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Research article

Investigation of moisture content and higher heating value in refuse-derived fuel from agricultural residues using statistical modelling

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Abstract: There is an increasing interest in using agricultural residues and wastes for energy production due to concerns regarding climate change and energy security issues. One of the alternative fuels considered is Refuse-derived fuel (RDF) from biomass, which has a Higher Heating Value (HHV) comparable to coal. This study aims to investigate the relationship between the moisture content and the HHV value. Palm kernel shells (PKS), coconut husks (CH), and coconut shells (CS) were blended at various ratios (10%–80%) and moisture levels (5%, 7%, 10%). The HHV was analyzed through a proximate analysis, with JMP Pro 17.0 modelling the HHV against the moisture content. Then, the Tukey-Kramer analysis identified the optimal energy ratio, thus providing insights into maximizing the RDF efficiency. The result showed that the highest HHV was 21.617 MJ/kg with the RDF2 formulation. Notably, the RDF2 energy content was less than 4% of that of coal, thus demonstrating the potential of utilizing agricultural waste to produce solid fuel with a positive environmental impact.

Keywords: agricultural residues; refuse-derived fuel (RDF); proximate analysis; higher heating value (HHV); energy security

1. Introduction

The energy demand has been increasing over the years due to various factors such as population growth, economic development, and technological advancements [1]. Electricity is a form of energy generated from primary sources of energy, such as coal, natural gas, and nuclear, and renewable sources, such as wind, solar, and hydropower. In Malaysia, electricity is commonly derived from non-renewable resources, with 88.4% coming from conventional fossil fuels, primarily coal, and is followed by natural gas [2]. There has been an increase in the global usage of coal for electricity production from 2020 to 2022, where it led to a sharp rise from 6% to 42% in 2022 [3]. Between these two years, the average proportion of electricity generated was almost 43.55%. The reduction in electricity generation, which amounted to a 2.7% decrease, was attributed to transformations in the hydropower approach [4]. An increased demand for electricity leads to higher coal costs, making it more expensive to generate electricity. According to Malaysiakini News, Malaysia heavily relies on imported coal, with Indonesia being the largest supplier at 63%, followed by Australia at 24%, Russia at 11%, and South Africa at 2% [5]. According to Tenaga National Berhad (TNB), an increase in the price of coal can result in higher surcharge rates for customers through the Imbalance Cost Pass-Through (ICPT) surcharge. Recently, increases in the global coal prices have dramatically raised the electricity generation costs by 45 percent in the peninsular Malaysia [6]. Although the government approved the increase in electricity tariffs through the ICPT surcharge, the actual impact on TNB's income is still unclear. As the price of imported coal is unstable, it can pressure the TNB's profit margin. TNB's earnings could face a downward pressure if the fuel cost parameters provided in the ICPT rate adjustment formula were raised without the corresponding increases to the base tariff rates.

Coal makes up 59% of the country's generation capacity and affects the tariff rates [7]. Additionally, a reliance on imported coal exposes it to global market price shifts, as a recent statement highlighted that the war in Ukraine has affected the global markets by driving up coal prices. To reduce the dependence on coal, transitioning to renewable energy can enhance the energy justice, stabilize prices, and advance the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) [8] . Beyond this, the challenges in using renewable energy have highlighted the need for robust energy infrastructure and improved financial frameworks. For instance, India's large-scale solar energy projects showcase the potential to mitigate the effects of global energy market fluctuations while promoting greener energy sources [9,10]. On the other hand, the combustion of coal in power plants will generate greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases cause the greenhouse effect, thereby trapping heat in the atmosphere and causing global warming and climate change. In 2022, it was reported that Malaysia emitted at least 291.07 million tons of CO_2 gas from fossil fuel sources, thus indicating an increase of 4% compared to the previous year [11]. Alternatively, coal can be substituted with renewable energy sources that would reduce the dependence on imported coal over the long term. Previous studies have shown that Refuse Derived Fuel (RDF) from biomass is a potential solution to reduce the coal dependency due to its similar energy content [12]. This approach has gained attention for its environmental benefits, thereby providing a sustainable way to convert waste into solid fuel, known as RDF, for use in large power plants or the production of liquid fuel for cogeneration systems. This study focuses on increasing the thermal energy of fuel and enhancing its efficiency, thereby optimizing the energy use in the production of RDF in the pellet form [13].

Reportedly, more than 70% of the global agricultural waste is produced each year [14]. In Malaysia, 1.2 million tons of agricultural waste is dumped in landfills annually. Moreover, approximately 15% of Asia's total waste consists of agricultural waste [15]. In 2009, Malaysia generated approximately 0.122 kg of agricultural waste per capita per day, with projections indicating an increase to 0.210 kg per capita per day by 2025 [16]. According to studies by Kaniapan et al., palm kernel shells (PKS) exhibit the highest Heating Value (HHV) at 20.73 MJ/kg, followed by coconut shells (CS) at 20.53 MJ/kg, and empty fruit bunches (EFB) at 16.98 MJ/kg, with variations depending on the moisture content [17]. In addition, previous studies have indicated that CS contain 57.00% volatile matter (VM) and 19.20% fixed carbon (FC), with an energy value of 16.70 MJ/kg. Research on VM and ash of CS and PKS were calculated at around 71.80% and 5.80% and 73.87% and 6.28%, respectively [18]. The HHVs were 19.73 MJ/kg for CS and 18.52 MJ/kg for PKS. Several investigations in the past aimed at finding methods to calculate the HHV. The proximate analysis was utilized to obtain the fuel's qualities by knowing the amount of moisture, ash, and combustible to carry out the calculations [19]. The HHV amounts can be determined using the known proximate analysis data without the need for the calorimetric approach [20]. There are several equations when determining the HHV, as shown in Table 1.

According to the studies, important factors including the moisture and ash content determine the quality of the RDFs. In energy recovery plants, a moisture level of less than 15 weight percent is ideal for an efficient operation. An advantage for waste management and the environment is that ash in the range of 0.49 to 12.58% may contain trace amounts of salts, heavy metals, chloride, and organic pollutants [21]. It was suggested that a high ash content reduces the fuel quality, while a greater amount of fixed carbon and volatiles improve fuel properties. In summary, feedstocks with low amounts of ash and high amounts of carbon and volatiles are preferred for optimal combustion and energy recovery [22]. Previous studies have highlighted the importance of developing effective strategies for the energy conversion of agricultural products, thereby identifying that olive mill effluent (OME) can be converted into a low-cost solid biofuel, thus providing a viable alternative for energy production with an energy value of approximately 5600–5700 kJ/kg [23]. On the other hand, transforming agricultural waste into RDF presents an innovative approach to waste management that offers an exciting opportunity to generate sustainable energy [24]. However, there is a lack of studies on mixed agricultural residues (Ag-residue) in producing RDF. Therefore, this study aims to investigate the relationship between the moisture content and the HHV value for RDF. The HHV value will be evaluated using a proximate analysis and by identifying the best RDF blending using the HSD Tukey-Kramer post hoc test for a reliable statistical comparison. In addition, this study will develop a statistical prediction model to estimate the HHV values based on the fit model statistical modeling approach.

2. Materials and methods

2.1. Material

Figure 1 shows the procedure of the RDF production. The Ag-Residue used in this study are CS, CH, and PKS. These Ag-Residues were collected from local palm coconut shops and plants near Gambang, Pahang, Malaysia.

The Ag-Residues were dried in a hot-air oven at 105 °C for 24 hours to reduce the moisture content. Then, the samples were crushed into very small particles using IKA Multidrive Milling (MI 250 Multidrive Basic). A tap sieve shaker with 4.0 mm mesh sieves was utilized to obtain the powder particles for easier mixing. The procedure outlined in ANSI/ASAE S319.4 Standard was followed for the particle size distribution. The RDF composition involves blending PKS, CH, and CS in specific ratios ranging from 10% to 80%, with moisture contents of 5%, 7% and 10%.

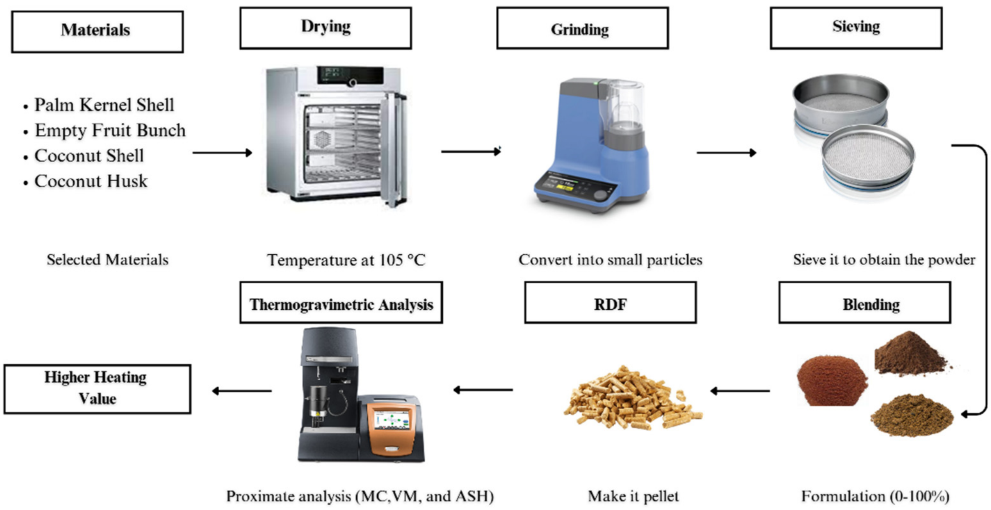

Figure 1. RDF production procedure.

2.2. Methodology

In this analysis, a Thermalgravimetric Analyzer (TGA) (Hitachi / STA7000 Model) was employed to analyze the RDF that was thermally treated from an ambient temperature to a set temperature of 900 °C in an air environment with an airflow rate of 20 mL/min. Furthermore, the effect of the heating rates on the sample was investigated at 20 C/min, with weight samples in the range of 8–10 mg. This study conducted a TGA-based proximate analysis of the RDF using the American Society for Testing and Materials (ASTM) Standard D5142 [25]. Several factors, including moisture content (MC), ash, fixed carbon (FC) and volatile matter (VM) contents were determined. The respective value was calculated as percentages of the total weight using standard testing procedures. A temperature range of 25–107 °C was selected to determine the MC by analyzing thermogravimetric (TG) and differential TG (DTG) graphs. The samples were held at this temperature for 120 min without air exposure. The VM was measured from 107 to 950 °C, rapidly heated to 950 °C at 30 °C/min, and then held for 7 min. Then, the RDF was cooled to 600 °C in air. Ash was found by steadily heating the samples to 815 °C at 3.6 °C per minute and holding for 150 minutes. The FC was calculated by subtracting the sums of the MC, VM, and Ash percentages from 100% total [26].

The HHV (MJ/kg) value was determined based on the guidelines outlined in ASTM D7582-15 by the American Society for Testing and Materials. Table 1 presents the equation used to determine the experimental HHV value for the RDF based on previous studies.

Table 1. Equation of experimental HHV value.

HHV value model	References
HHV1 = 0.312FC + 0.1534VM	[26]
HHV2 = 0.3543FC + 0.1708VM	[27]
HHV3 = 0.1905VM + 0.2521FC	[28]
HHV4 = 19.914 − 0.2324 Ash	[29]

The HHV test was performed using JMP Pro 17.0 (SAS Corporation, USA). The statistical analysis worked on the null hypothesis (P-value < 0.05) by first stating that each parameter and the associated interaction had no significant effect on the HHV of the RDF samples. A correlation test was conducted by primarily finding out the relationship between the two variables of observations as the HHV and the MC of the RDF sample production. The correlation coefficient ranged from +1 to −1. Additionally, a full factorial design was used to evaluate the influence of the variables MC, VM, ASH, and FC. The HHV was based on the estimate parameters of a linear model using the method of least squares. An HSD Tukey's analysis was used to evaluate significant differences between the group means and to indicate the HHV of RDF. It is typically performed after a one-way analysis of variance (ANOVA), which indicates that there are overall significant differences among the group means, with the statistical significance at a probability level of 0.05.

3. Results and discussion

3.1. Analytical analysis

Six samples of RDF formulations containing PKS, CS, and CH were used to compare the HHV. The Ag-Residue was randomly mixed with ratios ranging from 10% to 80% each. The values of the MC, VM, FC, and ash with different MC (% dry basis) are tabulated in Table 2.

Table 2. Proximate analysis based on design of experiment.

Moisture content (% dry basis)	RDF sample	Volatile matter (%)	Fixed carbon (%)	Ash (%)
5%	RDF1	62.22	24.60	3.01
	RDF2	39.45	43.80	11.89
	RDF3	40.10	42.75	12.37
	RDF4	58.41	29.45	8.27
	RDF5	46.30	36.58	12.56
	RDF6	44.00	35.93	15.28
7%	RDF1	64.78	26.28	2.86
	RDF2	40.32	41.56	10.64
	RDF3	41.46	40.36	11.28
	RDF4	56.23	29.22	8.11
	RDF5	46.56	34.57	12.09
	RDF6	44.84	33.15	15.12
10%	RDF1	58.12	28.80	3.08
	RDF2	43.08	38.08	8.84
	RDF3	43.51	36.78	9.71
	RDF4	52.96	28.88	8.16
	RDF5	46.95	31.55	11.50
	RDF6	46.09	28.98	14.93

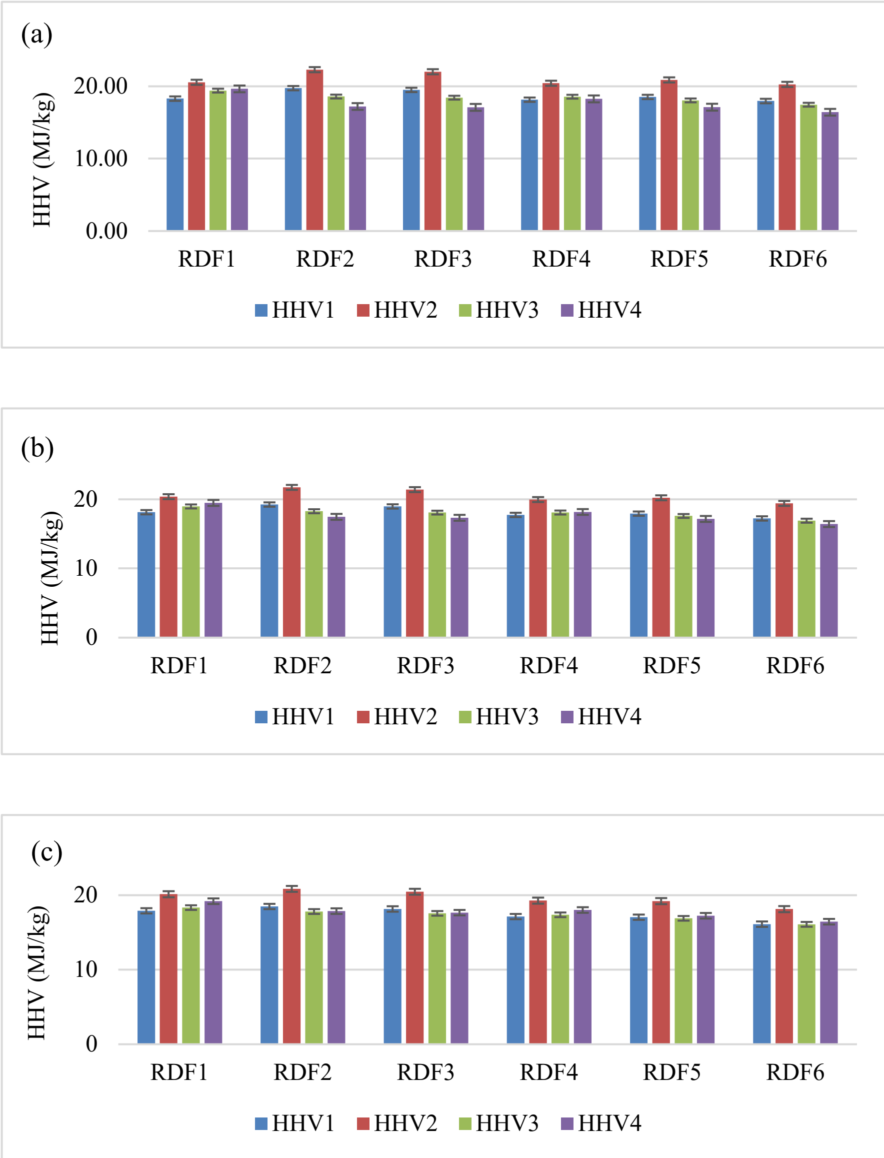

Figure 2. Comparison of experimental HHV (MJ/kg) value for different moisture content (a) 5% (b) 7% (c) 10%.

Figure 2 illustrates four HHV models used at different MCs, as mentioned in Table 2. The value of the HHV using all models (i.e., HHV1, HHV2, HHV3, and HHV4) provides a significant finding. By comparing the results across the samples, it was observed that different HHV calculation methods can yield different results. However, for each MC, the HHV2 model consistently produced the highest values compared to HHV1, HHV3, and HHV4. RDF2 was identified with the highest HHV value among the others with the respective values of VM, FC, and ash at different levels of MC. For an MC at 5%, the VM, FC, and ash values were 39.45%, 43.80%, and 11.89%, respectively. Meanwhile, in the range of an MC at 7%, the VM, FC, and ash values were 40.32%, 41.56%, and 10.64%, respectively. At a 10% MC, the VM, FC, and ash values were maintained at 43.08%, 38.08%, and 8.84%, respectively. In short, as the moisture decreases, there is a clear increase in the ash content. Similarly, lower MCs potentially results in the highest HHV. The permissible range of ash content to achieve high efficiencies in mass burning incinerators recommended by the US Environment Protection

Agency is 5–15% (dry basis) [30]. To have a better understanding of the coal rank, it was found that the maximum ash content allowed was 8%, since higher ash contents cause a drop in the productivity of coke in the combustion chamber [31]. In addition, previous studies demonstrated that the least amount of ash in the RDF showed the potential to be used as a waste derivative for energy purposes in terms of the calorific value. The data indicates that the VM averaged 43% for each MC level. However, it's worth noting that recommendations suggest that the VM should ideally exceed 45% for suitability in the incineration process [2]. The RDF2 demonstrated an HHV value of 22.29 MJ/kg at 5% of MC, 21.71 MJ/kg at 7% MC, and 20.85 MJ/kg at 10% MC, thus indicating that an increase in the MC leads to a decrease in the energy content. Meanwhile, according to D. Sedha (2023), the RDF with a high MC has a negative influence on the emission of gases as a reduction in the combustion efficiency [32]. Therefore, a further investigation was conducted on the HHV2 model with RDF2 using statistical methods to derive a predictive model that takes the interaction with MC values into account.

3.2. Statistical analysis

A moderate negative correlation was observed between the MC and the HHV of the samples, with a correlation coefficient of −0.5630, as shown in Table 3. This analysis shows that lower MCs correspond to higher HHV. In this study, hypothesis testing for the correlation coefficient was not conducted because it was only intended to examine the relationship between the HHV and the MC.

Table 3. Correlation.

Value	Correlations	Correlations
HHV (MJ/kg)	1.000	−0.5630
MC (%)	−0.5630	1.000

Table 4 shows the one-way ANOVA analysis, which consists of the standard error and the lower and upper bounds of the 95% confidence interval for each RDF sample. From this analysis, the mean of experimental HHV was then compared using Tukey-Kramer HSD test at an alpha = 0.05 for all six RDF samples, as tabulated in Table 5. It indicated that the RDF2 sample (HHV mean = 21.61759 MJ/kg) was significantly higher than the other RDF samples. Thus, RDF2 are considered to be evaluated as the statistical prediction model.

Table 4. Mean for One-way ANOVA experimental HHV value for all sample.

Ranking	HHV (MJ/kg)	Std Error	Lower 95%	Upper 95%
RDF2	21.617	0.4303	19.412	21.287
RDF3	21.282	0.4303	20.680	22.555
RDF1	20.349	0.4303	20.344	22.213
RDF5	20.090	0.4303	18.948	20.823
RDF4	19.886	0.4303	19.153	21.028
RDF6	19.265	0.4303	18.327	20.202

Table 5. Mean experimental HHV value for all sample.

Ranking	HHV (MJ/kg)
RDF2	21.617
RDF3	21.282
RDF1	20.349
RDF5	20.090
RDF4	19.886
RDF6	19.265

From the statistical analysis using the fit model, the P-value for all the parameters, namely the MC, VM, FC and ash, are less than 0.05. Thus, it has strong statistical evidence that all the parameters significantly affect the HHV value of the RDF. The statistical prediction model equation for the HHV value, Y, as a function of the HHV (MJ/kg) is found to be as follows:

$$Y = -1.0089 + 1.15MC + 0.1806VM + 0.3643FC + 0.0103Ash\ (MC - 0.00733) \quad (1)$$

Equation (1) demonstrates that a one-unit increase in the MC results in a 1.1586 decrease in the predicted HHV (MJ/kg) value of the RDF, while holding the VM and the FC constant. The tested model does not appear to violate the assumptions made. Additionally, the residual-by-predicted plot demonstrates a somewhat even spread across the predicted values, as illustrated in Figure 3. This consistency in the residual variance across the predicted values suggests a good fit, as all the points were located close to the diagonal line (predicted values were equal to the experimental values of HHV).

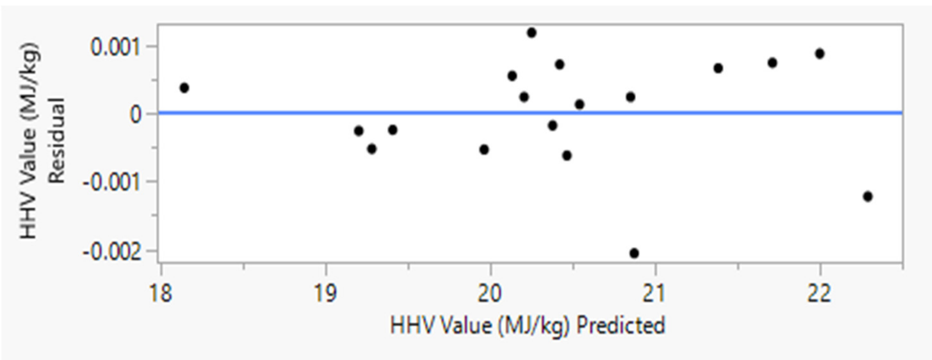

Figure 3. The HHV(MJ/kg) value residuals vs predicted plot analysis.

Figure 4 depicts the comparison between values from the statistically predicted model and the experimental adopted HHV2 model for the RDF2 sample at different levels of MC. The experimental HHV2 values for the MC at different ranges of 5%, 7%, and 10% are closely aligned with the predicted actual HHV values. Thus, the results demonstrate that the statistically predicted model is fairly accurate, with variations around 0.4% to 0.5%, thus indicating a relatively small difference between the two sets of values. In other words, this suggests that the JMP model effectively predicts the HHV based on independent variables.

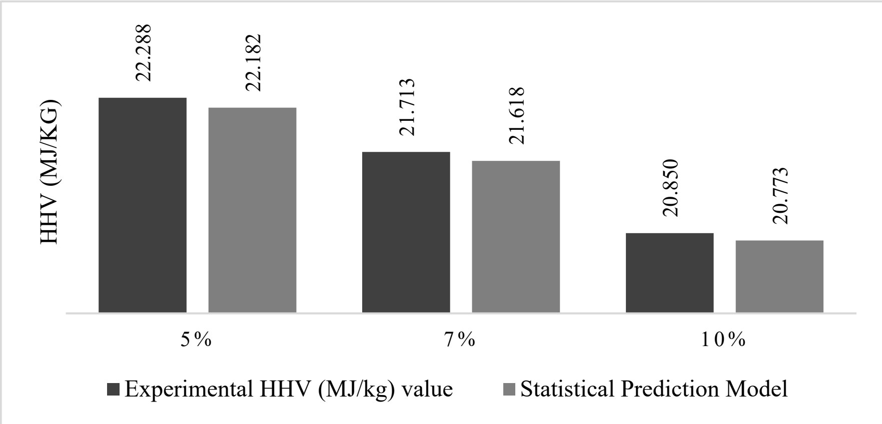

Figure 4. Comparison HHV(MJ/kg) values between statistical prediction model and HHV2 model for RDF2 sample at different moisture content (%).

4. Conclusions

The study investigated the formulation of RDF utilizing Ag-Residue from CS, PKS, and CH blended at various ratios for combustion in power generation. Proximate analysis parameters such as the MC, VM, FC, and ash were assessed using a TGA at different blending ratios. Additionally, the HHV for six RDF samples were determined. The results indicated that RDF2 presented the highest HHV among all samples tested, with RDF2 yielding an average HHV of up to 21 MJ/kg. Remarkably, the HHV analysis revealed that the HHV2 formula for the RDF samples exhibited the highest values compared to other models, with absolute and bias errors of 1.70 and 0.68%, respectively. The correlation between the MC and the HHV of the RDF samples revealed that as the MC decreased, the HHV increased. These findings underscore the significance of controlling the moisture levels in RDF production processes to optimize the energy efficiency and top maximize the heating value. As noted, the energy value of coal is typically in the range of 25–35 MJ/kg. The anthracite type of coal is recognized as the highest quality coal due to its carbon content of more than 90% and the highest calorific value [33]. Although the energy value of RDF2 is 16% lower than coal, it still qualifies as a renewable energy source, thus offering a positive impact from an environmental and economic perspective. By utilizing Ag-residue instead of coal and natural gas, Malaysia can work towards achieving its target of reducing the greenhouse gas emissions intensity by 45% under Vision 2030, as outlined in the Malaysia Beyond 2025 plan [34]. The utilization of these alternative fuels can effectively reduce the carbon footprint of the power generation industry. RDF presents a viable solution to waste management issues by optimizing waste mixing to achieve the highest energy value. However, a further study is required to assess the economic and environmental impact on RDF production compared to coal pricing.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that they have no conflicts of interest.

Author contributions

Materials preparation, data collection and analysis were performed by Nuranis Yasira Abd Halim and Noor Intan Shafinas Muhammad; Writing—original draft preparation: Nuranis Yasira Abd Halim; Writing—review and editing: Noor Intan Shafinas Muhammad Supervision: Noor Intan Shafinas Muhammad. All authors read and approved of the final manuscript.

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