemented for the production of LW to RDF of 25 tons/hr of LW; (i) the LW was placed in a pre-shredder, which was followed by a primary crusher; (ii) metals were removed from the waste stream using a magnetic separator; (iii) the LW was transferred using a conveyor belt to a dynamic disc screen, where recyclable waste was separated into smaller sizes less than 80 mm.; (iv) the waste passed through an air separator to reject high-density materials (soil and glass); (v) the undesired material were separated manually, and (vi) the desired material were baled. RDF composition consisted of 78.16-67.93% plastics, 2.29 -4.34% rubber, 1.27% wood, 1.53-2.19 % textile, and other (soil-like material) 12.19-26.72%. The proximate and elemental analysis of RDF was determined according to the ASTM method. The moisture content was reduced, and the heating value increased to 18.08-29.41 MJ/kg. The results suggested high carbon and low nitrogen content suitable for energy conversion. The separation can effectively convert LW to RDF, which can be applied as an alternative fuel. Therefore, RDF can contribute to a more sustainable and circular economy.

.**Keywords:** RDF, Landfill waste, landfill mining, Renewable energy, Waste management, Sustainable energy, Waste to energy

Received: 10th March 2023; Revised: 27th July 2023; Accepted: 18th August 2023; Available online: 31th August 2023

1. Introduction

Municipal solid waste (MSW) management is a significant environmental problem arising from economic development, rapid industrialization, and a growing population (Fayad *et al.,* 2022; Pizarro-Alonso *et al.,* 2018; Thanh *et al.,* 2015; Thanopoulos et al., 2020; Zhou *et al.,* 2022). The total volume more than 22% of collected wastes are improperly disposed by open dumping and open burning (Nittaya *et al.,* 2019). The waste-to-Energy (WTE) of 600 plants worldwide converted the amount of 130 Mt MSW each year (Zhao *et al*., 2016). The WTE plants offer an excellent substitute to release the environmental burdens from landfilling (Payomthip *et al.,* 2022; Zhao *et al.*, 2016). Incineration effectively extends the service life duration of the only landfill to reduce land scarcity (Kosajan *et al.*, 2021). The thermochemical recycling process of waste plastics to generate valuable liquid fuel is a favorable alternative for plastic waste management (Homdoung *et al.*, 2019; Rahma *et al.*, 2021; Wiyono *et al.,* 2021). This method can be used as an energy-efficient procedure to decrease the volume of solid waste in landfill and energy recovery (Kaewpengkrow *et al.,* 2012). Thailand Ministry of Energy has aimed to increase WTE output to 100 ktoe of thermal energy and 160 MW of power by 2021 (Srisaeng *et al.*, 2017). Energy recovery through WTE technology is one of the most important options and beneficial solutions for obtaining energy recovery from industrial waste and municipal solid waste in the face of rising energy prices (Duangjaiboon *et al.*, 2021; Homdoung *et al.,* 2019).

The production of RDF is most closely related to the treatment of solid waste (Ribeiro *et al.,* 2019), Therefore, RDF is an internal resource that can efficiently respond to problems related to waste management; it can reduce the accumulation of MSW in landfill. The industrialized cement industry is one of the biggest energy consumers in the world and is currently dealing several environmental and economic challenges. In addition, the industry faces challenges related to the availability and cost of raw materials, as well as increased competition and regulations (Hemidat *et al.*, 2019; Kosajan *et al.*, 2021). According to the studies of Kosajan et al., (2021), the results indicated that cement kiln co-processing (CKC) is an effective method for reducing municipal solid waste (MSW) and minimizing emissions compared to other solid waste treatment technologies such as mechanical biological treatment, incineration, and landfill. Consequently, there is great potential to use MSW as a renewable fuel in this sector (Kosajan *et al.*, 2021; Sharma *et al.*, 2022). The use of solid waste to produce RDF in cement manufacturing has been demonstrated in data from European nations with well-established waste collection

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systems and high disposal costs Moreover, it is an alternative to regulated waste disposal. Therefore, using RDF as a renewable fuel in the cement industry or power plants will decrease the waste required to landfill, energy consumption, high usage of raw materials, and greenhouse gas emissions (GHG) (Hemidat *et al.*, 2019; Martins *et al.*, 2022; Zhao *et al.,* 2016). Moreover, solid waste can be used as a source of energy as well as the electricity to achieve carbon neutrality. Electricity generated from waste helps reduce greenhouse gas emissions from a climatic perspective. The biggest reduce is up to 18.4 million tonnes in 2030, and it rises to 45.5 million tonnes in 2060. (Zhou *et al.*, 2022).

Normally, RDF is produced after removing non-combustible materials such as glass, ferrous materials, grit, soil, etc., which are high calorific value fuels. In RDF production, the RDF contains plastic, paper, textiles, and other burnable resources (Infiesta *et al.*, 2019; Srisaeng *et al.,* 2017; Tejaswini *et al.*, 2022). RDF produced from municipal solid waste (MSW) treatment has a high heating value of nearly 3,500 kcal/kg (Białowiec et al., 2017; Rotheut *et al.,* 2017; Triyono et al., 2019; Ummatin et al., 2019). However, producing high-grade RDF requires a multi-stage solid waste process and separation procedure to ensure consistency and high calorific value. Proper drying of the waste is also crucial to ensure the quality of the RDF. (Białowiec et al., 2017; Infiesta *et al.*, 2019; Recari *et al.*, 2017). Consequently, it leads to a suitable property, increasing the product's market prospect. There are studies that determined effective methods to reprocess waste as energy in RDF manufacture (Infiesta *et al.*, 2019; Recari *et al.*, 2017; Thanopoulos *et al.*, 2020; Zhao *et al.,* 2016). A solid waste processing line (SWPL) plant's conversion of MSW to RDF was studied by Infiesta *et al.* (2019). They discovered that an industrial SWPL and gasification power plant in Boa Esperança, Brazil, with a processing capacity of up to 55 tons/day of MSW, can produce about 30 tons/day of RDF. The average moisture content of RDF was 17 ± 8 wt%, and LHV of 14.6 ± 1.3 MJ/kg, respectively(Infiesta et al., 2019). Akdag et al. (2016) studied the RDF combustion only and co-combustion in mixtures with petroleum coke and coal in a small system at specific percentages of energy sources as 3%, 5%, 10%, 20%, and 30% (Sever Akdağ *et al.*, 2016). The outcome showed that adding RDF to the fuel mixtures decreased SO_2 emissions but had no effect on NOx emissions. However, only RDF has been burned, and the ash's slagging and fouling indicators were higher than that of the allowable standards. Rotheut *et al.* (2017) conducted a study on the energetic RDF utilization produced from landfill waste treated through automated waste separation treatment, and its impact on the incineration plant's procedure. (Rotheut *et al.*, 2017).

For the RDF standards, the ASTM D6866 standard is used for the US and other regions, whereas EN ISO 21644 is used for Europe. In Thailand, the RDF standard is usually based on ASTM standards that are classified into seven groups, but only the RDF-1 to RDF-5 are used. According to the ASTM classification of RDFs, RDF-1 (MSW) refers to raw MSW that was removed from oversized bulky waste. RDF-2 (Coarse-RDF) refers to coarse particle size with 95% by weight passing through a 6-in mesh. RDF-3 (Fluff-RDF) refers to MSW that was shredded and 95% by weight passed through a 2-inch mesh. RDF-4 (Powder-RDF) refers to a combustible waste fraction with 95% by weight passing through a 10-mesh that was processed into powder form. RDF-5 (Densified-RDF) refers combustible waste fraction compressed into pellets, slugs, cuvettes, and briquettes (ASTM D6866).

It was discovered that a 1:1 mixing ratio of co-incineration seemed adequate for co-incinerating fresh RDF or MSW with landfilled RDF. The combustion of untreated material, however, was troublesome and left a significant level of fine particulate residue behind. A few technical, economic, and safety barriers were also identified with the RDF end users and potential suggestions were discussed for the thriving RDF market in Thailand. Therefore, the multi-separation process is necessary to improve the landfill waste before utilization as fuel. However, few studies applying of these technologies to pre-treat landfilled waste on a pilot scale.

There is a lack of waste composition related to physicochemical properties for the current study area. This research aimed to generate a high-grade RDF by recovering resources from landfill waste in Nonthaburi province, Thailand. The energy content and physicochemical properties of LW components were investigated to conclude their proper for producing RDF. The classification of compositions and elimination of non-combustible materials from the landfill waste stream is an essential step in RDF production. RDF produced from properly processed waste has been shown to have a high calorific value and low environmental impact compared to traditional fuels.

2. Materials and method

2.1 Materials

In this work, Refused Derived Fuel (RDF) was obtained from a local company in the Nonthaburi region of the province. The geography of Nonthaburi Province Landfill is shown in Fig.1. The Landfilled waste from MSW of Nonthaburi aged 10 years and 15 years are shown in Fig.2 The opportunity to recover recyclable materials and create RDF, which is usable for producing electricity in WTE power plants, is presented by the opening up of landfills. The possibility of using landfill-excavated materials for producing RDF was evaluated in this study. This procedure can lengthen the useful life of an existing landfill site and decrease the volume of waste that must be landfilled.

The composition of landfill waste was highly contaminated with fine material (soil-like material), as shown in Fig. 2. The physical composition analysis of landfill waste was performed by the quartering method. The performance of the quartering sampling operation was determined by collecting the amount of waste in 1 m^3 using a backhoe to randomly sample from the landfill. Then, the workers divided the landfill waste into 4 parts; the samples were taken on the opposite side and left with 0.5 m^3 of solid waste. Then the workers divided the 0.5 m^3 of solid waste into 4 parts, the samples were taken on the opposite side, leaving 0.25 m^3 of sample waste. Then, the

Fig. 1 Study area and sampling locations in the Nonthaburi Province landfill

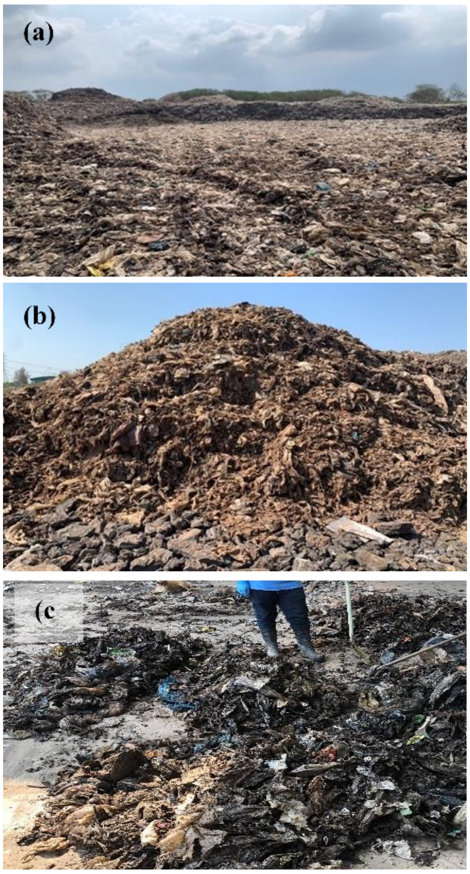

Fig. 2 (a) Landfill waste pit A;15 years (b) Landfill waste pit B; 10 years (c) Landfill waste sampling

samples are taken on the opposite side, divided into 4 parts, and removed from the waste on the opposite side, leaving 0.125 m^3. Remove the waste on the opposite side and divide the waste into 4 parts, leaving a waste pile of 0.0625 m^3. Finally, a sample of 0.0625 m^3 (62.5 L) of waste was taken for further analysis of density, moisture content, and physical and chemical composition. The analysis of the physical composition of waste after the sorting process does the same.

2.2 RDF production line

RDF production from landfill was recognized as an appropriate method for MSW treatment in Thailand. RDF technology, which has a high capacity for co-combustion with other petroleum fuels and is used in other WTE technologies such as gasification and combustion, recovers resources from landfill waste by recycling combustible elements and recovering energy. (Intharathirat *et al.*, 2016).

The multi-stage separation for the RDF production line is shown in Fig. 3. The RDF trials were performed in one line of the multi-separation plant, a state-of-the-art WtE facility of Nonthaburi. The plant's layout processes called for a waste stream input of 25 tons per hour for separation. First, the pre-shredder was carried out to receive any kind of landfilled solid waste (LW). The power rating of the waste shredding system in this work is 264 kW. Technically, the conveyor belt solid waste is 1.4 m wide and 1.2 m wide, using a power motor of 7.5 kW. The system is capable of shredding the incoming waste to a size smaller than 80 mm. The second step in the waste treatment process in this work involved magnetic material separation, the power consumption of a of 4 kW, and the round speed of the conveyer magnetic belt is 194 r/min. This procedure, which was at the end of the rubber conveyor belt, was used to screen the waste materials containing ferrous metals. The disc screen is a mechanical screening device used in the solid waste management industry to separate and sort different components of solid waste materials based on their size and shape. The disc screen in this process is 2 m. wide, 6 m in length and motor power is 15 kW. The air classify uses 90 kW of electricity and a wind force of 175 m^3/hr. The ferrous metals were not eliminated by selective crew workers and needed to be removed to produce RDF with consistent quality and high calorific value. It was placed to operate in the next position to the conveyor belt. The solid waste takes about 1 hour to transport the 100 m length of the RDF processing line. RDF input to the process with an estimated production of 25 tons /hour of Landfill waste. The RDF output averaged 12 tons/ hour at the end of the separation process.

Firstly, (i) the LW was placed in a pre-shredder to an initial crusher to reduce the LW size; (ii) the magnetic separator removed the residue metals (ferrous); (iii) the LW was conveyed while a dynamic disc screen separated the recyclable waste, glass, metals, and soil to select the size less than 80 mm; Then, (iv) the waste materials were passed through an air separator as

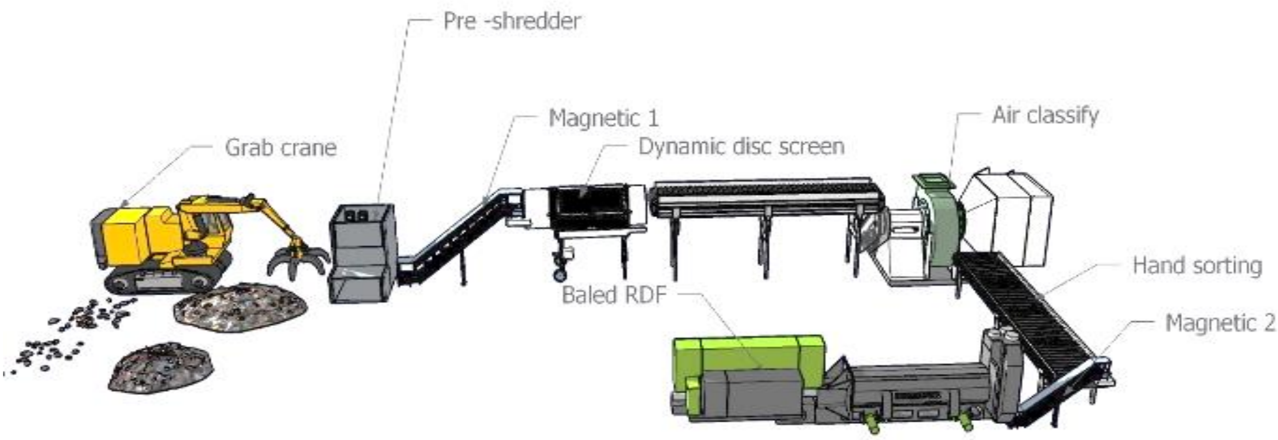

Fig. 3 RDF production line

Fig. 4 a) RDF landfill baled b) Rejected landfill waste.

the fourth step in the RDF production process. The air separator was used to reject the materials with high density, such as soil, stones, and glass. At the same time, the light material such as plastic bags and plastic waste were transferred to the next step; (v) the undesired material was separated manually by four workers to remove the undesired material, especially, the PVC and (vi) the desired material was baled. The RDF from landfill waste was baled to increase densification (700 m^3/ton) for convenient transportation to the power plant, as shown in Fig. 4 (a). The pre-treated waste fuels are transported to the power plant (fluidized bed system) by the trucks.

2.3 Material analysis

2.3.1 Sample analysis on-site work

The amount of waste is increasing every year from the consumption of people in Nonthaburi province, especially in 2020, as a result of the COVID-19 situation, as shown in Fig 5. As a result, the landfill space is reduced. Therefore, using waste and RDF from landfill to produce energy is an appropriate waste management alternative. Generally, solid waste is sampled by the quartering method. The approximately 200 kg of unloaded waste undergoes quartering twice to reduce the sample size to roughly 50 kg. In the quartering work, waste in bags is removed and thoroughly mixed, while bulky and long-size wastes are quartered and separated. The total sample weight (WT) of roughly 50 kg following quartering is weighed as a sample for bulk density measurement. The remaining samples are also similarly weighed using a container with known cubic capacity. Then, the total sample weight sent to the lab is 10 kg to waste characteristics analysis further.

2.3.2 Proximate analysis

This study used material analysis to determine the characteristics of the RDF made from municipal solid waste. For the proximate analysis, the RDF's volatile matter, moisture, ash, and fixed carbon contents were measured. Volatile matter (VM) refers to the combustible components of the RDF, such as organic compounds, that are released as gas during the combustion process. Moisture content refers to the amount of water present in the RDF, which can affect the fuel's calorific value. Ash content (AC) refers to the non-combustible minerals and inorganic compounds that remain after (MC) the RDF is burned, and fixed carbon (FC) refers to the non-volatile, carbonaceous component of the RDF. Firstly, the MC of RDF samples was determined following the ASTM standard. Then, the AC and VM analyses followed the ASTM D7582-15 method. Finally, the FC was determined by subtracting the percentages of the moisture, volatile matter, and ash contents. The FC was conducted and calculated by difference using Equation 1 (Ibitoye et al., 2022)

$$FC = 100 - (MC+VM+AC)\ \% \qquad (1)$$

2.3.3 Ultimate analysis

The chemical compositions were the hydrogen (H), carbon (C), sulfur (S), nitrogen (N), and oxygen (O), which are all naturally occurring elements commonly found in organic matter, and make up a significant portion of solid waste. The chemical analysis is very significant in estimating the accuracy of material balance. Therefore, the C, H, O, N and S of the samples were examined by the Truspec Leco CHNS-932 analyzer, and the outcomes were presented on a dry basis. Calculating the amount of oxygen in a sample involves subtracting the total percentage of all the elements present in the sample from the sum of the percentages of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S). Moreover, the solid fuel samples were also determined the calorific values (HHV) by the bomb calorimeter (ASTM: D5865).

3. Results and discussion

3.1 RDF production

The Ministry of Natural Resources and Environment of Thailand's Pollution Control Department (PCD) reported the generation of MSW from 2008 to 2019 raised from 23.9 million tonnes (Mt) to 26.8 Mt. Solid waste production increased fromone kg/person/day in 2008 to 1.15 kg/person/day. (Intharathirat et al., 2016; Nittaya et al., 2019). Fig. 5 showed the amount of MSW disposed in Nonthaburi province between 2014 and 2021. The MSW raised from 409,507 tonnes in 2014 to 571,993 tonnes in 2021. These wastes were transferred to disposal at the landfill. The best approach for municipal solid waste m anagement (MSW) depends on a variety of factors, including local conditions and the characteristics of the municipality. (Cifrian et al., 2012). Four classes were identified

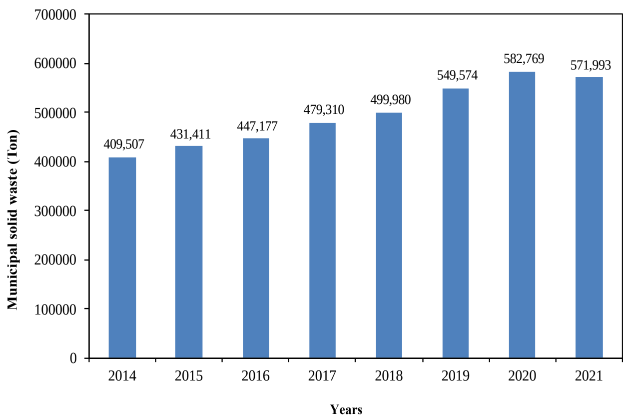

Fig. 5 The amount of Nonthaburi MSW

the physical composition examination of the landfilled waste samples: organic waste, general garbage, recycled waste, and home hazardous waste (Nittaya et al., 2019). According to Safo-Adu et al. (2022), the characterisation of MSW was required for creating a sustainable and practical process of MSW management systems across the area because it provides appropriate and dependable information on the MSW generation (Safo-Adu et al., 2023).

The MSW from landfill contains residues from the consumer, including kitchen waste, yard waste (wood, bamboo, straws), combustible waste (plastic, rubbers, leathers, paper, and textiles), and incombustible waste (glass and metals), among others, as shown in Fig. 5. About 65 % of the MSW consisted of combustible waste; plastic, rubbers, and leathers were widely present, including the general waste group, more than 30 %. Organic waste (kitchen waste) represented 26 % of the total weight, while the other types of waste (Incombustibles and others) accounted for 8 % and 1 %, respectively. The result indicated that a high fraction of combustible waste could be utilized as fuel and caused higher heat generation for power plants (Tejaswini *et al.,* 2022). The result corresponded to Dastjerdi *et al.* (2019) conducted a study on waste management that evaluated the electricity generation and greenhouse gas (GHG) emission abilities of different waste-to-energy (WtE) technologies. The study considered four different scenarios of waste management that involved different integrations of WtE technologies. These technologies included anaerobic digestion (AD), incineration, and landfilling with energy recovery. The result suggested that WtE technology can apply the MSW as a raw material and convert the chemical composition to power (Dastjerdi *et al.,* 2019; Sapuay, 2016; Tejaswini *et al.,* 2022). The solid waste stream can be classified into different categories based on its composition and characteristics. One common classification system divides the waste stream into three categories: food waste, non-combustible waste, and combustible waste.

In general, the composition of waste is considered (Fig. 6); organic waste includes kitchen waste and garden waste (wood, bamboo, straws); however, it was challenging to measure the exact amount of organic waste because of commingled and waste decomposition. For recyclable materials, the highest percentage of recyclable waste generated (by weight) were plastic (beverage containers), rubber, and leathers, followed by paper, and incombustible waste (metal) according to the weight percentage of 33 %, 25 %, and 8 %, respectively. This result similar to Nittaya *et al.* (2019) who reported the MSW from Chiang Rai Province (a highland rural tourist region in Thailand) was composed primarily of plastic bags and organic waste, accounting for more than 60% weight of the general waste.

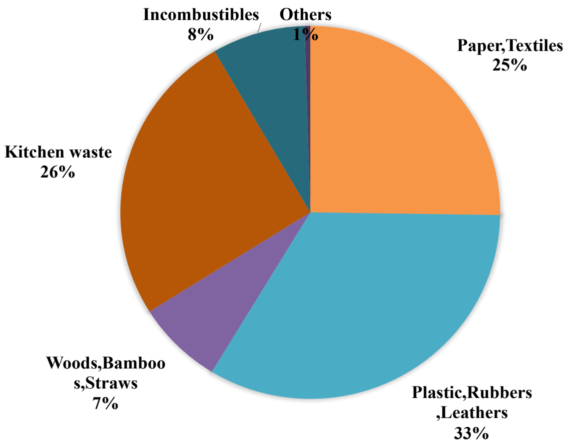

Fig. 6 Waste composition of Nonthaburi (2020)

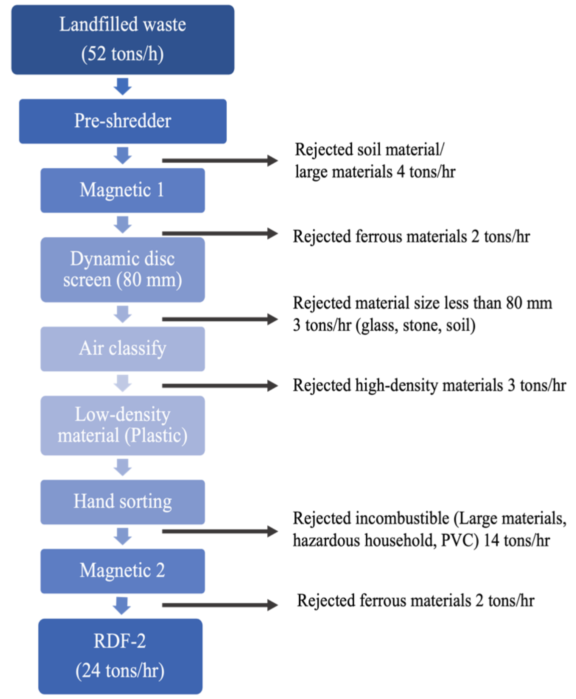

Fig. 7. Material flow diagram of RDF production

(Nittaya et al., 2019). Therefore, the results of MSW compositions in Nonthaburi province would be related to the landfill waste composition.

On the RDF production line, the RDF obtained from a pre-shredder was sized less than 80 mm, and the rejected soil material and large materials are 4 tons/hr, while the residual metals (ferrous) were removed by magnetic separator by magnetic belt step 1 that can reject the ferrous material to 2 tons/hr. The recyclable waste, glass, and ferrous (remaining) were then separated from the LW stream using a dynamic disc screen after being transferred by a conveyor belt from the LW. At this step, the undesired waste (including soil, stone, glass, and non-ferrous) was rejected 3 tons/hr. The remaining waste stream is then sent through an air separator, where materials with a high density are removed (3 tons/hr), resulting in a waste stream that has been separated into different fractions. This step obtained the main composition of plastic waste.

Four workers separated the undesired material manually to remove the incombustible material, especially the PVC pipe, large metal, and household hazardous waste (rejected 14 tons/hr) because they can generate toxic air pollution like dioxin. Finally, the remained ferrous material passes through the magnetic belt in step 2 to the last particular screening (ferrous materials rejected as 2 tons/hr), and the screened material was baled in size of 1m x 1.2 m. According to RDF production, recyclable and general wastes can convert to energy as a solid fuel (RDF 2) following the ASTM standard. The material flow diagram of RDF production is shown in Fig. 7. The valuable waste components, including paper, recyclability plastic, rubber, glass, and metal, are screened and selected by multi-separation step mechanical. The RDF composition was classified into eleven categories (Fig. 8).

RDF components were mainly combustible, including plastic rubbers, textiles (rag and fabric), and wood, while the incombustible included glass and other (soil-like material). RDF composition consisted of 67.93% plastics, 2.29% rubber, 1.27% wood, 1.53% textile waste, and 26.72% other. The landfill waste passed through the multi-stage separation displayed a higher plastic waste composition from 47.32 to 67.93 %wt. On the other hand, the soil-like material considered incombustible was

Table 1
Characterization of chemical-physical of MSW and RDF

Physicochemical	MSW*	Landfill waste pit A (15Y)	Landfill RDF-A (screened)	Landfill waste pit B (10 Y)	Landfill RDF-B (screened)	RDF (Infiesta *et al.*, 2019)	RDF (André *et al.*, 2018)
Elemental (% as dry basis)							
Carbon	48.38	40.70	67.06	58.89	66.24	47.00	56.2
Hydrogen	5.45	8.24	6.86	9.97	7.22	7.00	0.91
Nitrogen	2.45	5.73	0.44	0.75	0.47	0.81	7.14
Oxygen	30.74	14.91	17.07	22.15	18.37	45.00	37.57
Sulfur	0.01	0.31	0.42	0.24	0.30	0.11	-
Chlorine	0.02	0.33	0.37	0.29	0.41	1.50	-
Proximate analysis (% as dry basis)							
Moisture (% as received)	52.26	41.30	39.20	42.20	37.90	9.90	5.70
Ash (% as dry basis)	6.26	29.78	7.76	7.71	6.99	27.00	15.00
Volatile (% as dry basis)	41.48	62.39	57.79	83.35	74.60	-	77.20
Fixed carbon (% as dry basis)	-	7.78	34.45	8.94	18.41	-	2.10
Calorific value; HHV (MJ/Kg as received)	9.11	12.75	18.08	23.03	29.41	16.30	24.33

reduced from 37.7 to 26.72 %wt. The findings suggested that paper, plastics, textiles, and leather were responsible for the higher heat generation from combustible waste. In addition, it found that garden yard waste (wood) demonstrated a higher LHV than organic waste or non-combustible waste (Dastjerdi *et al.,* 2019). The composition of LW varies depending on socio-economic conditions, dietary habits, seasonal variations, recycling rates, geographic location, and informal sector activity (Cheela *et al*., 2021).

3.2 Effect of landfill waste age

The data collection was collected from multiple mining locations with age and spatial differences. The effect of landfilled waste age was divided into two periods, namely 10 years and 15 years old waste that went through a multi-step separation process. The composition of RDF from the landfill was studied with the same machine and process from the LW pits A (15 years) and B (10 years), as shown in Fig. 6.

The physical composition was sampled by the quartering method; it was found that older wastes had soil accumulation higher than 30%. Similarly, Cheela *et al.* (2021) observed that the trend of soil-like material increases with the age of waste landfilling. In addition, the soil volume of LW from pits A and B decreased after screening by multi-stages sorting were 26.72% and 12.19%, respectively. The results of the comparative analysis of the age of screened wastes suggested that the plastic waste from newer LW (pit A) is higher than pit B. The result indicated that the waste from the newer landfill had high-quality material that resulted in high calorific value and chemical properties, which will be investigated in the next section.

3.3 RDF characterization

The RDF was characterized to verify the properties of the alternative fuel. The results show that plastic waste separated includes polypropylene (PP), polyethylene (PE), polystyrene (PS), and the main plastic inform plastic bags. The results of the proximate analysis for the MSW and RDF waste components are displayed in Table 1. The moisture content is an important parameter that affects the gas product composition in the gasification power plant (Intharathirat *et al*., 2016). Therefore, the wetness content, volatile matter, and ash content (wt.%) could afford a good suggestion for RDF combustibility (André *et al*., 2018). The fuel properties like heating value strongly influence the application for industrial waste utilization, and the HHV values in this work were calculated on a wet basis. These plastic wastes contained a higher percentage of volatile matter and higher calorific value.

The result corresponded with Sarc *et al.* (2013), who studied the characterization, classification, production, and application of RDF and the resulting RDF (or SRF) final quality. It depends on the source of raw materials input, the volume, and the separation method intensity in fuel production (Liu *et al.,* 2020; Sarc *et al.,* 2013). Regarding the proximate analysis, the high ash content displayed in the Table 1 was attributed to the residence of fine material (soil or sand). These are the main component in both pits of landfill waste. The plastic and fabric (textile) component in the RDF landfill appear to be attached to these small materials that make up the ash contents.

This result could be proved by a separate process of landfill waste compared in Table 1. Carbon contents of LW were in the range of 40.70 – 67.06 wt%. According to Cheela *et al.* (2021), a range of 42.9–71.6% of carbon was detected from waste recovered from landfills between the ages of 5 and 15 years. A high percentage of carbon is due to the amount of plastic content. The result indicated that carbon was the main element of the landfilled RDF A and B, which were higher than 60 % and caused a high calorific value of RDF. In addition, the nitrogen contents of LW were in the range of 0.44 – 5.73 wt%, the highest nitrogen content obtained from landfilled RDF-A. The nitrogen content analysis is necessary to carry out because it causes the formation of NOx emissions. In the landfill-recovered waste process, an appropriate pre-cleaning technique may be used to

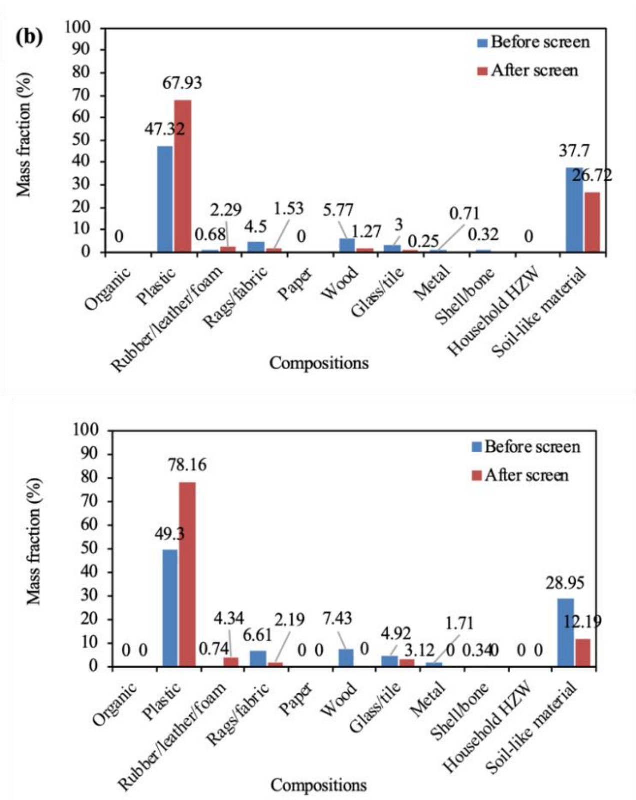

Fig. 8 Composition of generated RDF (a) landfilled waste 15 years; pit A (b) landfilled waste 10 years; pit B

remove the inert material and contaminants from the landfill-recovered waste components. As a result, they increase RDF's volatile solids content and heating value and reduce the ash content.

Moreover, the low percentage of sulphur (0.24-0.42%) was comparable with the study of Rotheut and Quicker (2017), which had a range of 0.1-0.5%. In contrast with Cheela *et al.* (2021), the percentage of sulfur was 1.4–32.9%. Sulfur content is another significant element because sulfur causes the acid gas generation SO_2, which can contribute to air pollution and corrosion of the environment (Sever Akdağ *et al.*, 2016). Interestingly, the high volatile content of landfill waste indicated that landfill waste consists of organic compounds with incomplete degradation. The result showed that the high content of volatile and nitrogen in landfill waste A might be caused by ammonia compounds during the decomposition of solid waste.

To ensure the RDF quality and prevent environmental issues caused on by burning, the heating value and chemical compositions of chloride and heavy metals contents are typically taken into consideration (Hemidat *et al.*, 2019; Zhao *et al.*, 2016). The result demonstrates the multi-step separation with the capacity to perform 250 tons/day of LW pits A and B with a heating value of 12.75 and 23.03 MJ/kg. It was feasible to produce RDF with the moisture content of RDF-A and RDF-B were 39.20 wt% and 37.90 wt%, and the heating value was 18.08 MJ/kg and 29.41 MJ/kg, respectively. However, the waste rejected from the production line was approximately 13.92-21.84%, including soil-like material, PVC pipe, large rubber, metal, and other larger materials. According to these results, solid fuels made from RDF can be used in power plants instead of combining fossil fuels. Moreover, the amount of sulfur is less than 0.5%, as shown in Table 1, in which the S content is lower than the coal standard (0.23–0.93%) (Infiesta *et al.*, 2019), and the N content (0.44%) revealed a similar performance. The Cl content contained in the RDF-A and RDF-B from landfill waste was 0.37 and 0.41%, respectively, a value within the acceptable kind of biomass and coal. One advantage of the RDF landfill is its low content of Cl compared with other sources (0.3-0.6 wt%) (Rotheut et al., 2017; Ummatin et al., 2019). Therefore, it is suggested that this waste is not a source of dioxin emission. Nitrogen and sulfur content is another significant element because sulfur causes the acid gas generation of SO_2 and NO_x, which can contribute to air pollution and corrosion of the environment. Therefore, the appropriate quality of RDF should follow the RDF-2 standards, and also low moisture content, high heating value (more than 13.15- 19.32 MJ/kg), low percentage of nitrogen and sulfur in RDF (TPI Polene Power Company Limited, 2015).

The concentrations of chlorine and sulfur are harmless because the values are below 1.0 and 0.3 %, respectively. As a result, the materials had low sulfur and nitrogen contents, which led to low SOx and NOx emissions, that are anticipated to be used as potential fuels. These related results were achieved through a probability study of the potential energy recovery to generate electricity from MSW (André *et al.*, 2018; De Gisi *et al.,* 2018; Infiesta *et al.,* 2019; Srisaeng *et al.*, 2017). The RDF characteristics demonstrate the RDF production line feasibility, which is proposed in this research. Conclusively, the RDF production line can upgrade the fuel properties suitable for gasification power plants (André *et al.*,2018).

The RDF elements include C, H, O, and N related ratios, which are usually carried out by solid fuel or RDF characteristics. Consequently, the diagram of Van Krevelen was plotted using the relative proportion of H, C and O atoms to understand better solid fuel composition (Fig. 9). In addition, the diagram includes the results from this study compared with other studies (Zhao *et al.*, 2016; Kaewpengkrow *et al.*, 2012; Duangjaiboon *et al.,* 2021; Infiesta *et al.,* 2019; André *et al.,* The ratio of H/C and the O/C of RDF were in the range of 1.16-2.69 and 0.02-0.72, respectively. Moreover, the elemental H/C ratio of the coal was 0.69 and less than 0.03 for O/C. Therefore, the RDF screened by multi-step separation of landfill waste achieved the closest H/C and O/C ratios to solid petroleum fuel. The plot shows that RDF's H/C and O/C ratios are relative to petroleum coal compared to the other landfill wastes. The results suggested that the landfill waste should be screened using multi-step separation to improve the properties before being applied as the RDF alternative fuel.

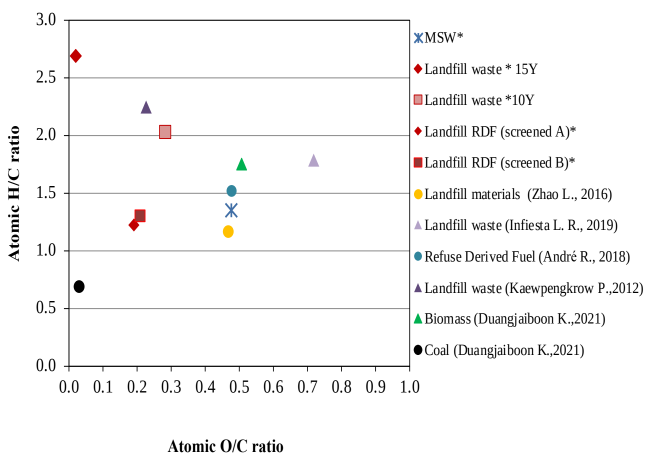

Fig. 9 Van Krevelen diagram of RDF from landfill waste (* this study)

4. Conclusions

This work establishes the industrial multi-step separation of the capability to process 250 tons/day of landfill waste. The waste rejected from the production line was approximately 30-40 %, including soil-like materials, PVC pipe, large rubber, metal, and other larger materials. The landfill waste passed through the multi-separation displayed a higher composition of plastic waste, more than 60% wt., which the higher heat generation caused by combustible waste (plastics, paper, leather, and wood). Therefore, the RDF utilization as an alternative fuel can help to reduce the amount of solid waste that is referred to landfills, which can help to conserve space and reduce the environmental impacts associated with waste disposal. This result led to a suggestion to intensify waste separation at the pilot plant, a multi-stage separation process, implement waste recycling concepts to decrease the quantity of landfill waste, and convert the combustible waste to energy. The common waste and recyclable wastes can also convert to renewable energy in terms of RDF-2 (ASTM standard); the average heating value of this RDF-2 production of RDF-A and RDF-B were 18.08 and 29.41 MJ/kg, respectively. The proximate and elemental analysis of RDF from landfill was investigated according to the ASTM method. Low sulfur and nitrogen concentrations in the elemental analysis led to the low SOx and NOx emissions anticipated when using these wastes as solid fuel. The results suggested high carbon and low nitrogen content suitable for energy conversion. To effective landfill waste management in Thailand, the multi-step separation process is necessary to improve the landfill waste quality by removing the incombustible prior to utilization as a renewable fuel in power plants. The multi-separation can effectively convert LW to RDF, which can apply as a renewable fuel. They are considered good fuels for power plants and could be potential end-users of RDF in Thailand.

Acknowledgments

The Siam Power Company is acknowledged by the authors for providing useful information and providing financial support. The authors also thank the Nonthaburi Provincial Administrative Organization for providing useful data and information. We appreciate the support provided by the King Mongkut's Institute of Technology Ladkrabang's Scientific Instrument Center, School of Science, for the instrument.

Funding: This research was funded by Nonthaburi province in Thailand and no financial support for the research, authorship, and/or publication of this article.

Conflicts of Interest: The authors declare no conflict of interest.

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