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Characterization of Screened Municipal Solid Waste and Assessment of the Application Potential of Refuse-Derived Fuel for Coal Replacement in Vietnam

Minh Nguyen Thi Binh[1], Truong Do Xuan[2,*], Nga Dang Huyen[2], Minh Nguyen Thao[2], Son Le Thanh[3], Hung Nguyen Dinh[4], Anh Nguyen Nhat Dinh[4]

[1]*Hanoi University of Natural Resources and Environment, Ha Noi, Vietnam*
[2]*School of Chemistry and Life Sciences, Hanoi University of Science and Technology, Ha Noi, Vietnam*
[3]*Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, Ha Noi, Vietnam*
[4]*Hoabinh High Tech Environment Joint Stock Company, Phu Tho, Vietnam*
[*]*Corresponding author email: truong.doxuan@hust.edu.vn*

Abstract

Approximately 2 billion tonnes of municipal solid waste (MSW) are generated worldwide each year, posing significant environmental and waste management challenges. The study investigates the physicochemical characteristics, fuel properties, and energy-recovery potential of the oversized fraction of MSW (above 40 mm) for refuse-derived fuel (RDF) production. Without source separation, the screened fraction primarily consists of plastics, paper, textiles, and rubber, making it suitable for conversion into a secondary fuel. The screened MSW exhibited an average moisture content of 32.32 wt%, which can be substantially reduced through appropriate pretreatment, and a higher heating value (HHV) of 25.96 MJ/kg, indicating considerable energy-recovery potential. The average ash content was 22.97 wt%, while carbon and hydrogen contents ranged from 50–60 wt% and 6–8 wt%, respectively. The addition of black liquor can improve pellet binding, enabling pelletization at lower pressing temperatures and reducing electricity consumption, while CaO can promote reactions with sulfur and chlorine during combustion, potentially reducing the formation of toxic gaseous emissions. An economic assessment estimated annual savings of approximately USD 20.2 million from partial fossil-fuel substitution in a representative Vietnamese cement plant. Furthermore, 5% co-firing of RDF derived from screened MSW in Vietnam's coal-fired power plants could potentially reduce annual coal expenditures by approximately USD 225 million. Compared with conventional studies on MSW-derived RDF, this work provides an integrated assessment of fuel properties and practical energy-recovery potential. The findings demonstrate the significant potential of screened MSW for RDF production, fossil-fuel substitution, energy recovery, and sustainable waste management.

Keywords: Coal replacement, municipal solid waste, refuse-derived fuel, waste-to-energy.

1. Introduction

More than 2 billion tonnes of municipal solid waste (MSW) are generated worldwide each year [1]. Global MSW generation has increased rapidly, from 2.01 billion tonnes in 2016, and is projected to reach 2.59 billion tonnes by 2030 and 3.4–3.54 billion tonnes by 2050 [1]. MSW consists mainly of organic waste (44%), followed by paper and cardboard (17%), plastics (12%), glass (5%), metals (4%), rubber/leather (2%), wood (2%), and other materials (14%). Waste composition varies considerably with income level. In high-income countries, organic waste accounts for approximately 32% of MSW and recyclable materials for 51%, whereas in low- and middle-income countries, these fractions are approximately 53–56% and 15%, respectively. Despite the increasing potential for resource recovery, approximately 70% of collected MSW is still landfilled, while only 19% is recycled and 11% is incinerated for energy recovery [2]. A global review of 1,764 MSW-related projects implemented during 2014–2019 further indicated that waste-treatment capacity has not kept pace with the rapid growth in waste generation [3]. These trends highlight the urgent need for effective waste-management strategies that reduce landfill disposal while recovering energy and materials. In this context, converting the combustible fraction of MSW into refuse-derived fuel (RDF) pellets represents a promising approach that can simultaneously reduce waste volume, recover energy, mitigate environmental impacts, and create additional economic value. Reliable physicochemical characterization of MSW is therefore essential for evaluating its fuel potential and optimizing pellet production.

In Vietnam, approximately 24.5 million tonnes of MSW and 8.1 million tonnes of industrial solid waste are generated annually [4, 5]. Plastic waste and plastic packaging have become particularly serious environmental concerns. Vietnam generates

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approximately 2,500 tonnes of plastic waste per day, of which an estimated 0.28–0.73 million tonnes are discharged into the ocean annually [6]. According to the United Nations Environment Programme, Vietnam ranks among the world's leading contributors to marine plastic pollution [7]. The country has 112 coastal river mouths, and approximately 80% of marine plastic waste has been attributed to coastal areas, with household waste being a major source [6]. Spatially, the Southeast and Red River Delta regions have the highest MSW generation rates in Vietnam because of their large populations, intensive industrial and service activities, and high consumption levels [8]. Waste-related environmental pollution is further aggravated by limited source separation, inadequate treatment technologies, and constraints in financial and human resources. These challenges indicate the need for more effective and integrated approaches to MSW management and resource recovery.

The composition of Vietnamese MSW presents both significant challenges and opportunities for valorization. Organic waste accounts for 56.71% of the total MSW, followed by low-quality or non-recyclable plastics (19.49%), wet paper/diapers (8.03%), recyclable plastics (7.31%), paper/cardboard (3.72%), metals/cans (2.07%), glass (0.58%), other waste (2.07%), and hazardous waste (0.02%) [9]. The high proportion of organic matter creates substantial challenges for conventional treatment because of its high moisture content and biodegradability, but it also provides considerable potential for composting and energy recovery. Meanwhile, plastics and paper/cardboard contribute to the combustible fraction and can increase the energy content of RDF.

The addition of black liquor as an additive enhances the binding properties of pellets, thereby allowing pelletization at a lower pressing temperature and consequently reducing electricity consumption. Black liquor, a liquid waste from the alkaline cooking process in paper production containing dissolved lignin (30–45 wt%), hemicellulose, and inorganic chemicals, possesses a high heating value of 12–15 MJ/kg (dry basis). The addition of CaO promotes reactions with sulfur (S) and chlorine (Cl) in MSW, which can help reduce the emission of toxic gases during combustion. The effectiveness of these additives will be further evaluated in future studies.

Previous studies have demonstrated the fuel potential of MSW, with waste from Muscat, Oman, showing a heating value above 18 MJ/kg and volatile matter content of 47–82% [10]. However, high moisture content (21.5-43.3%), undesirable materials, and heterogeneous composition necessitate appropriate pretreatment, while the lack of standardized characterization procedures remains a challenge in Vietnam. Therefore, this study develops a pretreatment method for the screened MSW fraction, evaluates its potential for coal replacement in the cement industry and thermal power sector, and investigates the use of combustion ash as an adsorbent and construction-material additive, providing a basis for MSW-derived fuel pellet production and integrated waste-to-energy and material-recovery pathways. Beyond RDF production, MSW can be valorized through a wide range of technological pathways. Waste-to-energy incineration and microbial fuel cells have been increasingly investigated and applied for electricity generation [11]. Co-processing MSW in cement kilns and recovering its thermal energy for steam or district heating can reduce both coal consumption and the volume of waste requiring disposal [12]. Thermochemical gasification, including plasma gasification, can convert the carbonaceous fraction of waste at high temperatures (approximately 1,400-2,000 °C) under oxygen-deficient conditions into syngas containing CO, CH_4, and H_2 [13]. Plastics, rubber, and selected organic fractions can be converted into liquid fuels through pyrolysis, fermentation, and esterification, producing pyrolysis oil, bioalcohols, and biodiesel, respectively [14]. MSW can also be densified into fuel pellets or converted into hydrochar through hydrothermal carbonization [15]. In addition to energy recovery, MSW combustion residues may provide opportunities for material recovery. The concentrations of valuable metals in fly ash and bottom ash can exceed their corresponding concentrations in the Earth's crust, suggesting that MSW could potentially be regarded as an “urban mine” for secondary resource recovery [16].

Therefore, this study focuses on the pretreatment and physicochemical characterization of the screened fraction of Vietnamese MSW. The effects of sample preparation and screening on key fuel properties are evaluated, including moisture content, heating value, ash content, volatile matter, and elemental composition. Based on the measured characteristics, the potential applications of the screened waste as a feedstock for coal replacement in the cement industry and thermal power sector are assessed. The potential utilization of combustion ash as an adsorbent and construction-material additive is also investigated. The results provide a basis for selecting suitable additives for MSW-derived fuel pellets and for developing integrated waste-to-energy and material-recovery pathways that can reduce landfill disposal, minimize environmental impacts, and contribute to a circular economy.

2. Methodology

2.1. Feed preparation

MSW was collected from the Hoa Binh High-Tech Environmental Technology Joint Stock Company (CNC Hoa Binh) waste treatment plant in Phu Tho Province, Vietnam. The plant has a design capacity of approximately 500 t/d and employs an integrated treatment system comprising mechanical sorting, biological treatment, RDF production, waste incineration with heat recovery, and ash disposal. The

collected MSW mainly originates from urban and surrounding areas and is characterized by a high organic fraction, substantial inert contaminants, and limited source separation.

After reception, the waste undergoes preliminary mechanical sorting using conveyors, rotary screens, magnetic separators, air classifiers, and manual sorting. The screened fraction (above 40 mm), consisting mainly of plastics, textiles, rubber, paper, nylon, and other combustible materials together with inert contaminants such as soil, stones, and glass, was selected as the feedstock for this study because of its potential for RDF production. The raw feedstock had a moisture content of approximately 25–50 wt%. Before analysis, the samples were air-dried under sunlight for 2–3 days to reduce moisture and suppress microbial and fungal growth, thereby improving sample stability and the reliability of subsequent physicochemical characterization.

Fig. 1 summarizes the experimental workflow, including waste drying, manual sorting, weighing, size reduction, physicochemical characterization, and evaluation of the application potential of the screened MSW. After drying to achieve sufficient stability for subsequent processing, the waste was manually sorted into major material categories, including textiles, nylon, plastics, paper/cardboard, residual organic matter, and minor inorganic fractions. Each fraction was weighed separately and then manually cut into smaller pieces using scissors to obtain a relatively homogeneous feedstock for subsequent physicochemical analyses and application assessment.

2.2. Feedstock Characterization

Moisture content: The dried waste, with a moisture content of approximately 28%, was further analyzed for moisture content according to ISO 18134-1:2022 [17]. The moisture content (w) was calculated using (1):

$$w = \frac{\mathrm{m_i} - \mathrm{m_f}}{\mathrm{m_i}} \times 100 \ (\%) \quad (1)$$

where m_i is the mass of the waste before drying (g), and m_f is the mass of the waste after drying (g). The measurement was performed in triplicate, and the average value was used to improve accuracy and minimize random errors.

Higher heating value (HHV): HHV was determined using a bomb calorimeter following ISO 18125:2017 [18], which specifies the determination of gross calorific value at constant volume and 25 °C. After size reduction, the waste was slowly fed into a pelletizer via a screw conveyor to ensure controlled feeding and uniform mixing. Three RDF formulations were prepared: 100% screened MSW, screened MSW + 2% black liquor, and screened MSW + 2% CaO, with additives used to improve pellet binding and reduce combustion emissions. Composite samples were pelletized into cylindrical pellets (1 cm diameter × 0.5 cm height) and analyzed in pellet form due to their low bulk density. The measured heating values were compared with calculated values based on the heating values and proportions of individual components.

Ash content and composition analysis: After size reduction and pelletization, the RDF pellets were dried at 105 °C to constant mass and then ashed to determine the ash content according to ISO 18122:2022 [19]. The ash content was calculated using Eq. (2):

$$A_d = \frac{m_3 - m_1}{m_2 - m_1} \times 100 \times \frac{100}{100 - M_{ad}} \ (\%) \quad (2)$$

where m_1 is the mass of the pre-weighed crucible (g), m_2 is the mass of the crucible and sample before ashing (g), m_3 is the mass of the crucible and ash after ashing (g), A_d is the ash content on a dry basis (%), and M_{ad} is the analytical moisture content of the sample (%). The screened MSW and ash samples were analyzed using a Hitachi TM4000Plus SEM coupled with an Oxford EDS MICSF+/X-STREAM2 detector to determine major elements (C, H, O, S, and P), trace elements (Si, Ca, Mg, and Cl), and heavy metals (Pb, Cd, and Zn).

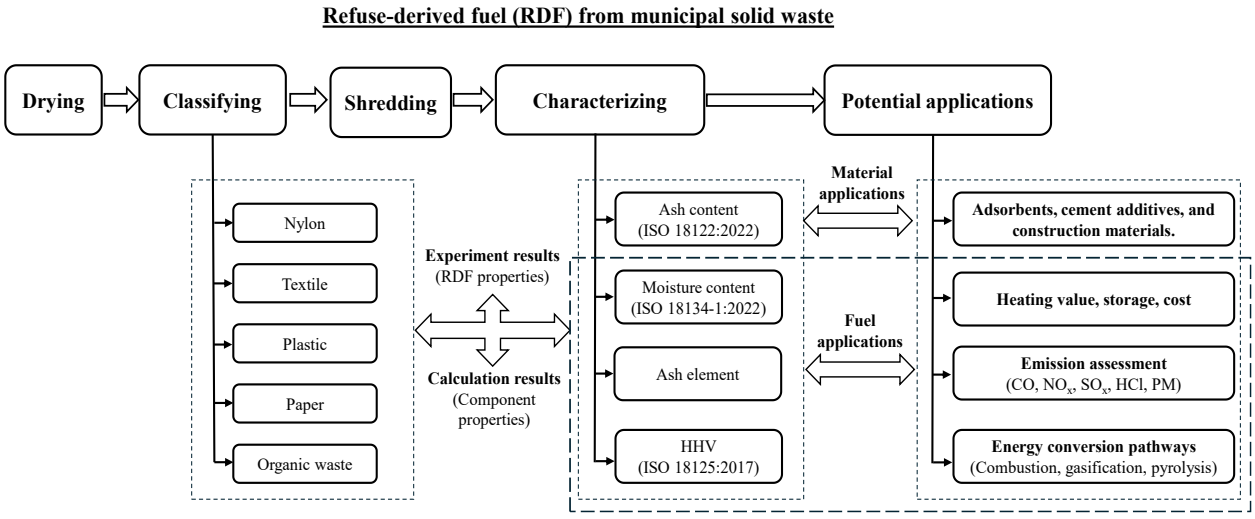


Fig. 1. Workflow for determining the properties and application potential of screened MSW

2.3. Application Potential of Screened MSW

The potential assessment model for screened MSW was developed based on actual operating data from a representative Vietnamese cement plant in 2025, combined with technical norms reported in studies of the Vietnamese cement industry. The plant produced 1.52 million tonnes of cement and 1.32 million tonnes of clinker in 2025 [20]. Coal consumption was 0.133 t/t clinker for clinker production and 0.164 t/t cement for cement production [21], corresponding to an estimated total coal consumption of approximately 427,000 t/y. Clay accounted for 15-20% of the raw meal for clinker production, equivalent to approximately 385,000–513,000 t/y.

The thermal substitution rate (*TSR*) was used to evaluate the potential replacement of coal by screened MSW. The amount of coal saved was calculated using (3):

$$M_{\text{coal_saved}} = M_{\text{coal_base}} \times TSR \quad (3)$$

where $M_{\text{coal_saved}}$ is the annual amount of coal saved (t/y) and $M_{\text{coal_base}}$ is the baseline annual coal consumption (t/y). The corresponding substituted thermal energy was calculated using following equation:

$$Q_{\text{sub}} = M_{\text{coal_saved}} \times HHV_{\text{coal}} \quad (4)$$

where Q_{sub} is the substituted thermal energy (GJ/y), and HHV_{coal} is the higher heating value of coal (GJ/t). The required MSW feedstock was then determined by as follow:

$$M_{\text{MSW}} = Q_{\text{sub}}/HHV_{\text{MSW}} \quad (5)$$

The amount of ash generated from MSW combustion and potentially replacing clay in the raw meal was estimated as follow:

$$M_{\text{ash_clay}} = M_{\text{MSW}} \times A_{\text{MSW}} = M_{\text{MSW}} \times 22.97\% \quad (6)$$

The economic assessment considered three benefits: coal cost savings, waste-treatment revenue, and clay cost savings from MSW ash utilization. Coal, waste-treatment, and clay costs were assumed at \$85/t, \$19.2-42.3/t, and \$29.9-38.8/t, respectively.

The annual coal cost saving was calculated using following equation:

$$S_{\text{coal}} = M_{\text{coal_saved}} \times 85 \quad (7)$$

The annual revenue from waste-treatment fees was calculated using following equation:

$$R_{\text{gate}} = M_{\text{MSW}} \times C_{\text{gate}} \quad (8)$$

The annual clay cost saving was calculated using following equation:

$$S_{\text{clay}} = M_{\text{ash_clay}} \times C_{\text{clay_unit}} \quad (9)$$

Finally, the total annual economic benefit was calculated using (10):

$$\Delta OPEX = S_{\text{coal}} + R_{\text{gate}} + S_{\text{clay}} \quad (10)$$

3. Results and Discusion

3.1. Result of Feedstock Characterization

The moisture content of the screened MSW is presented in Table 1. The total sample mass was 26.00 kg, comprising 17.60 kg of dry matter and 8.40 kg of water, corresponding to an overall moisture content of 32.32 ± 0.05%. The reported uncertainty was determined from three replicate measurements. This relatively high residual moisture content is consistent with previous findings that high moisture is a major challenge for waste-to-energy conversion, particularly in developing countries [2]. Importantly, the moisture content was measured after natural air-drying, representing a common preliminary treatment practice at waste-processing facilities. Thus, the measured value reflects the residual moisture after primary drying rather than the original moisture content of freshly collected waste. This parameter is particularly relevant to RDF production and combustion because it indicates whether further drying, blending, or process adjustment is required. Under Vietnamese conditions, where solar drying can reduce pretreatment costs compared with industrial drying, the post-drying moisture content provides a practical basis for designing and operating RDF production systems.

As shown in Table 1, moisture contents of the individual waste fractions ranged from 31.43 ± 0.08% for plastic to 35.71 ± 0.10% for paper. Paper exhibited the highest moisture content, which can be attributed to the porous cellulose structure and abundant hydroxyl groups that facilitate hydrogen bonding with water.

Table 1. Results of moisture content of screened MSW

Waste component	Wet mass (kg)	Dried mass (kg)	Water mass (kg)	Moisture content (wt%)
Nylon	8.11	5.50	2.61	32.18 ± 0.09
Textile	4.47	3.04	1.43	31.99 ± 0.09
plastic	2.80	1.92	0.88	31.43 ± 0.08
Paper	0.28	0.18	0.10	35.71 ± 0.10
Organic waste	10.34	6.96	3.38	32.69 ± 0.12
Total	26.00	17.60	8.40	32.32 ± 0.05

In contrast, plastic showed the lowest moisture content because polymers such as polyethylene and polypropylene are hydrophobic and have non-polar surfaces, resulting in limited water absorption. The relatively small variation among the fractions also indicates that, even after natural drying, substantial moisture remains in the screened MSW, which may influence its energy content and pelletization performance. Further drying could reduce the moisture content and improve the fuel quality; however, it would also increase the energy consumption of the pretreatment process. During pelletization, the heat generated by pressing may further reduce the moisture content, suggesting that excessive pre-drying may not be necessary.

The HHV of the screened MSW is presented in Table 2. The mixed waste exhibited a relatively high average heating value of 26.42 MJ/kg, which exceeds the reported global range of 3–17 MJ/kg for MSW [22]. This high heating value can be attributed to the predominance of combustible fractions, particularly nylon and plastics, which were the main contributors to the energy content, along with textiles and paper. Although nylon accounted for only 31.25 wt%, its HHV of 43.2 MJ/kg contributed 13.50 MJ/kg (51.1%) of the total, while plastic contributed a further 4.35 MJ/kg (16.5%). Thus, these two polymer fractions accounted for approximately 67.6% of the total HHV, confirming the dominant role of polymeric materials in the energy potential of MSW. In contrast, the largest mass fraction (39.55%) had a relatively low heating value of 16.1 MJ/kg, contributing only 24.1% of the total energy, likely because of its high content of soil, minerals, and degraded organic matter.

Table 2. Results of heating value screened MSW

Waste component	**Dried mass (kg)**	**Weight fraction (%)**	**HHV (MJ/kg)**
Nylon	5.50	31.25	43.2
Textile	3.04	17.27	16.6
plastic	1.92	10.90	39.9
Paper	0.18	1.02	12.1
Organic waste	6.96	39.55	16.1
Total[1]	17.60	100	26.42
Exp. HHV[2]			25.96

[1]Calculation based on the HHV of each waste component

[2]Determined by experiment of screened MSW

The experimentally measured heating value of the untreated mixed waste was 25.96 MJ/kg, closely matching the calculated value and differing by less than 2%, demonstrating the reliability of the mass-fraction-based estimation method. The HHV also exceeded the 16 MJ/kg threshold commonly associated with RDF Class 3 under CEN/TS 15359, indicating strong potential for RDF production and waste-to-energy applications. However, excessive addition of inorganic additives such as quicklime may reduce the heating value; therefore, additive dosage should be optimized to balance fuel quality with emission control and ash stabilization.

Table 3 presents the effects of 2% CaO and black liquor addition on the HHV and ash content of screened MSW. The screened MSW had an ash content of 22.97 ± 0.18 wt%, comparable to the 22.9 ± 5.8 wt% reported for MSW-derived material [23]. The addition of CaO decreased the HHV from 25.96 to 22.14 MJ/kg, whereas black liquor increased it to 26.99 MJ/kg. Meanwhile, the ash content increased from 22.97% to 26.76% and 25.96% with CaO and black liquor addition, respectively. Overall, black liquor showed a more favorable effect on the fuel properties of screened MSW. The effects of black liquor on pellet strength and CaO on emission reduction, as demonstrated in our previous studies [24, 25] are expected to be applicable to MSW-derived RDF, but will be experimentally verified in future laboratory- and industrial-scale combustion tests.

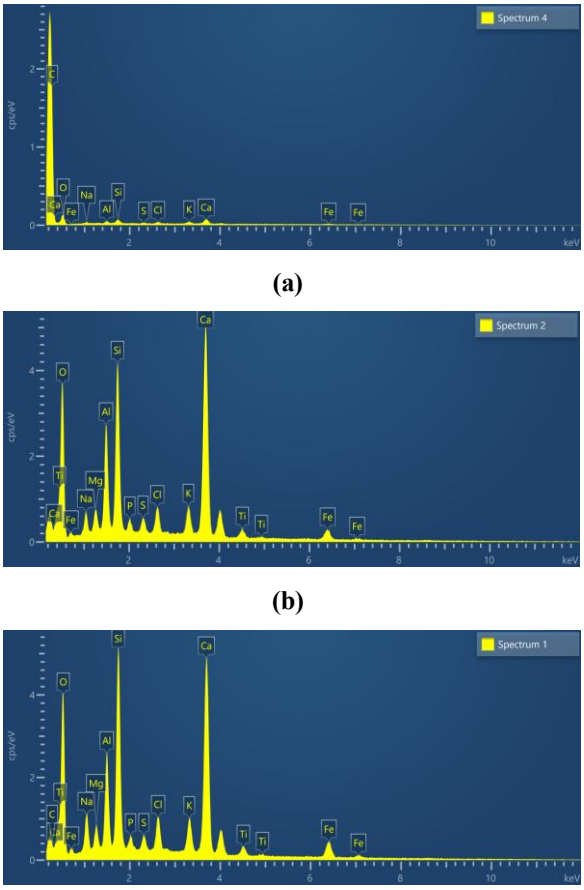
Table 3. HHV and ash content of screened MSW, MSW + CaO 2%, and MSW + Black liquor 2%

Sample	**HHV (MJ/kg)**	**Ash content (%)**
MSW	25.96	22.97
MSW + CaO 2%	22.14	26.76
MSW + Black liquor 2%	26.99	25.96

Table 4. Major elemental composition of screened MSW and oxide composition of ash on a dry basis

Element	**Composition** (wt%)
Carbon (C)	50 – 60
Hydrogen (H)	6 – 8
Oxygen (O)	25 – 35
Nitrogen (N)	0.3 – 1
Sulfur (S)	0.1 – 0.3
	Ash
Oxide	Composition (wt%)
CaO	15 – 30
SiO_2	20 – 35
Al_2O_3	5 – 15
Fe_2O_3	3 – 10
MgO	2 – 6
K_2O	1 – 5
Na_2O	0.5 – 3

The major elemental composition of the screened MSW and the oxide composition of its ash are presented in Table 4. The corresponding energy-dispersive X-ray (EDX) spectra are shown in Fig. 2, including screened MSW (Fig. 2a), screened MSW with 2 wt% black liquor (Fig. 2b), and screened MSW with 2 wt% CaO (Fig. 2c). The screened MSW contained approximately 50- 60 wt% carbon on a dry basis, substantially higher than the 27.4–32.4 wt% on a wet basis reported for MSW in Hung Yen, Vietnam [26].



(a)

(b)

(c)

Fig. 2. EDX analysis results of ash from screened MSW: (a) screened MSW; (b) screened MSW with 2 wt% black liquor; and (c) screened MSW with 2 wt% CaO

The higher carbon content is mainly attributed to the relatively large fractions of carbon-rich and energy-dense materials, particularly plastics, paper, and rubber [27]. Combined with 6–8 wt% hydrogen, the high carbon content contributes to the high heating value and supports the potential use of screened MSW as a solid fuel [26, 27]. The oxygen content of 25–35 wt% is mainly associated with cellulose and other oxygen-containing polymers [27]. Meanwhile, the relatively low nitrogen and sulfur contents, consistent with previous studies in Hung Yen, are favorable for limiting harmful emissions and corrosion during combustion.

The major ash oxides included CaO, SiO_2, Al_2O_3, Fe_2O_3, and MgO, with their proportions depending on the inorganic materials present in the waste. The Al_2O_3 content (5–15 wt%) was also within the range reported in previous studies (4.97–14.18 wt%), while the Fe_2O_3 content (3–10 wt%) was comparable to the value reported for Singapore (3.82 wt%) [28]. These results indicate that the ash contains substantial mineral components that may influence combustion behavior and provide potential for subsequent material utilization.

3.2. Application Potential of Screened municipal solid waste

As shown in Fig. 3, the HHV of screened MSW is lower than those of conventional fossil fuels such as coal and oil but remains substantially higher than the typical heating value of wood pellets. This indicates its potential for use as a fuel for energy recovery. Unlike non-renewable fossil resources, which are gradually being depleted, the supply of MSW is virtually continuous and tends to increase with population growth and human activities. Therefore, converting MSW into fuel could not only reduce the pressure on Vietnam's waste-management infrastructure, which still relies heavily on landfilling, but also recover energy from waste and reduce dependence on conventional fuels at potentially lower cost.

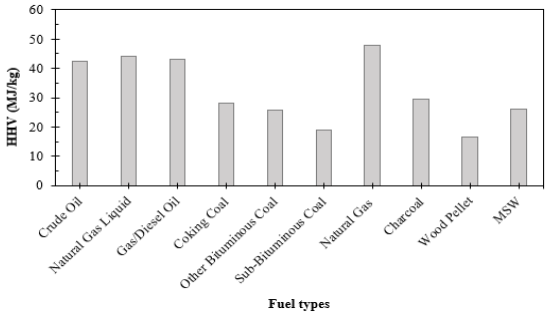


Fig. 3. HHV comparison of screened MSW and conventional fuels

The key properties of the screened MSW were HHV of 25.96 MJ/kg and an ash content (A_d) of 22.97%. Based on practical conditions in Vietnam, three TSR scenarios were considered: 15%, corresponding to the national target; 25%, based on the substitution rate reported for But Son Cement; and 35%, based on the rate reported for Thanh Cong Cement. Because the mineral compositions of clay and MSW ash are relatively similar, 100% of the generated MSW ash was assumed to replace clay as a raw material for clinker production. These economic estimates are subject to uncertainty because actual coal substitution rates and MSW ash utilization as a clay replacement may vary with plant operation, ash composition, and technical requirements.

As shown in Table 5, using screened MSW to partially replace coal in cement production could generate an annual economic benefit ranging from $M 7.1 under the

conservative scenario to $M 20.2 under the optimal scenario.

The optimal co-firing ratio compatible with the existing infrastructure and technologies of thermal power plants in Vietnam is approximately 5% [29], practical considerations include RDF handling and feeding, combustion compatibility with coal, and potential changes in gaseous emissions and ash characteristics. Vietnam consumes more than 90 million tonnes of coal annually, including approximately 60 million tonnes for thermal power generation, 10 million tonnes for cement production, and 10 million tonnes for steel production, with the remainder used in other industries such as fertilizer production. The potential of screened MSW for thermal power generation was evaluated in Table 6. Under a 5% co-firing scenario across Vietnam's thermal power plants, EVN could save more than $ 225 million annually in coal procurement costs.

Table 5. Economic potential of screened MSW in the cement industry

List	**Unit**	**Scenario 1 (15%)**	**Scenario 2 (25%)**	**Scenario 3 (35%)**
Coal reduction	t/y	64,072	106,787	149,502
Total heat replaced	GJ/y	1,608,476	2,680,793	3,753,111
Amount of screened MSW replacing coal	t/y	61,959	103,266	144,572
Economic benefit				
Coal purchasing cost savings (S_{coal})	$M/y	5.45	9.08	12.71
Waste treatment fee revenue (R_{gate})				
$R_{gate, min}$	$M/y	1.19	1.99	2.78
$R_{gate, max}$	$M/y	2.62	4.37	6.12
Clay cost savings (S_{clay})				
$S_{clay, max}$	$M/y	0.57	0.95	1.32
$S_{clay, min}$	$M/y	0.43	0.71	0.99
Total potential economic benefit				
Conservative scenario ($R_{gate, min} + S_{clay, min}$)	$M/y	7.07	11.78	16.49
Optimal scenario ($R_{gate, max} + S_{clay, max}$)	$M/y	8.64	14.40	20.15

Table 6. Economic potential of screened MSW in the thermal power sector

Annual coal consumption	Million t/y	60.00
Coal heating value	GJ/t	25.10
Replacement ratio	%	5.00
RDF heating value	GJ/t	25.90
RDF replacing	Mt/y	2.9
Coal saving	Mt/y	3.0
Coal price	$/t	115
Cost for RDF processing	$M/t	40
Economic potential	$M/y	225

4. Conclusion

This study established a systematic approach for characterizing the physicochemical properties of screened MSW for energy recovery applications. The average moisture content was 32.3%, exceeding the recommended limit for direct combustion and indicating the need for pretreatment. The ash content was 22.97 wt%; although additives increased the ash content of the pellets, they were essential for improving pellet durability and reducing combustion emissions. The screened waste exhibited a high average HHV (25.96 MJ/kg), mainly due to its high polymer content. Black liquor further enhanced the heating value, whereas quicklime caused a slight reduction. The high carbon and hydrogen contents confirm the suitability of screened waste as an alternative solid fuel, while appropriate flue gas treatment is recommended to control sulfur emissions during combustion. The economic analysis demonstrated the strong industrial potential of screened waste-derived RDF, with annual economic benefits of approximately $M 20.2 in the

cement industry and over $M 225 in reduced coal costs through nationwide co-firing in coal-fired power plants.

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References

[1] A. M. Yatoo, B. Hamid, T. A. Sheikh, S. Ali, S. A. Bhat, S. Ramola, M. N. Ali, Z. A. Baba, and S. Kumar, Global perspective of municipal solid waste and landfill leachate: generation, composition, eco-toxicity, and sustainable management strategies, Environmental Science and Pollution Research, vol. 31, no. 16, pp. 23363–23392, Apr. 2024. https://doi.org/10.1007/s11356-024-32669-4

[2] A. Kumar, E. Singh, R. Mishra, S. L. Lo, and S. Kumar, Global trends in municipal solid waste treatment technologies through the lens of sustainable energy development opportunity, Energy, vol. 275, Jul. 2023, Art. no. 127471. https://doi.org/10.1016/j.energy.2023.127471

[3] A. Maalouf, A. Mavropoulos, and M. El-Fadel, Global municipal solid waste infrastructure: Delivery and forecast of uncontrolled disposal, Waste Management and Research, vol. 38, pp. 1028–1036, Sep. 2020. https://doi.org/10.1177/0734242X20935170

[4] V. E. Agency, National environmental status report 2023, 2023.

[5] D. X. Truong, Investigation of the status and the prospect of fuel pellet production and utilisation toward net zero emissions by 2050 in Vietnam, Vietnam Journal of Science, Technology and Engineering, vol. 66, no. 4, pp. 113–124, Dec. 2024. https://doi.org/10.31276/VJSTE.2024.0002

[6] United Nations Environment Programme (UNEP), From pollution to solution: A global assessment of marine litter and plastic pollution, Environment Programme, Nairobi, Kenya, May 2021.

[7] United Nations Environment Programme (UNEP), Single-Use Plastics: A Roadmap for Sustainability, Gigiri, Nairobi, Kenya, 2018.

[8] Intergovernmental Panel on Climate Change, Climate change 2021: Mitigation of climate change, Geneva: Switzerland, 2021.

[9] Ministry of Natural Resources and Environment, National environmental status report 2020: Household solid waste management, 2020.

[10] T. Etri, O. Al Samsami, and M. Baawain, Characterization of landfills solid waste in muscat and estimation of their energy recovery, Environmental Science and Pollution Research, vol. 30, no. 47, pp. 104901–104915, Sep. 2023. https://doi.org/10.21203/rs.3.rs-1948005/v1

[11] W. -T. Tsai and K. -C. Kuo, An analysis of power generation from municipal solid waste (MSW) incineration plants in Taiwan, Energy, vol. 35, pp. 4824–30, Dec. 2010. http://doi.org/10.1016/j.energy.2010.09.005

[12] A. B. Trindade, J. C. E. Palacio, A. M. González, D. J. R. Orozco, E. E. S. Lora, M. L. G. Renó, and O. A. d. Olmo, Advanced exergy analysis and environmental assesment of the steam cycle of an incineration system of municipal solid waste with energy recovery, Energy Conversion and Management, vol. 157, pp. 195–214, Feb. 2018. https://doi.org/10.1016/j.enconman.2017.11.083

[13] U. Arena, Process and technological aspects of municipal solid waste gasification: A review, Waste Management, vol. 32, no. 4, pp. 625–639, Apr. 2012. http://doi.org/10.1016/j.wasman.2011.09.025

[14] S. Jamilatun, J. Pitoyo, S. Amelia, A. Ma'arif, D. C. Hakika, I. Mufandi, Experimental study on the characterization of pyrolysis products from bagasse (Saccharum officinarum L.): Bio-oil, biochar, and gas products, Indonesian Journal of Science and Technology, vol. 7, pp. 565–82, 2022. https://doi.org/10.17509/ijost.v7i3.51566

[15] T. R. Sarker, M. L. Khatun, D. Z. Ethen, M. R. Ali, M. S. Islam, S. Chowdhury, K. S. Rahman, N. S. Sayem, and R. S. Akm, Recent evolution in thermochemical transformation of municipal solid wastes to alternate fuels, Heliyon, vol. 10, no. 17, 2024, Art. no. e37105. https://doi.org/10.1016/j.heliyon.2024.e37105

[16] T. T. T. Nguyen, T. X. Vuong, T. T. H. Pham, A. Q. Hoang, M. B. Tu, and T. H. Nguyen, Comprehensive assessment of precious metal concentration, distribution, and recovery potential in municipal solid waste incineration residues from northern Vietnam. RSC Advances, vol. 16, no. 4, pp. 2937–2957, 2026. https://doi.org/10.1039/D5RA08421K

[17] ISO, ISO 18134-1:2022, Solid biofuels - Determination of moisture content, 2022. [Online]. Available: https://www.iso.org/obp/ui/en/#iso:std:83191:en

[18] ISO, ISO 18125:2017 Solid biofuels - Determination of calorific value. [Online]. Available: https://www.iso.org/standard/61517.html

[19] ISO, ISO 18122:2022, Solid biofuels - Determination of ash content. [Online]. Available: https://www.iso.org/standard/83190.html

[20] VICEM Hoang Mai Cement Joint Stock Company, Annual Report 2025, Nghe An, Vietnam, 2025.

[21] L. D. Long, C. T. T. Mai, T. T. Cham, Current status of production, resource consumption, and potential for resource conservation, waste reuse, and circular economy implementation in Vietnam Cement Industry, Journal of Material and Construction, vol. 15, 2025. https://doi.org/10.54772/jomc.02.2025.859

[22] Y. Ding, J. Zhao, J.-W. Liu, J. Zhou, L. Cheng, J. Zhao, Z. Shao, Ç. Iris, B. Pan, X. Li, and Z.-T. Hu, A review of China's municipal solid waste (MSW) and comparison with international regions: Management and technologies in treatment and resource utilization, Journal of Cleaner Production, vol. 293, 2021. https://doi.org/10.1016/j.jclepro.2021.126144

[23] N. Soobhany, Assessing the physicochemical properties and quality parameters during composting of different organic constituents of municipal solid waste, Journal of Environmental Chemical Engineering, vol. 6, pp. 1979–1988, 2018. https://doi.org/10.1016/j.jece.2018.02.049

[24] T. X. Do, P. Q. Nguyen, N. H. Dang, and M. T. Nguyen, Effect of additives on the reduction of gas and particulate emissions from rice straw pellet fuel: Experimental study and modeling, Sustainable Energy Technologies and Assessments, vol. 83, 2025, Art. no.104624. https://doi.org/10.1016/j.seta.2025.104624

[25] T. X. Do, K. T. Tran, A. T. Vu, T. D. S. Van, S. T. Le, and P. Q. Nguyen, Effects of pelletizing conditions and additives on properties of rice straw fuel pellets and ash characteristics, Biomass Conversion and Biorefinery, vol. 15, pp. 16971–16985, 2025. https://doi.org/10.1007/s13399-025-06566-w

[26] B. V. A. Pham, T. T. Trinh, T. T. Trinh, and T. M. Vu, Analysis of physicochemical characteristics of municipal solid waste in Hung Yen city, Vietnam Journal of Science and Technology - MOST 66, vol. 66, no. 10, pp. 83–88, 2022. https://doi.org/10.31276/VJST.66(10).83-88

[27] T. Wang, Y. Zhai, Y. Zhu, C. Li, and G. Zeng, A review of the hydrothermal carbonization of biomass waste for hydrochar formation: Process conditions, fundamentals, and physicochemical properties, Renewable and Sustainable Energy Reviews vol. 90, pp. 223–247, 2018. https://doi.org/10.1016/j.rser.2018.03.071

[28] A. Zhou, Z. Hu, M. B. Ahmad, Z. Zhang, W. Yu , Y. Zhu, J. Li, X. Wang, and H. Tan, Ash fusion and migration characteristics of municipal solid waste and sewage sludge co-fring in power plants, Journal of the Energy Institute, vol. 125, Apr. 2026. https://doi.org/10.1016/j.joei.2025.102430

[29] Ha Truong, Hoang Anh Tran, M. Ha-Duong, Cost-benefit analysis of biomass co-firing with coal: The case of Ninh Binh Thermal Power Plant, HAL open science, 2016.