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MSW-TO-RDF CONVERSION FOR CEMENT PLANT IN INDONESIA THROUGH PILOT PROJECT AND MODELING

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ABSTRACT

This study investigates MSW management and its application in the cement industry through the conversion of MSW into RDF in four Indonesian regions: Jakarta, Bogor Regency, Depok, and Bekasi. Collectively, these areas produce 14,500 Mg/day of MSW. Samples totaling 1,265 Mg of this MSW were analyzed to determine their physical and chemical properties, particle size distribution, and fraction. Results indicated LHV of 5.4 MJ/kg and a high moisture content of 55%, underscoring the need for improved MSW treatment processes. The most common particle size was 50-80 mm, accounting for 31.6% of the MSW. The organic fraction was predominant at 43%, followed by plastics at 24% and paper at 13%. In a pilot project involving 10 trials with 1,000 Mg of MSW, processing through a series of pre-shredder, trommel, magnetic separator, wind-shifter, and fine shredder produced RDF with an LHV of 8.7 MJ/kg and 47% moisture, along with a lower-grade RDF with an LHV of 3.0 MJ/kg and 61% moisture. This effort resulted in 441 Mg of low-grade RDF and 423 Mg of higher-grade RDF, resulting in an estimated reduction of 217 Mg of CO_2 emissions. Further modeling suggested that using hot gases at the cement plant could produce drier RDF. To meet the cement plant's demands, thirteen RDF production units processing 6,500 Mg/day of MSW would be required. This would generate 3,100 Mg/day of RDF, achieving a 51% fuel substitution rate at the cement plant, reducing CO_2 emissions by 24%, and cutting MSW by 45% across the regions

1. INTRODUCTION

Cement is an essential building material known for its durability and versatility. It serves as a fundamental component widely used in the construction and development of infrastructure, playing a significant role in advancing human life. According to Cembureau (2023), the global cement production capacity in 2022 stood at 4.3 billion Mg and is expected to continue increasing. However, this upward trend in cement production is likely to intensify the challenges faced by the cement industry in reducing CO_2 emissions. The global cement industry currently faces at least three global issues that require continuous solutions. The first challenge is reducing global CO_2 emissions from the cement industry. The second challenge involves production efficiency, encompassing cost efficiency, natural resource efficiency, and fuel usage. The third challenge pertains to the implementation of economic circularity. Previous research on CO_2 emissions reduction in the cement industry has led to savings in the purchasing of materials required during cement production (Rootzén & Johnsson, 2017). Therefore, the cement industry bears a significant responsibility for climate protection, particularly in addressing CO_2 emissions reduction and preserving natural resources (Salamanova et al., 2020; Schneider, 2019).

Similar to global challenges, the cement industry in Indonesia also faces similar issues, including production efficiency, CO_2 emissions reduction, and concerns about sustainable business practices. According to the Ministry of Industry of the Republic of Indonesia (Kemenperin) (2022), cement production in Indonesia contributes to 28% of the country's CO_2 emissions. One of the leading cement companies in Indonesia, Indocement, is actively seeking to address these environmental challenges with the goal of becoming a more sustainable cement producer. In its 2022 Sustainability Report, Indocement stated that sustainable practices, such as greenhouse emission reduction, waste management through circular economy, and water and energy efficiency, were carried out (Indocement, 2022). Indocement also puts attention on the use of alternative fuel (AF) sources with a target to achieve a 50% coal substitution rate by 2030. This is estimated to equate to around 6,000 Mg per day of alternative fuel.

MSW management in Indonesia is a pressing issue, as the country generates nearly 69 million Mg of MSW

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annually. This poses challenges for landfills and raises health concerns, especially in the densely populated cities of Jakarta, Bogor, Depok, and Bekasi, known as Jabodebek, which contribute approximately 14,500 Mg of MSW daily (BPS Jakarta, 2023; KLHK, 2023). Despite having regulations in place for waste reduction and comprehensive waste management, the execution of these measures remains inefficient (Fatimah et al., 2020). To address this problem, the conversion of MSW to refuse-derived fuel (RDF) emerges as a potential solution that aligns with the government's waste policies. RDF, derived from MSW through specific processes, offers a cross-sectoral remedy for environmental performance and waste management issues. It presents a cost-effective and ecologically friendly fuel replacement, supporting the cement industry's transition towards sustainable practices (Mateus et al., 2023).

RDF shares similar characteristics with conventional fuel as it predominantly consists of the combustible fractions of MSW (Paszkowski et al., 2020). Ideally, RDF composition has a high content of paper, plastic, wood, and textiles, contributing to higher heating value. It has a high calorific value (around 16-18 MJ/kg), low production costs, and a homogeneous particle size. Despite its benefit as an AF and its positive environmental impact, RDF has several disadvantages related to heterogeneity, moisture, and sulphur, chlorine, and ash contents (Brás, 2017; Paszkowski et al., 2020). To circumvent these disadvantages, optimizing RDF production from MSW through pilot project and modeling is required. In European countries, a legal framework has been established to promote waste valorization as a way to reduce the amount of waste by RDF production from the rejected streams of multi-municipal waste management systems (Brás, 2017). For instance, in Europe and globally, cement manufacturers currently use RDF as a common AF to replace coal, aiming to optimize fuel costs (Paszkowski et al., 2020).

The utilization of RDF presents a convergence of solutions between cement production challenges, including production efficiency, CO_2 emission reduction, and the implementation of sustainable business practices, with MSW management issues. This signifies a promising cross-sectoral solution that has the potential to address two distinct yet interconnected challenges. Processing MSW into RDF for AF can also be a collaborative solution between cement producers and the government, particularly at the city level. Thus, this research aimed to examine RDF's feasibility as an AF in Indocement, located in the Jabodebek region cement industry, proposing a model that harmonizes resource optimization with industrial sustainability.

2. MATERIALS AND METHOD

2.1 Study area description and MSW collection

The study was conducted on four regions located near Indocement, a cement plant in Bogor, Indonesia. These regions were Jakarta, Bogor Regency, Depok, and Bekasi (Jabodebek). MSW was collected from local intermediate MSW storage facilities located in these four regions, and these storage facilites were located within 50 km of the cement plant. The MSW sample collection for each region is summarized in Table 1.

The MSW samples were collected from December 2022 to June 2023, which also comprised the rainy and summer seasons. The samples were transported to the cement plant using trucks with a capacity of 6-8 m^3, with an average carrying capacity of 2-3 Mg per truck. The MSW analysis and RDF production and analysis were conducted at the cement plant.

2.2 Experimental design

The research consisted of three phases (Figure 1). First, the collected MSW was analyzed. Next, the MSW was processed into RDF on a pilot project scale, followed by RDF production modeling.

TABLE 1: MSW Sample Collection.

Item	Unit	Urban Area				Total
		Jakarta City	Bogor Regency	Depok City	Bekasi City	
Sample collection duration	days	8	8	8	8	32
Sampling in summer						
Sampling schedule	N/A	8-15 May 2023	22-29 May 2023	5-12 Jun 2023	19-26 Jun 2023	N/A
Trucks sample count	unit	56	56	56	56	224
Rainfall	mm/month	50-100				N/A
Sampling in rainy						
Sampling schedule	N/A	12-19 Dec 2022	9-16 Jan 2023	28 Nov - 5 Dec 2022	23-30 Jan 2023	N/A
Trucks sample count	unit	56	56	56	56	224
Rainfall	mm/month	250-400				N/A
Total trucks sample count	unit	112	112	112	112	448
Samples taken per truck	Mg	2.84	2.79	2.78	2.88	2.82
Total samples taken	Mg	318	313	312	323	1,265
Daily waste generation	Mg/day	8527	2688	1400	1830	14,445

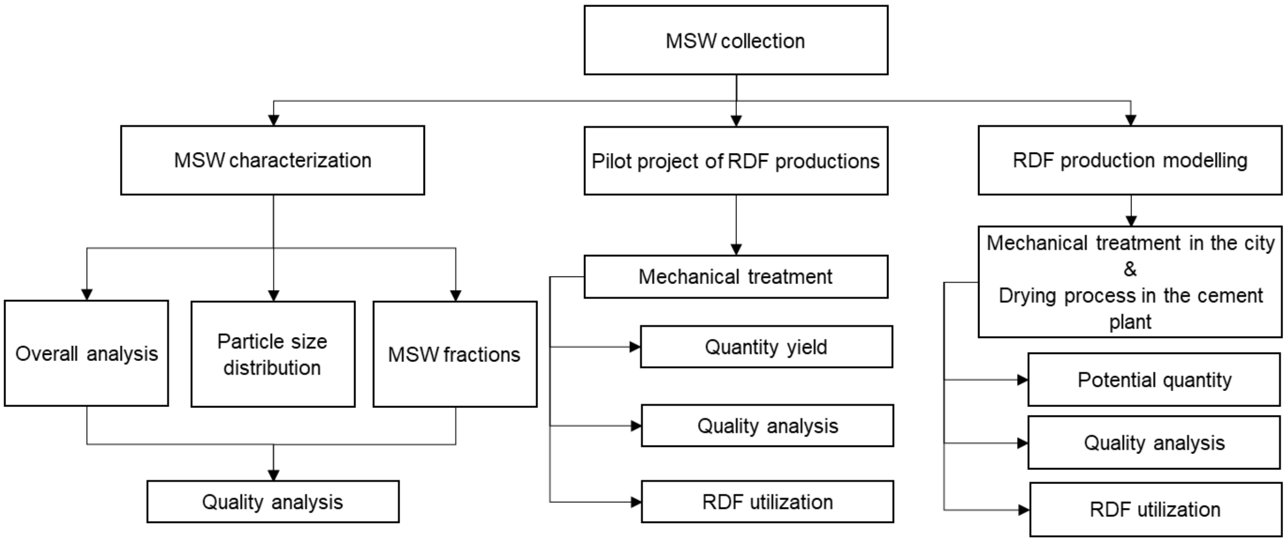

FIGURE 1: Schematic flow of the study.

2.2.1 MSW characterization

The MSW collected from different areas was properly mixed, as advised by Wirosoedarmo et al. (2021), to ensure sample homogeneity and consistent results (Figure 2). Then, the samples were subjected to the following analysis:

- Chemical and physical properties.
  Moisture content (MC), calorificc value, and ash content were determined according to EN 15414-3: 2011, EN 15400: 2011, and EN 15403: 2011, respectively. Total carbon (C), hydrogen (H), and nitrogen (N) analysis was done following EN 15407: 2011, while oxygen content was deduced stoichiometrically by subtracting carbon, hydrogen, nitrogen, and ash percentages from 100%. Total contents of sulfur (S) and chlorine (Cl) were assessed using XRF Epsilon 5 analyzer.
- Particle size distribution.
  To devise effective strategies for waste processing and management, a particle size distribution analysis was conducted (Zhang et al., 2019). The particle size range employed in this study was >200 mm, 100-200 mm, 80-100 mm, 50-80 mm, 10-50 mm, and <10 mm. Combustible, non-combustible, biomass, and non-biomass fractions were determined. Combustible fraction was the sum of the organics, paper, wood, textile, plastic, and rubber components while the sum of the other components was non-combustible fraction (Dharmendra, 2022). The sum of organics, paper, and wood components was considered as biomass fraction and the sum of the rest of the components was considered as non-biomass fraction (Perea-Moreno et al., 2019).
- MSW fraction.
  The MSW fraction analysis was carried out to identify the proportion of combustible and non-combustible

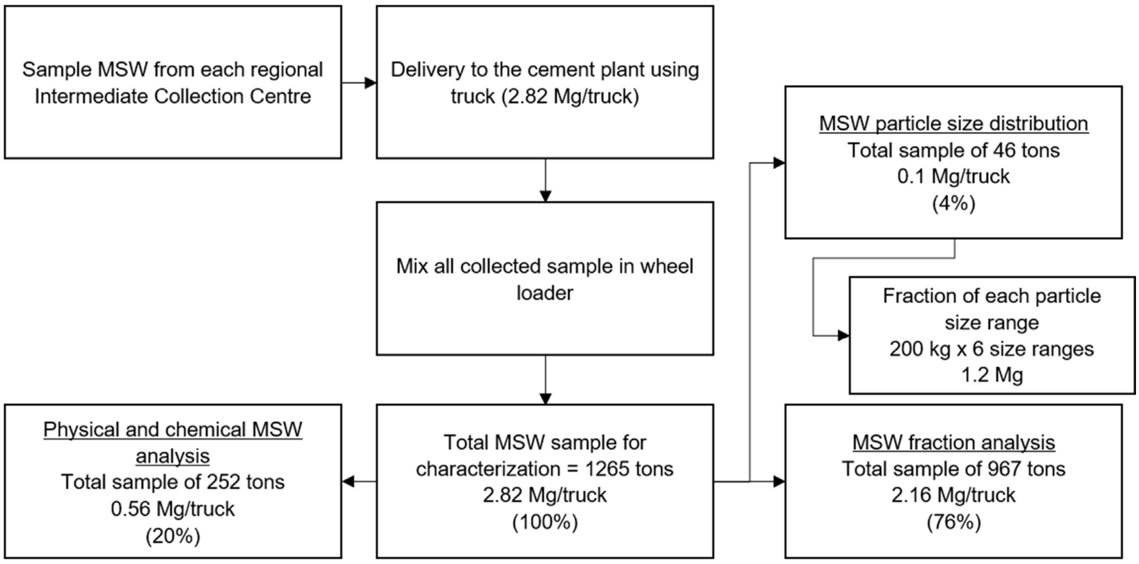

FIGURE 2: MSW sample collection, processing, and distribution for characterization.

materials in the samples, allowing further identification of the waste compositions. This analysis is crucial for treatment design and determining RDF quality (Alfè et al., 2022). The chemical and physical properties of each fraction along with the biomass fraction was also evaluated.

2.2.2 Pilot project of RFD production

In the second phase, a pilot project was conducted to process MSW into RDF. The pilot project consisted of 10 trial runs, initiated in December 2023, with around 100 Mg of MSW utilized and transported to the cement plant's pilot facility for each trial. The MSW went through the pre-shredder to produce materials sized between 200-300 mm. This equipment effectively reduces MSW to a smaller, more consistent size, improving later treatment processes (Oladejo et al., 2020). Next, the MSW was processed using a trommel (80 mm mesh) to ensure the RDF is within the optimal size range of 50-80 mm, capturing combustible fractions and accommodating the lower calorific value of finer materials (Malaťák et al., 2018). A magnetic separator installed above the conveyor belt removed ferrous metals from waste, and then a wind-shifter was utilized to divide waste into heavier and lighter fractions. Lastly, a fine shredder was used to produce a consistent and homogeneous particle size of 50x50 mm, ensuring the output reliably meets standard fuel quality specifications (Nanda & Berruti, 2021). Two RDFs were produced in this study: one underwent processing through a fine shredder (<50 mm), and the other was low-grade RDF with a size of <80 mm (Figure 3).

The RDF produced was quantified and analyzed to determine its quality. Chemical and physical properties analysis, as stated in 2.2.1, were performed and the result was compared to standard specification. Following the analysis, the RDF was supplied to the existing RDF feeding point and was conveyed to the calciner. The RDF output consisted of calorific value, total energy generated, and CO_2 emission factor and emission reduction were determined. Total energy generated was calculated by multiplying the RDF's LHV with its production quantity. The CO_2 emission factor was obtained by multiplying CO_2 (converted from carbon content) with the non-biomass fraction, then divided by the LHV. Meanwhile, CO_2 emission reduction was calculated by substracting CO_2 emission factor of coal (97.6) with CO_2 emission factor of RDF, then multiplied the result with net heat generated.

2.2.3 RDF production modeling

The pilot project served as the basis for RDF production modeling. Modeling occurred in two locations: the pre-drying process in the city and the drying process at the cement plant using a box dryer with hot gas (Figure 4). This modeling arrangement reduced land usage, a significant factor in urban settings, as the cement plant features a spacious location with 10 kilns. Two units of box dryer were designated to dry the fine and low-grade RDF separately and op-

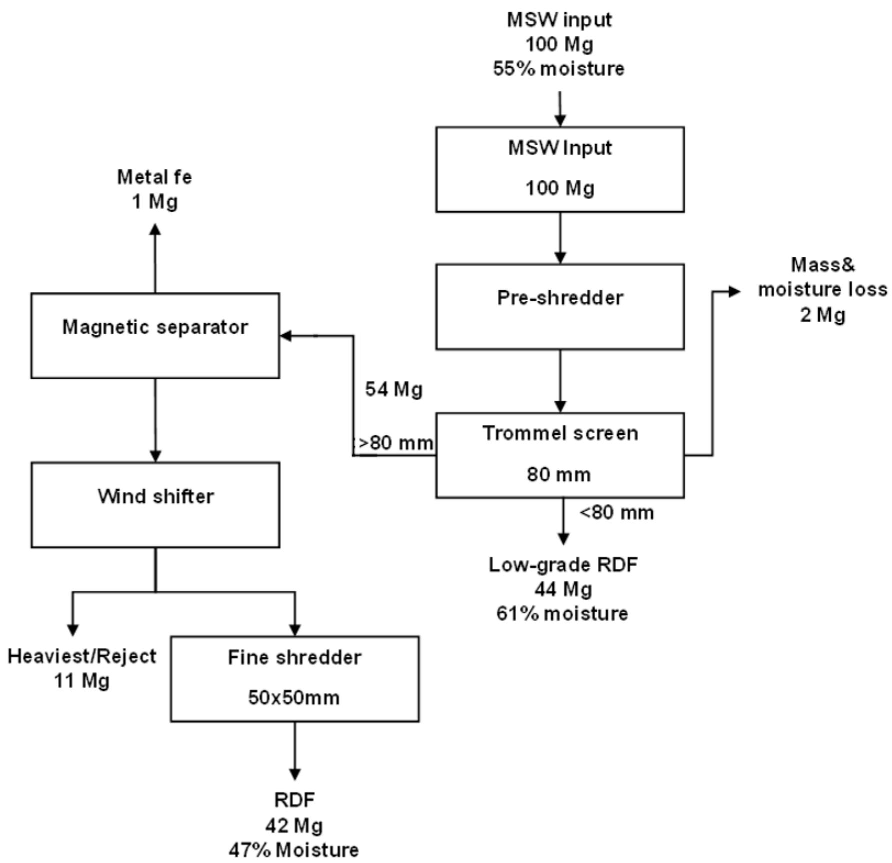

FIGURE 3: RDF pilot project process.

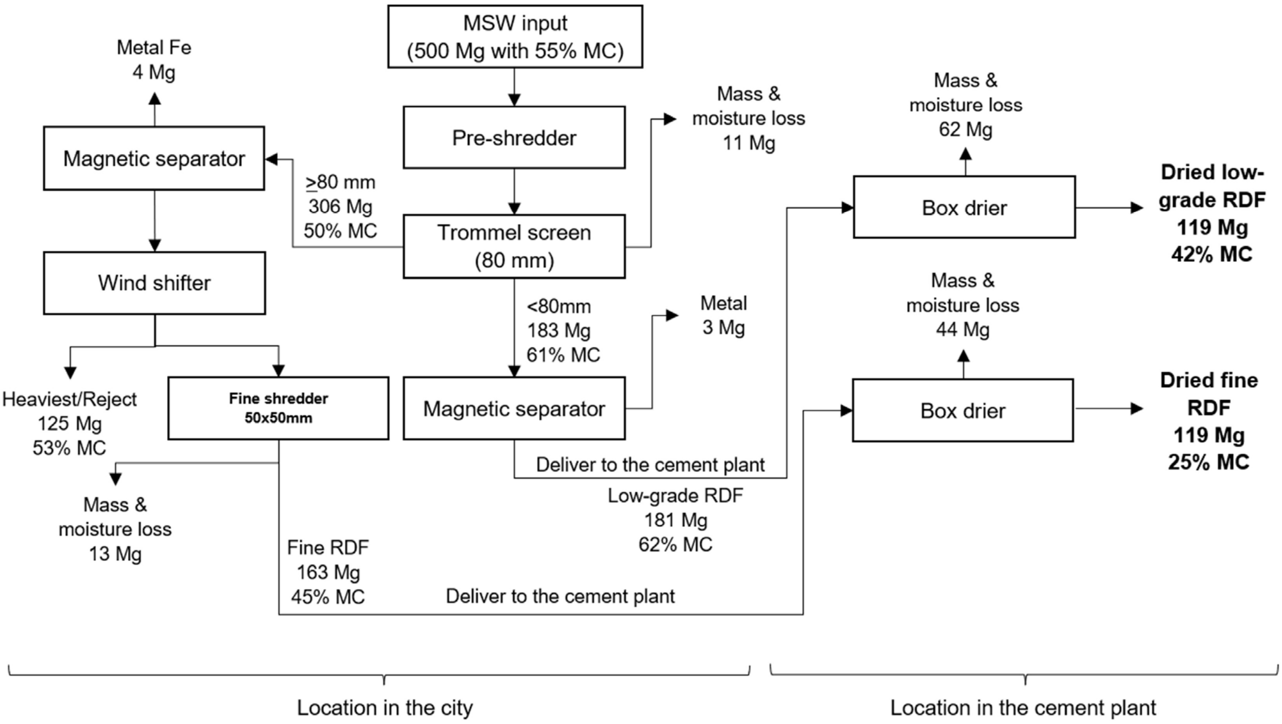

FIGURE 4: Schematic of RDF production modeling.

erated at 130-175°C. The type of box drier was concrete with a grab crane with an air blowing capacity of 24 m^3/min. The hot gas exited from the bag filter, and the drier had moisture reduction input of 55-60% wt. (ar) and output of 30-35% wt. (ar). The dryer had a capacity of 270 Mg, and the drying process was completed in 1 day.

The yield, net heat, physical and chemical properties, biomass percentage, and CO_2 emission factor and savings were determined. CO_2 emission savings was calculated by substracting CO_2 emission factor with RDF and multiplying the result with total net heat. Lastly, feasibility was done to examine the potential of RDF to replace 50% of the cement plant's fuel, as targeted by the cement plant.

3. RESULTS AND DISCUSSION

3.1 MSW characterization results

3.1.1 The chemical and physical properties of MSW

The total sample size of this study was approximately 46 Mg, in which Jakarta, Bogor, Depok and Bekasi contributed to 12, 11, 11, and 12 Mg, respectively. The chemical and physical properties of MSW collected from each city were determined during the summer and rainy seasons (Table 2). Table 2 reveals a lower average MC (54%) during the summer compared to the rainy season (56%), with a notable low of 52% MC in Jakarta during the summer. Overall, across all cities and seasons, the average MC was 55%. The MSW properties across cities showed consistent results, likely due to similar population behaviors, commuting population (Sadewo, 2018), as well as waste preconditioning at intermediate storage facilities. MC is a vital parameter in the selection and design of MSW treatment technologies due to its impact on other significant parameters, including heating value and overall system efficiency. This underscores the importance of monitoring moisture levels during the MSW-to-RDF treatment process to enhance the quality and performance of the resulting fuel (He et al., 2022). The average MC did not meet RDF specifications for Indocement. RDF specifications in the cement plant requires MC ≤ 45% wt (ar), HHV ≥ 6 MJ/kg, sulfur ≤ 0.6% wt (db), and chlorine ≤ 1.25% wt (db) (Indocement, 2024). Therefore, additional treatment was needed to achieve the minimum requirement.

3.1.2 Particle size distribution

Next, particle size distribution, an important factor that affects combustion, was determined. The figure below presents the size distribution of the MSW (Figure 5). The particle size distribution composition between each area was similar, where particles sized 50-80 mm constituted the larger proportion of the MSW (31.6%; Figure 5A). Further analysis showed that the total percentage of particles sized >80 mm was 47.8%, while particles sized <80 mm represented 52.2%. The 80 mm size marks the optimal combustion threshold in cement plants. Meanwhile, a study in Jordan reported particle size measurement of MSW yielded 31.6% for sizes >100 mm, 31.0% for the 50-100 mm, 22.8% for 10-50 mm, and 13.6% for <10 mm (Al-Hajaya et al., 2021).

The composition of combustible and non-combustible materials within various particle size distributions was further analyzed, with around 400 kg sampled per category, making up a total sample of 2.4 Mg. This analysis helps identify particle sizes with a higher likelihood of combustibility. Combustible fraction dominated the MSW across all particle sizes. Particle sized 10-50 mm had the highest

TABLE 2: The Chemical and Physical Properties of MSW Samples.

Parameters	Unit	Summer				Rain				Mean±Std dev.	Rep. Value
		Jakarta	Bogor	Depok	Bekasi	Jakarta	Bogor	Depok	Bekasi		
HHV	MJ/kg	8.8	8.6	8.3	8.3	8.5	8.2	8.2	8.3	8.4±0.1	4-10[1]
LHV		5.9	5.4	5.1	5.3	5.9	5.4	5.1	5.3	5.4±0.1	5-10[2]
MC	% wt. (ar)	52	54	54	56	55	56	55	57	55±3	20-67[1]
Ash	% wt. (db)	11	11	11	12	11	11	12	11	11±1	1-30[3]
S		0.22	0.23	0.23	0.23	0.23	0.23	0.24	0.23	0.2±0.0	0.1-0.7[4]
Cl		0.40	0.38	0.39	0.42	0.41	0.38	0.39	0.43	0.4±0.0	0.24-1.9[5,6]
C		49	52	54	52	50	56	53	49	52±4	11-54[1,7]
H		7	8	6	7	8	9	7	8	7±2	6-10[1]
N		1	1	1	1	1	1	1	2	1±0	0.6-1.0[1]
O		32	27	28	28	29	23	27	30	28 ±1	30-55[1]

Rep. Value: reported value; [1] Amen et al., 2021; [2] Drudi et al., 2019; [3] Siddique, 2010; [4] Cheng et al., 2023; [5] Ma et al., 2010; [6] Shao et al., 2010; [7] Tursunov et al., 2015

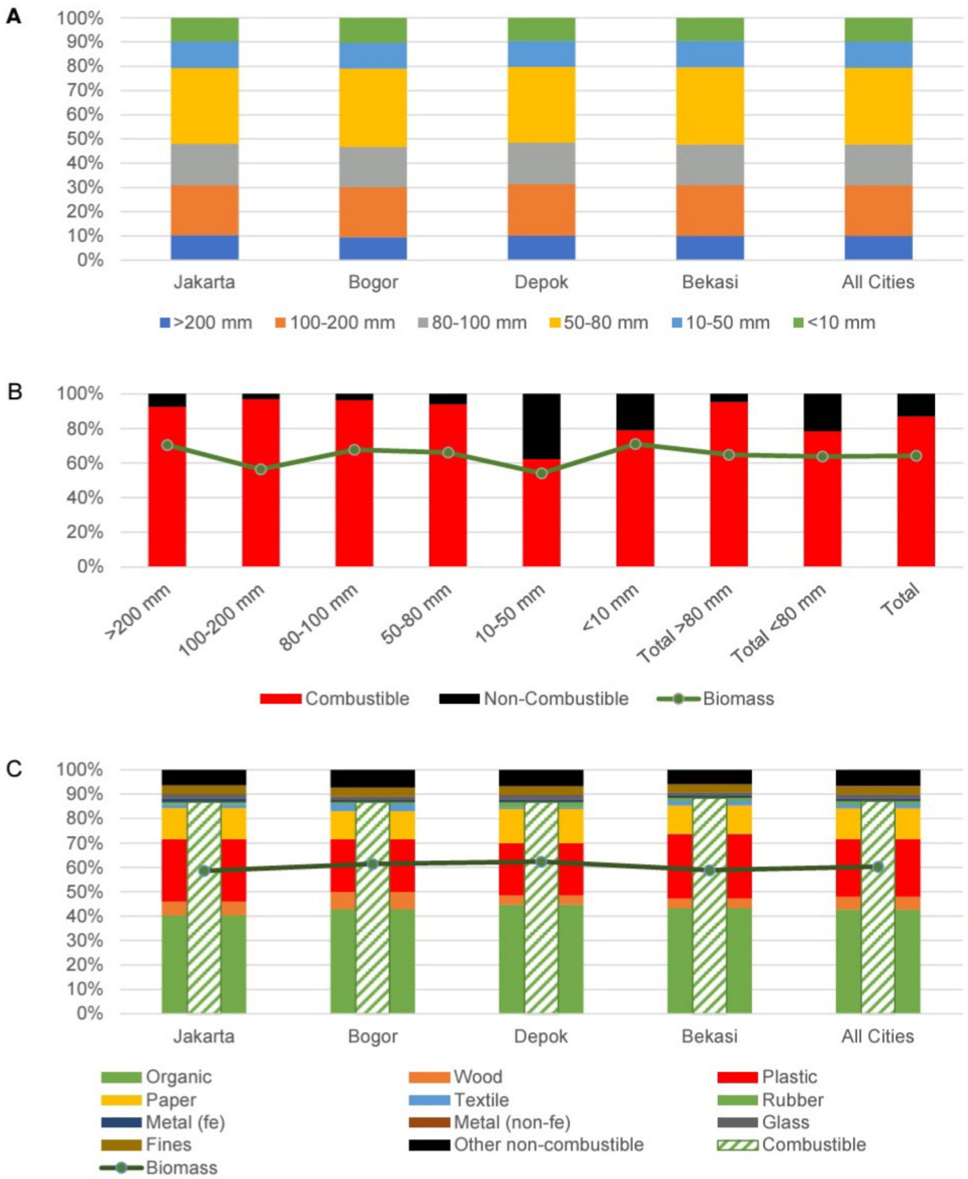

FIGURE 5: Particle size distribution and MSW fraction analysis results. (A) Particle size distribution in mm; (B) Combustible, non-combustible and biomass fractions of each particle size range; (C) MSW fraction analysis.

non-combustible rate of 38%, followed by particle sized 10-50 mm with a combustible rate of 21% (Figure 5B). The higher non-combustible rate may be attributed to inert content. Overall, 87% of MSW was combustible (Figure 5B). This finding is aligned with a study in Jordan that reported high combustibility across all sizes (Al-Hajaya et al., 2021). Our combustible fraction was similar to those reported in Indonesia and India, with values of 88% and 87%, respectively (KLHK, 2023; Singhal et al., 2022). This similarity suggests comparable waste habits and less source sorting in Indonesia and India (World Bank, 2020). Germany had a lower combustible fraction of 81%, indicating better waste management and segregation, futher implying simplified processing of MSW into RDF (BMUV, 2023).

The biomass content within particle size distributions was also determined by estimating the waste material types. Organic waste, including wood and paper, was classified as biomass fraction (Perea-Moreno et al., 2019). A larger proportion of the MSW particle sizes was biomass, with an average value of 64% (Figure 5B). The biomass fraction of MSW, industrial waste, and sewage sludge in incineration facilities were shown to be 57%, 41%, and 78%, indicating biomass fraction variability between sources (Kang et al., 2017). Biomass is considered a carbon-neutral source of energy because the CO_2 released during its combustion is roughly equivalent to the CO_2 absorbed by the plants during photosynthesis, making it a net zero carbon option on the path to carbon reduction (Zagaria et al., 2023). Therefore, in the calculation of CO_2 emissions, the biomass content can reduce the emission factor when it is combusted.

3.1.3 The MSW fraction analysis result

The collected MSW fraction samples constituted a total mass of 967 Mg (Figure 2). This substantial volume, due to the scale of sample collection, is crucial to ensure representativeness of the study. This extensive data set enables an in-depth understanding of the MSW stream's variety, essential for creating targeted waste management plans and models that inform strategic decisions. Organic materials constituted the largest fraction, averaging 43%, followed by plastics and paper, which accounted for 24% and 13% of the total fraction, respectively (Figure 5C). The plastic data is consistent with other data in Jakarta, which was reported as 23% (BPS Jakarta, 2023). Wood, textile, rubber, metals (Fe and non-Fe), glass, and fines were found to be in lesser quantities (Figure 5C). Other non-combustible materials, such as stones and ceramics, had an average value of 6%. Valuable items were detected in minimal amounts because the samples were taken from intermediate MSW storage facilities where items with commercial value, such as 3D plastic, glass, and metal, were often collected by waste pickers for resale (Mastufatul et al., 2023). In general, the data indicated diversity in the solid waste profile, consistent with previous studies (Brás et al., 2017; Świechowski et al., 2020).

The biomass fraction of each area was assessed. Similar to the biomass content of particle size distributions result, biomass content had a larger percentage in all areas, making up a total average of 60% (Figure 5C).

A table detailing the chemical and physical properties of each MSW fraction is presented in Table 3, where only the fines fraction was analyzed for non-combustible content. Organics exhibited an HHV of 4.5 MJ/kg with a high moisture level at 78%, possibly lowering its energy potential. Plastic had a high HHV at 17.8 MJ/kg and LHV of 13.8 MJ/kg with a moisture level of 48%, indicating a promising energy source. Paper and textiles also had notable calorific values with reasonable moisture content. The content of plastics and paper emerges as a crucial factor for producing high-calorific-value RDF, suggesting that higher fractions of these materials will lead to a correspondingly higher caloric value of the RDF (Tihin et al., 2023b). Rubber stood out with the highest calorific values (HHV of 28.5 MJ/kg and LHV of 25.7 MJ/kg) and low MC, enhancing its fuel quality. Overall, the HHV and LHV values of the fractions were found to be lower than in previous studies (Komilis et al., 2012; Zhou et al., 2014; Boumanchar et al., 2016; Zhen et al., 2019). The lower calorific values are likely due to high MC of the major fractions, which have been shown to decrease HHV and LLV (Komilis et al., 2012). In terms of carbon content, plastics have the highest percentage (64%), contributing to their combustion quality. The combined average of all MSW fractions had a moisture level of 55% and a carbon content of 47%, influencing MSW's viability as a fuel. Carbon is a crucial factor in assessing energy potential and CO_2 emissions, which affects environmental and carbon footprint evaluations (Wienchol et al., 2020). The majority of elemental analysis results was similar to the results of investigations in Marocco, China, and Greece (Komilis et al., 2012; Zhou et al., 2014; Boumanchar et al., 2016). Meanwhile, there is no earlier report on the the properties of fine fraction of MSW (Table 3).

To corroborate the findings with the overall MSW analysis, the weighted average of each parameter from each fraction was calculated by weighing it with % fraction wt, as presented in Figure 5C. The weighted average for each parameter was similar to the overall MSW analysis result, except for carbon content. The carbon content in the analysis was 52% (Table 2), while based on MSW fraction, the carbon content was 47% (Table 3 section C). This difference occurs due to differences in the total amount of sample used and the sample collection approach.

3.2 Pilot project of RFD production

The completed pilot project solely utilized mechanical treatment methods and did not incorporate drying processes. Each batch processed 100 Mg of MSW, and the pilot project was evaluated over 10 trials. The trial outcomes showed that the trommel screen's material processing performance dropped by approximately 50% from its initial capacity, processing only 3-7 Mg due to the 55% MC causing substantial spillage and separation challenges. The fine shredder's efficacy also fell to 1-4 Mg/hour, about 20-30% of its designed throughput, as moisture caused material clumping and machinery blockages. These challenges highlight the significance of moisture control for maintaining optimal mechanical treatment operations (Ismail et al., 2019).

TABLE 3: The chemical and physical properties of MSW fractions.

No.	MSW Fractions	HHV	LHV	Moisture	Ash	S	Cl	C	H	N	O
		MJ/kg		% wt. (ar)	% wt. (db)						
A	Combustible										
1	Organic	4.5±0.4	1.2±0.4	78±7	17±2	0.4±0.04	0.7±0.07	50±6.5	6±1	1.8±0.2	19±2
2	Wood	7.5±0.8	4.9±0.8	47±5	5±1	0.1±0.09	0.1±0.09	47±3.9	7±1	0.3±1	40±1
3	Plastic	17.8±1.6	13.8±1.6	48±5	6±1	0.1±0.01	0.3±0.02	64±6.6	13±1	0.1±0.0	15±1
4	Paper	11.2±1.2	8.3±1.2	51±5	3±1	0.2±0.02	0.1±0.09	43±3.8	7±1	0.4±0.0	44±1
5	Textile	11.6±1.1	8.7±1.1	53±6	13±1	0.1±0.01	0.1±0.01	49±5.7	7±1	3.2±0.4	22±1
6	Rubber	28.5±2.9	25.7±2.9	4±1	3±1	0.4 ±0.04	0.1±0.01	53±5.7	12±1	0.9±0.1	29±1
B	Non-combustible										
1	Fines	1.2±0.1	0±0	16±1.7	60 ± 5	0.4±0.04	0.1±0.01	26±3	3±0.3	0.2±0.0	11±1.4
C	Weighted average by % fraction	8.5±0.8	5.5±0.8	55±5	11±1	0.2±0.03	0.4±0.05	47±5	7±1	0.9±0.1	20±1

The pilot project produced two types of RDF, i.e., RDF and low-grade RDF (Figure 1). The analysis results of the RDF are shown in Figure 6. RDF had the highest HHV and LHV compared to MSW and low-grade RDF, with values of 12.1 and 8.7 MJ/kg, respectively (Figure 6A). Meanwhile, LHV values of the MSW, low grade, and RDF were lower than the respective HHV values, possibly due to water and hydrogen correction of MC. RDF also had a better characteristic since it had the lowest MC of 47% (Figure 6B). In contrast, low-grade RDF had the highest MC of 61%. This high moisture level happened because the refinement process did not include a sufficient drying phase, leaving the low-grade RDF with excessive dampness. Following a comparison with previous studies (Hemidat et al., 2019; World Bank, 2020; Sarquah et al., 2023), both RDFs produced had lower HHV and LHV values and higher MC, indicating a lower RDF quality.

Overall, the elemental measurements of low-grade RDF and RDF were all within the previously reported values (Gallardo et al., 2014; Alfè et al., 2022; Sarquah et al., 2023). However, an increase in ash content was observed during the conversion, hinting at an accumulation of non-combustible materials in the RDFs. Additionally, a modest rise in sulfur and chlorine was recorded post-conversion, especially in the low-grade RDF. The MSW-to-RDF conversion increased the carbon content, suggesting greater energy potential in RDF, attributable to the increased presence of plastic and paper in the RDF. The hydrogen content of RDF was higher than the low-grade RDF, while the oxygen content of low-grade RDF was higher than RDF (Figure 6C).

The HHV values of both products were still in the range of the cement plant's specifications, although both products had higher MC values than the specification (<45%). Both RDF products did not meet Indonesian standards while according to European standards ISO 21640:2021, they fell under class 5 (Kemenperin 2017; CEN, 2021). Since the low-grade RDF and RDF met the cement plant's specifications in terms of HHV, sulfur, and chlorine content, they were utilized in the cement plant, resulting in the output presented in Figure 7. The total amount of low-grade RDF and RDF utilized were 441 Mg and 423 Mg, respectively. RDF produced higher LHV and total energy generated than low-grade RDF, indicating RDF as a better source of fuel. The CO_2 emissions factor values in this project were 50 Kg CO_2/GJ and 65 Kg CO_2/GJ for RDF and low-grade

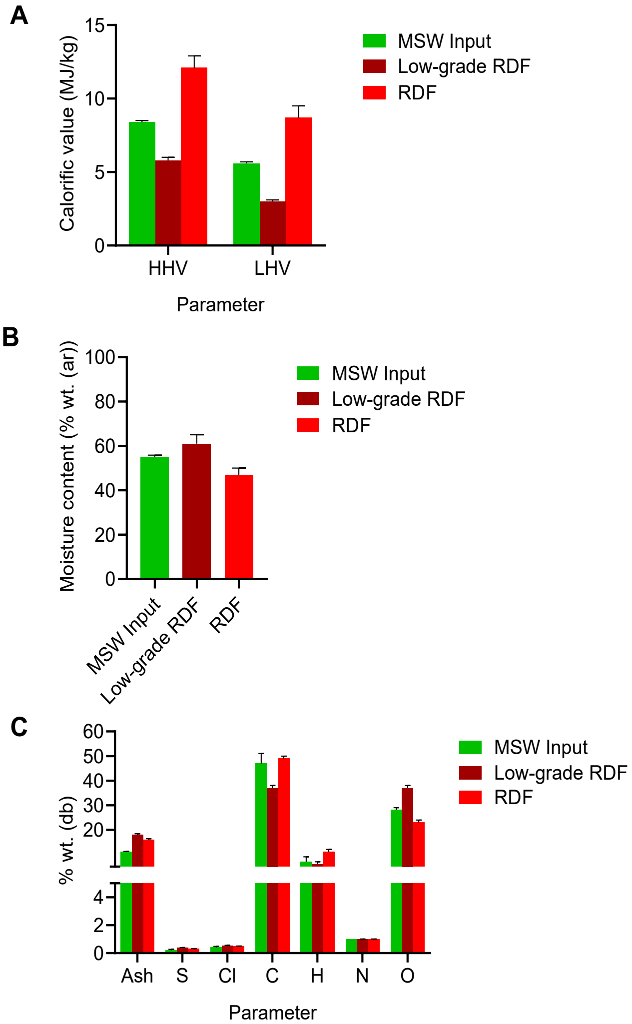

FIGURE 6: Pilot project output quality comparison with MSW input. (A) Comparison of calorific value; (B) Comparison of moisture content; (C) Comparison of ash and elemental.

RDF, respectively. In another study, the reported emissions factor was estimated to be around 27 Kg CO_2/GJ for RDF (MVW Lechtenberg & Partner, 2008). As low-grade RDF had a higher emission factor, the CO_2 emission reduction was lower than the RDF. In total, the RDF used led to an estimated total of 217 Mg CO_2 savings.

3.3 RDF production modeling

The pilot project indicates the need to incorporate a drying process in the production of higher quality RDF. Hence, two steps of drying processes were used in this modeling. The first involved a pre-drying process in the city, and the second involved a drying process at the cement plant using a box dryer with hot gas. This modelling arrangement reduced land usage, a significant factor in urban settings, as the cement plant features a spacious location with 10 kilns.

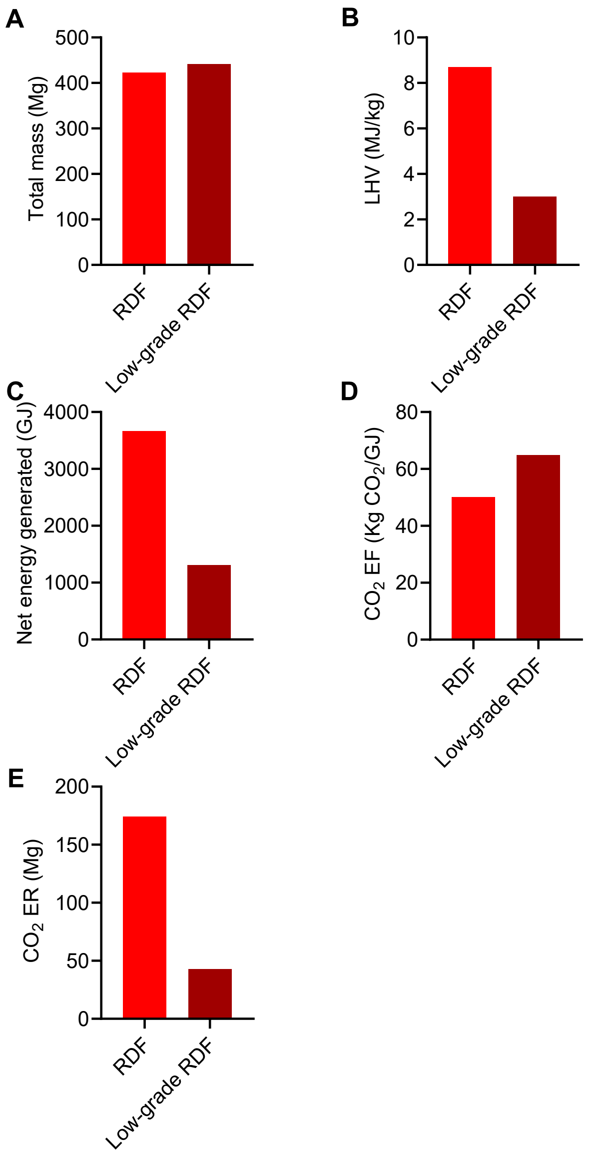

FIGURE 7: Utilization of pilot project output. (A) Total mass produced; (B) LHV value; (C) Net energy generated; (D) CO2 emission factor (EF); CO_2 emission reduction (ER).

The design and operational characteristics of the drying system are crucial for preparing the fuel for use in the calciner. Tests for the box dryer project have been carried out at the Heidelberg cement plant in China (Indocement, 2024), showcasing important performance metrics. The box dryer has a capacity of 270 Mg each. There were two units designated for processing material sizes greater than 80 mm and another two units for sizes less than 80 mm. The dryers were operated at 130-175°C, allowing the drying process to be completed in one day. The type of the box drier was concrete with a grab crane with an air-blowing capacity of 24 m^3/min. The hot gas exits from the bag filter, and the drier has a moisture reduction input of 55-60% wt. (ar) and output of 30-35% wt. (ar). This output is inline with previous studies that reported a thermal moisture reduction of 10-60% (Tun & Juchelková, 2019; Zamrudy et al., 2019). The drying system is pivotal for boosting RDF quality by increasing its calorific value and reducing moisture content. Its proximity to the cement kiln allows efficient use of the plant's thermal energy, streamlining operations and potentially cutting heat generation costs (Conceição & Rolim, 2019).

Figure 8 shows that the modeling results in better RDF output than that of produced in the pilot project. The yield of the total RDF product received was 48%, which aligns with a review by Gadaleta et al. (2022) focusing on the mass flow analysis of mechanical biological treatment (MBT) facilities, indicating that approximately 15-50% of the processed material becomes RDF. The RDF produced met the cement plant's RDF specifications, with fine RDF catering to medium-quality specifications (class 3 of ISO 21640:2021) and low-grade RDF as low-quality specifications (class 5 of ISO 21640:2021).

The RDF modeling and pilot project mainly composed of plastic and paper, reaching up to approximately 60% (Figure 9). In contrast, the organic materials in the MSW and low-grade RDF modeling made up the majority of the bulk. The differences emphasize the changes in material composition during the RDF process, with a decrease in organics and an increase in plastics and paper, thereby enhancing energy recovery potential (Tihin et al., 2023). Unfortunately, the analysis of the low-grade RDF fraction in the pilot project could not be conducted due to challenges in identifying smaller-sized stabilized materials. In low-grade RDF modeling, the non-combustible fraction was 30%, consisting of fine materials. For cement plants, this is not a significant issue as the ash content contains raw cement materials like silica, which can be utilized effectively in the calciner (Wang, 2021).

Lastly, a feasibility study to examine the potential of RDF to replace 50% of the cement plant's fuel, based on an annual heat requirement of around 12,650 TJ out of 24,800 TJ. The modeling processed 500 Mg/day of MSW, serves as the reference unit for an RDF production plant, and CO_2 emission reductions were calculated against coal, with its emission factor of 97.6 kg CO_2/GJ (Juhrich, 2022) and an LHV of 20.8 MJ/kg (Indocement, 2024). Two scenarios were set to represent a condition where coal consumption is 100% (scenario 1) and where 50% of fuel requirement is fulfilled by RDF modeling (scenario 2) (Figure 10).

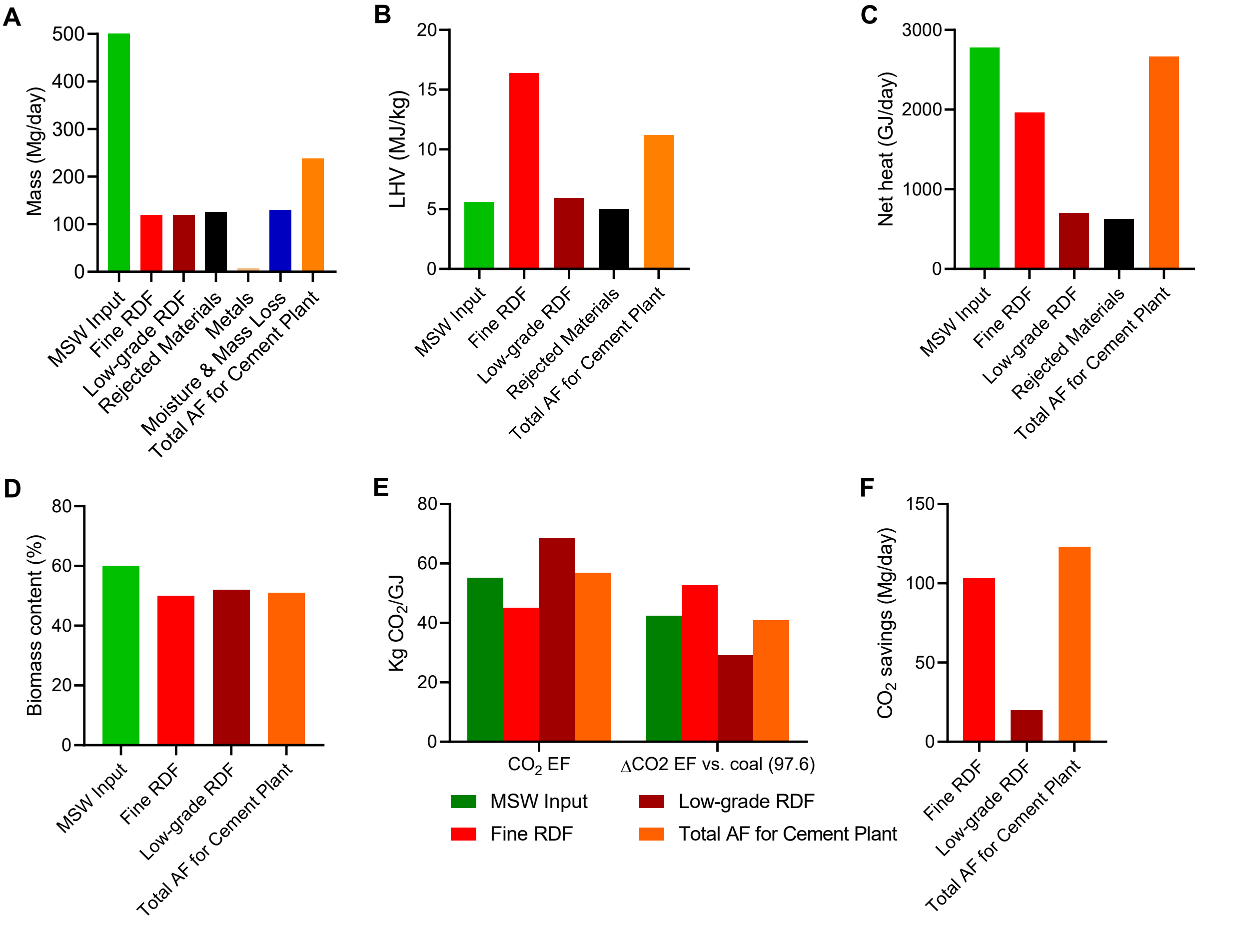

FIGURE 8: RDF Modeling analysis and output. (A) Total mass; (B) LHV; (C) Net heat; (D) Biomass content; (E) CO2 emission factor (EF) and CO_2 RF difference vs. coal (97.6); (F) CO_2 saving.

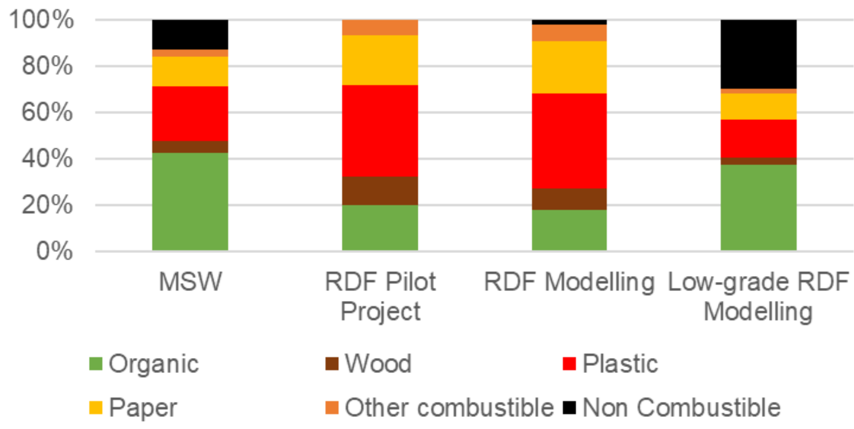

FIGURE 9: Comparison of MSW and RDF fraction analysis.

To meet the 24,800 TJ energy requirement, scenario 1 would require approximately 1.2 million Mg/year of coal. To achieve a minimum 50% AF substitution rate in scenario 2, 13 RDF plant units would be needed to produce a total RDF of 3,100 Mg/day. This setting would result in a 51% AF substitution rate, reducing coal consumption by 610,000 Mg/year and decreasing CO_2 emissions by 24% (585,000 Mg/year; Figure 10). Furthermore, implementing RDF at the cement plant could significantly reduce MSW output from the four cities by 500 Mg/day for each of the 13 available units, resulting in a daily MSW reduction of 6,500 Mg. This reduction could account for up to 45% of the daily MSW from the Jabodebek area, which produces approximately 14,500 Mg/day. The results demonstrate that utilizing RDF in the cement plant as an AF presents economic and environmental benefits by reducing the fossil fuel use, decreasing CO_2, and utilizing MSW from the nearby areas.

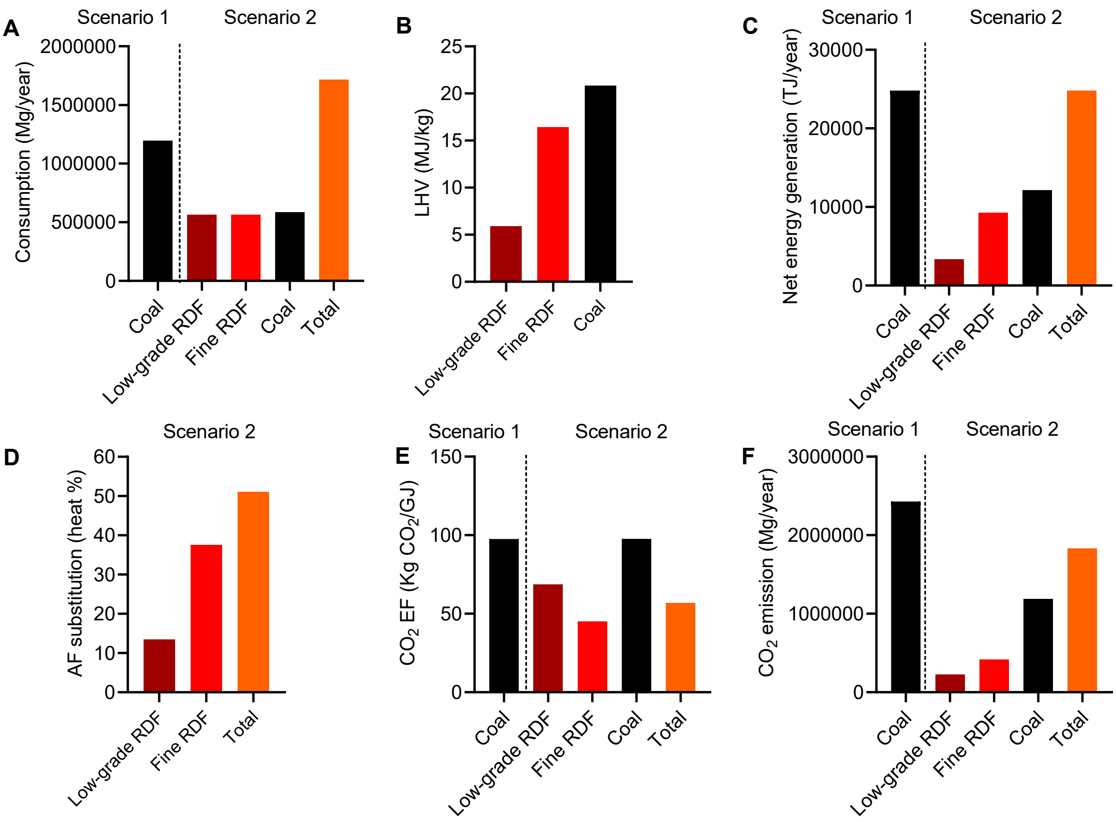

FIGURE 10: Energy and CO_2 emission of 100 % coal consumption (scenario 1) and 50% alternative fuel (AF) substitution using RDF (scenario 1). (A) Fuel consumption; (B) LHV of fuel; (C) Net energy generated by the fuel; (D) AF substitution of scenario 2; (E) CO_2 emission factor (EF); (F) CO_2 emission.

4. CONCLUSIONS

Low LHV and high MC of the MSW collected from Jabodebek underscore the need to further process MSW before RDF conversion, where the combustible material composition corresponds to RDF quality. The high MC also presented challenges in the mechanical treatment operations during the pilot project. Without the drying process in the pilot project, 1,000 Mg of MSW resulted in RDF with an LHV of 8.7 MJ/kg and MC of 47%, and low-grade RDF with an LHV of 3.0 MJ/kg and MC of 61%. Albeit the RDF output comply with the cement plant's specification, the output did not meet quality standards in Indonesia and other countries, indicating the need for additional intervention. Consequently, a drying process was implemented in the modeling stage.

The RDF plant production modeling involved pre-drying in the city and drying at the cement plant, utilizing excess hot gas from a plant producing 10,000 Tg of cement annually from 10 kilns. The drying process resulted in better RDF quality output than RDF produced in the pilot project. Processing 500 Mg/day of MSW yielded 119 Mg of fine RDF with 25% MC and an LHV of 16.4 MJ/kg, along with an equivalent amount of low-grade RDF with 42% MC and an LHV of 5.9 MJ/kg. CO_2 emission factors of RDF were lower than coal, which could contribute to reducing CO_2 emission. After a feasibility was conducted, achieving a minimum 50% substitution of AF at the cement plant would require 13 RDF plant units derived from 6,500 Mg/day of MSW. This setup would yield a 51% substitution rate, cut coal consumption by 610,000 Mg/year, and lower CO_2 emissions by 24%, totaling a reduction of 585,000 Mg/year. The adoption of RDF could significantly cut the daily MSW volume from the four regions by 6,500 Mg, potentially reducing the Jabodebek area's daily waste generation by up to 45%. Overall, the results highlight the potential of MSW-to-RDF conversion as a cross-sectoral solution for environmental performance and waste management issues.

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