Development of refuse derived fuel technology from biomass waste by utilizing plastic waste adhesive materials to produce new and renewable energy

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ABSTRACT

The energy crisis and the demand for increasing the new and renewable energy (EBT) mix encourage the utilization of biomass waste as raw material for refuse derived fuel (RDF). Tanah Bumbu Regency has the potential for veneer waste, empty oil palm bunches (EFB), and oil palm fronds that can be converted into valuable alternative energy. This study aimed at analysing the morphological characteristics and elemental composition of the three biomass and determining the most optimal RDF formulation. The study was conducted from August to November 2025 with sampling at PT Hutan Rindang Banua and PT Kodeco Agrojaya Mandiri, and testing at the Integrated Laboratory of Lambung Mangkurat University and UPTD ESDM Banjarbaru. The methods included purposive-composite and duplex sampling techniques, proximate and ultimate tests, calorific value using a bomb calorimeter, RDF briquette production with composition variations A, B, and C, and morphological and structural analysis using SEM and XRD. The results showed the dominance of lignocellulosic structure with carbon content of more than 80% and good porosity, and the highest calorific value was obtained in composition A (veneer 45%, 25% EFB, 20% palm oil palm leaf, 10% plastic) of 7,170.36 kcal/kg, exceeding composition C (7,012.12 kcal/kg) and B (6,949.51 kcal/kg), and far above the minimum standard of RDF co-firing in the cement industry (4.300 kcal/kg). Thus, formulation A is the most optimal RDF composition and local biomass waste has strong potential as a renewable energy source which supports waste management and sustainable energy transition in the industrial sector.

Keyword: RDF, biomass, calorific value, SEM, XRD, renewable energy.

INTRODUCTION

The energy crisis caused by dependence on fossil fuels and growing environmental awareness is driving Indonesia to accelerate its transition to clean energy. The government has targeted a 23% share of New and renewable energy (NRE) by 2025, but as of 2022, the realization is still below 15% (Loy et al., 2024). One priority effort to achieve the national energy mix target is through the utilization of urban and industrial waste to produce refuse-derived fuel (RDF), an alternative fuel processed from organic and inorganic solid waste that has a high calorific value and improved combustion stability (Gathut and Dahlan, 2024).

Tanah Bumbu Regency, South Kalimantan, has significant potential for developing biomass-based RDF due to its location as a center of the palm oil industry and veneer wood processing, such as at PT Kodeco Agrojaya Mandiri and PT Hutan Rindang Banua. These two sectors produce

large amounts of organic waste, such as empty oil palm fruit bunches (EFB), palm fronds, and veneer waste, which have not been optimally utilized. Various processing efforts, such as pyrolysis, direct combustion, and composting, remain limited due to technical and economic constraints, as well as the low commercial value of the processed products. Consequently, most waste is burned openly or piled up, causing environmental pollution without any added economic value. On the other hand, the high demand for RDF in the cement industry in South Kalimantan, particularly in Kotabaru Regency, opens up significant opportunities to convert this waste into a useful alternative fuel.

In Indonesia, demand for RDF from the industrial sector is increasing rapidly, in line with policies to reduce dependence on coal and the transition to clean energy. The use of RDF in co-firing in the cement industry is emerging as a solution for waste management and CO_2 emission reduction, in line with Indonesia's Nationally Determined Contribution targets and the global decarbonization agenda (Fitrianingrum and Surjasatyo, 2023). Various studies have shown that industrial biomass waste, or organic solid waste, has the potential to be a promising alternative energy source. After going through the torrefaction and pelletization process, empty oil palm bunch waste (TKKS) can reach a calorific value of 4.200 to 4.300 kcal/kg, approaching the calorific value of young coal. Meanwhile, tropical bark waste (such as from wood veneer) after being dried and pelletized has a calorific value ranging from 4.300 to 5.000 kcal/kg, depending on the wood species (Haryanto et al., 2021; Hidayat et al., 2020; Telmo and Lousada, 2011). These characteristics make them highly suitable for use as RDF, especially in co-firing schemes in the cement industry, which is one of the sectors with the highest energy consumption and a significant contributor to carbon emissions globally.

Most RDF in Indonesia is still based on domestic and textile waste, which have different characteristics from agro-industrial biomass-based RDF, particularly in terms of calorific value, ash content, chlorine content, and combustion stability. These differences affect the fuel's suitability for the cement industry's combustion system. Given that research on RDF based on agro-industrial and wood processing waste in South Kalimantan is still limited, a comprehensive study is needed to formulate RDF based on

local waste such as EFB, oil palm fronds, and veneer to suit the technical needs of the regional cement industry. This research was conducted in three main stages. The first stage focused on testing the characteristics of RDF raw materials derived from veneer waste, EFB, and oil palm fronds through proximate and ultimate analysis, as well as calorific value testing to determine their energy potential. The second stage included the process of producing RDF in briquette form with varying material compositions and blending simulations based on the weighted average calorific value, with the goal of obtaining a formulation which met the minimum standard of 4.300 kcal/kg for co-firing applications in the cement industry. The third stage included characterization of the formulated RDF through calorific value and water content testing, as well as further analysis using XRD and SEM to identify the crystalline phase, microstructure, and porosity which influenced combustion performance.

This research aimed at developing an optimal RDF formulation while encouraging the sustainable use of local biomass waste. In addition to supporting the energy transition and reducing carbon emissions, this research strengthened the implementation of a circular economy by converting waste into value-added energy. The results were expected to form the basis for developing efficient and sustainable small- to medium-scale RDF production models, contributing to waste management and improving the regional economy.

Based on this description, this research aimed at analysing the morphological characteristics and crystal structure of several types of biomass waste, namely veneer waste, oil palm EFB, and oil palm fronds, as potential raw materials for the production of RDF. Furthermore, this research aimed at determining the optimal RDF mixture formulation, based on the design of experiments, which produced the highest calorific value, thereby meeting the need for efficient and sustainable alternative energy for the industrial sector.

RESEARCH METHODS

Time, place, and object of the research

The research was conducted from August to November 2025. Veneer waste sampling was conducted at PT. The research was conducted at the Rindang Banua Forest, Sebamban Baru Village,

Sungai Loban District, Tanah Bumbu Regency. EFB and palm fronds were obtained from PT. Kodeco Agrojaya Mandiri, Danau Biru Mill.

The raw material testing, RDF production, and further analysis were conducted at the Integrated Laboratory of Lambung Mangkurat University and the Banjarbaru ESDM Technical Implementation Unit (UPTD ESDM) Laboratory.

The research subjects included three main types of biomass waste: veneer waste, EFB, and palm fronds, which are used as raw materials for RDF.

Research tools and materials

The equipment used included a shredder, hammer mill, oven, mixer, sieve, pelletizer, bomb calorimeter, scanning electron microscope (SEM), and X-ray diffractometer (XRD). The research materials consisted of veneer waste, EFB, palm fronds, and polystyrene (PS) plastic waste as the RDF adhesive.

Research procedures

Sampling and raw material preparation

Sampling was conducted using a purposive-composite sampling technique based on the availability and relevance of the materials to alternative energy needs.

Veneer waste was obtained as a multi-wood mixture, while OPEFB was divided into fresh and aged OPEFB. Oil palm frond waste was collected from several representative locations within the plantation area. PS waste was collected from household and light industry sources, cleaned, dried, shredded, and melted to form an adhesive.

To increase data representativeness, duplex sampling was used, taking samples in the morning (8:00–10:00 AM) and afternoon (3:00–5:00 PM). Each sample was composited from at least three locations, given an identification code, and stored in an airtight container.

Raw material characteristic testing

Raw material analysis included:
1. Proximate testing: moisture content, volatile matter, fixed carbon, and ash.
2. Ultimate testing: C, H, N, S, and O content using an elemental analyzer (ASTM standard).
3. Calorific value testing: using a bomb calorimeter to determine the energy potential of the raw material.

The analysis results were used to assess material quality and determine the optimal RDF formulation.

Biomass RDF production

The raw material, in the form of fine powder (≤50 mesh), was mixed with PS plastic adhesive based on the composition ratio (Table 3). The homogeneous mixture was moulded into cylindrical briquettes with a diameter of approximately 40 mm, then dried at 60 °C for 12 hours to reduce the moisture content and increase the calorific value.

RDF quality testing

RDF quality testing was conducted through:
- moisture content using the oven drying method,
- calorific value using a bomb calorimeter,
- XRD analysis to identify the crystalline phase, and
- SEM analysis to observe surface morphology and porosity.

This analysis provides a comprehensive overview of the thermal stability, structure, and combustion efficiency of RDF.

Data analysis

Data from proximate and ultimate tests, calorific value, XRD, and SEM were descriptively and statistically analysed using one-way ANOVA or Kruskal–Wallis to determine the effect of different material compositions on RDF characteristics. XRD diffraction patterns were analysed to determine the degree of crystallinity and phase of the material, while SEM results were used to evaluate particle morphology and distribution. The results of these technical and structural analyses were used to assess the most efficient, stable, and energetically feasible RDF formulation.

RESULTS AND DISCUSSION

The characteristics, morphology, and elemental composition of the three biomasses were analysed and the optimal RDF formulation was determined.

Morphological characteristics and elemental components of RDF

RDF composition A

The morphological results of RDF composition A showed a dense and homogeneous structure with strong interparticle bonds. The biomass particles appeared to be bonded together by the polystyrene (PS) phase, which acted as an adhesive, forming a compact, low-porosity layer. The dense surface and few cracks indicate that the mixing and moulding processes were optimal, resulting in an even particle distribution. The surface morphology was shown in Figure 1.

The RDF composition A sample was composed of a mixture of components: 45% veneer, 25% EFB, 20% palm fronds, and 10% plastic adhesive. The structure of composition A demonstrated good physical stability of RDF and had the potential to support combustion efficiency by maintaining shape integrity and slowing the release of volatiles during the thermal process. This was because RDF composed of larger particles creates larger pore spaces. According to Oke et al. (2016), particles with larger pore spaces facilitated air penetration into the RDF, resulting in easier combustion and increased calorific value.

The EDX spectrum results on the surface of RDF composition A (Figure 2) indicated that the RDF components contained predominantly organic compounds and minor minerals, which were still within reasonable limits for solid fuels.

The RDF composition was dominated by carbon, representing 88.70%, indicating a high lignocellulose organic fraction in the sample. Oxygen was detected at 9.78%, representing the structure of cellulose, hemicellulose, and lignin. Minerals such as potassium (1.14%) and calcium (0.38%) appear in small amounts, reflecting the natural minerals of the biomass (Table 1).

According to Sarquah et al., 2023, the highest peak appeared in carbon, indicating the dominance of organic components, while oxygen indicated the presence of the main structural constituents of oil palm biomass. Calcium appeared at several energy levels, indicating natural minerals, followed by magnesium, silicon, chlorine, and potassium, reflecting both process residues and biomass characteristics. Traces of plastic elements appeared in certain parts of the spectrum, confirming the presence of synthetic polymers in the RDF.
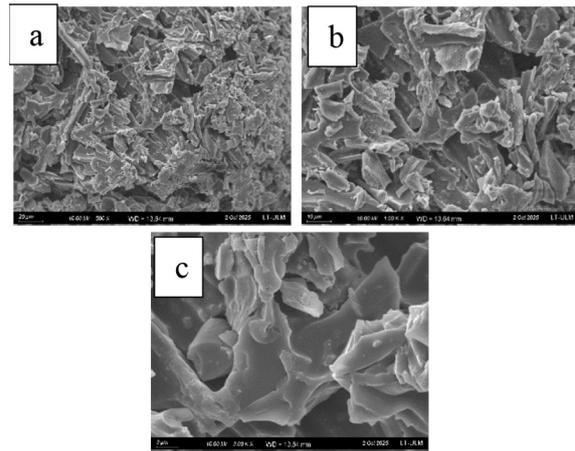

Figure 1. SEM test results of surface composition A (Vr45: Tk25: Pl20: Ps10) (a) magnification 500 x (20 μ), (b) magnification 1000 x (10 μ), (c) magnification 3000 x (3 μ)
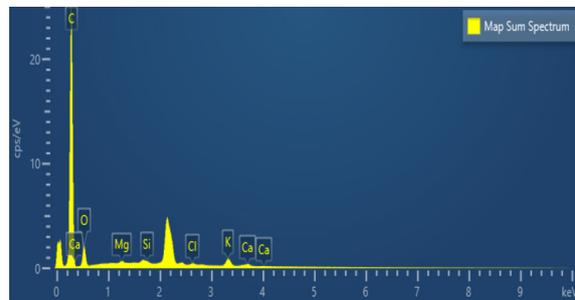

Figure 2. RDF sum spectrum map with composition A (Vr45 : Tk25 : Pl20 : Ps10)

Table 1. Composition of RDF chunks: composition A (Vr45: Tk25: Pl20: Ps10)

Element	Weight %	Weight % Sigma	Atomic %
C	87.99	0.12	92.19
O	8.35	0.11	6.56
Mg	0.18	0.02	0.10
Si	0.21	0.02	0.09
Cl	0.37	0.03	0.13
K	2.16	0.04	0.70
Ca	0.74	0.04	0.23
Total	100.00		100.00

RDF composition B

The morphology results for RDF composition B indicated that the surface structure of the RDF had a porous and inhomogeneous morphology, as shown in Figure 3.

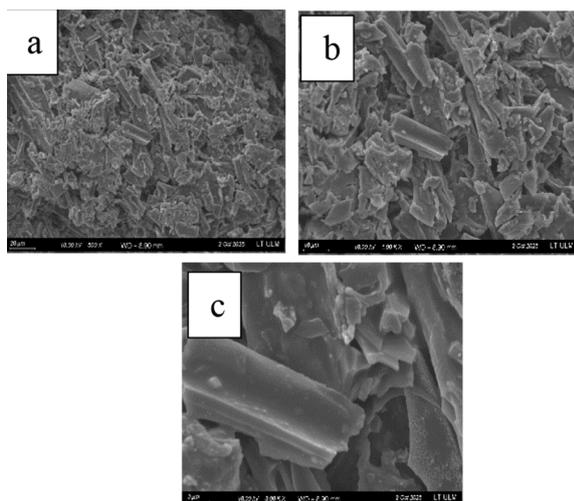RDF sample composition B was composed of a mixture of constituent materials, namely

Figure 3. SEM test results of surface composition B (Vr40 : Tk30 : Pl20 : Ps10) (a) magnification 500 x (20 μ), (b) magnification 1000 x (10 μ), (c) magnification 3000 x (3 μ)

Table 2. Elements composing RDF composition A chunks (Vr40: Tk30: Pl20: Ps10)

Element	Weight %	Weight % Sigma	Atomic %
C	83.97	0.20	90.43
O	8.73	0.15	7.06
Mg	0.34	0.03	0.18
Si	0.31	0.03	0.14
Cl	1.15	0.05	0.42
K	3.91	0.08	1.29
Ca	1.35	0.07	0.43
Br	0.24	0.06	0.04
Total	100.00		100.00

40% veneer, 30% EFB, 20% oil palm fronds, and 10% adhesive plastic. At 500× magnification, interlocking lignocellulose networks were visible, indicating that physical bonds among biomass components were still dominant. At 1000× magnification, a clearer fibril structure and a rough surface were visible due to the presence of cell wall fragments and biomass residue. At 3000× magnification, fiber-like fragments and solid particles of the adhesive material and cellulose components were visible, indicating that the interaction of the biomass material with the plastic was not completely homogeneous. According to (Aluri et al., 2018), the irregular, fiber-like shape with a wavy surface was the result of a decomposition mechanism involving cellulose-based components.

The EDX spectrum results on the surface of RDF composition B (Figure 4) showed the dominance of carbon indicates a high organic fraction of biomass, followed by oxygen as an indication
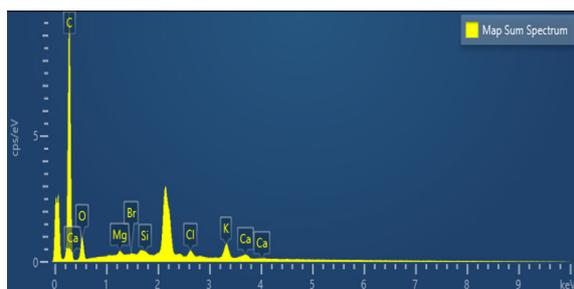
of the presence of lignocellulosic structures. Mineral elements such as Mg, Si, K, and Ca were detected at low intensities, reflecting the natural minerals of the biomass, while traces of Cl originated from residues or plastic components. This pattern confirmed that RDF composition B had a chemical character dominated by organic materials with minor mineral contributions.

The elemental composition of RDF composition A chunks showed a carbon dominance of 83.97%, indicating a high organic fraction of the biomass. Oxygen was detected at 8.73%, representing the lignocellulosic structure. Mineral elements such as Mg, Si, K, Ca, and Cl were present at low to moderate levels as natural inorganic components of the biomass and process residues, with potassium and calcium being the most prominent minerals. The presence of low traces of bromine indicated a minor, insignificant contaminant. Overall, this composition confirmed that RDF composition A was predominantly organic, with a mineral fraction which remained within reasonable limits for biomass-based solid fuels (Table 2).

According to (Wijaya et al., 2024), high carbon content significantly affected the calorific value and combustion efficiency of RDF briquettes, which impacted their overall energy contribution.

RDF composition C

The surface morphology of RDF composition C showed an inhomogeneous structure with a combination of biomass fragments, fibers, and adhesive particles, as shown in Figure 5.

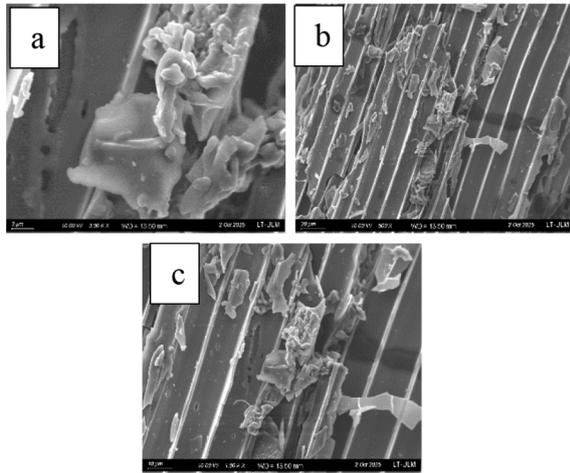The RDF composition C sample was composed of a mixture of components: 35%

Figure 4. Map sum spectrum of RDF with composition B (Vr40: Tk30: Pl20: Ps10)

Figure 5. SEM test results of the surface of composition C (Vr35: Tk35: Pl20: Ps10) (a) 500x magnification (20 μ), (b) 1000x magnification (10 μ), (c) 3000x magnification (3 μ)

veneer, 35% EFB, 20% palm fronds, and 10% adhesive plastic. At 500× magnification, an irregular fiber arrangement was visible, characteristic of lignocellulosic materials. At 1000× magnification, a rougher surface with cell wall fragments and small aggregates was revealed, indicating uneven interparticle bonding. At 3000× magnification, a more detailed fibril structure was visible, as were adhesive particles attached to the fiber surface, indicating that biomass-plastic interactions occurred but were not yet completely homogeneous. This morphology reflected the
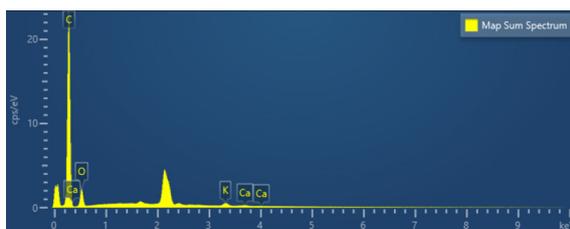

Figure 6. Map sum spectrum of RDF with composition C (Vr35: Tk35: Pl20: Ps10)

Table 3. Elements making up RDF chunks with composition A (Vr35: Tk35: Pl20: Ps10)

Element	Weight %	Weight % Sigma	Atomic %
C	88.70	0.13	91.91
O	9.78	0.12	7.61
K	1.14	0.04	0.36
Ca	0.38	0.04	0.12
Total	100.00		100.00

properties of RDF composites, which were influenced by variations in particle size and the distribution of constituent materials. According to Ani et al. (2025), the importance of surface and pore structure in determining RDF performance was a determining parameter in the calorific value and combustion efficiency of RDF briquettes.

EDX spectrum results on the surface of RDF composition c (Figure 6) showed the dominance of carbon (C) and oxygen (O) elements which indicated the high content of organic matter in RDF composition C. The presence of magnesium (Mg), silicon (Si), chlorine (Cl), potassium (K), and calcium (Ca) elements indicated the contribution of inorganic minerals from biomass to thermal stability and the formation of ash residue. The high intensity of the carbon peak confirmed the large energy potential, while alkali metal elements such as K and Ca played a role in increasing the combustion reactivity and efficiency of the RDF thermochemical process.

The elements making up RDF with composition C were based on EDX analysis. C was the most dominant element at 88.70% (by weight), followed by O at 9.78%, potassium (K) at 1.14%, and Ca at 0.38%, as presented in Table 3. The high carbon proportion indicated that the RDF had a significant organic content and has the potential to produce high calorific value. The moderate oxygen content reflected the presence of oxide group from the biomass, while the K and Ca elements indicated the contribution of inorganic minerals which played a role in thermal stability and ash formation during combustion.

According to Ani et al. (2025), when RDF was burned alone, its crust formation and ash fouling index were found to be higher than the threshold values for crust formation and fouling.

Comparison of physical and chemical characteristics of RDF chunks

RDF could be observed through the parameters of density, ash content, moisture content, and volatile matter, as shown in Figure 7. The graph showed a comparison of the physical characteristics of RDF in three material compositions. The ash content increased from 5.96% in composition A to 7.10% in composition B, then decreased to 6.28% in composition C, while the water content showed a similar pattern, namely 12.00%, 13.22%, and 11.61%. The volatile matter value of 52.75% in composition A decreased to 51.50%
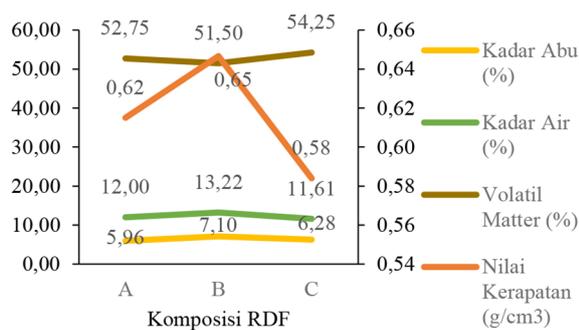
Figure 7. Density, ash content, moisture content, and volatile matter in RDF lumps of components A, B, and C

in composition B and increased again to 54.25% in composition C. Meanwhile, the density value was relatively stable, namely 0.62 g/cm³ in composition A, 0.65 g/cm³ in composition B, and 0.58 g/cm³ in composition C, which reflected the differences in the physical characteristics of RDF in each composition.

Figure 8 showed the variation in RDF calorific value across three material compositions. Composition A exhibited the highest calorific value of 7,170.36 kcal/kg, followed by composition C at 7,012.12 kcal/kg, while composition B had the lowest value of 6,949.51 kcal/kg. This difference indicated that the higher proportion of veneer in composition A significantly contributed to the increase in carbon content and total calorific value. Meanwhile, the decrease in calorific value in composition B was related to the increased proportion of OPEFB, which had higher ash and moisture content. Overall, all RDF formulations exceeded the minimum calorific value standard for RDF co-firing in the cement industry (4.300 kcal/kg), thus all three formulations had the potential to be used as alternative biomass-based fuels.
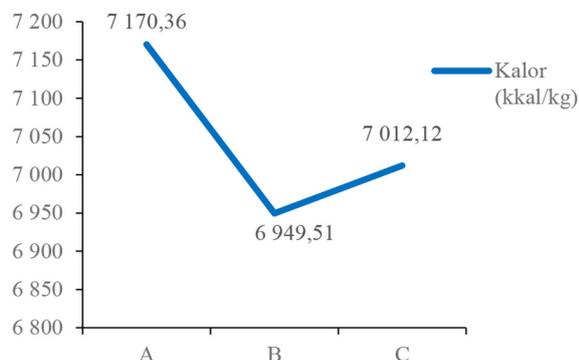

Figure 8. Calorific value of RDF chunks with compositions A, B, and C

The variation in the calorific value of RDF across the three material compositions showed quite significant differences. Composition A produced the highest calorific value of 7,170.36 kcal/kg, followed by composition C at 7,012.12 kcal/kg, while composition B had the lowest calorific value of 6,949.51 kcal/kg, as shown in Figure 8. These differences in calorific value indicated that the higher proportion of veneer in composition A significantly contributed to the increase in carbon content and total calorific value of RDF. Wood veneer had a relatively higher lignin and carbon content compared to EFB and palm fronds, thereby increasing the energy potential of solid fuels. This finding aligned with the study by Esteves et al. (2023), which stated that biomass with high lignin and carbon content tended to have higher calorific value.

The lower calorific value of composition B was related to the increased proportion of EFB, which had higher ash and relative humidity content. These high ash and moisture contents could reduce combustion efficiency because some of the heat energy was used for water evaporation, while the inert mineral components did not contribute to the combustion process (Racero-Galaraga et al., 2024).

The three RDF formulations produced in this study had calorific values exceeding the minimum RDF standards for co-firing applications in the cement industry. This indicated that all formulations had the potential to be used as alternative biomass-based fuels. These findings aligned with various studies which suggested that the use of biomass in energy generation could support the transition to renewable energy and partially replace fossil fuel use through the application of co-firing technology (Bachtiar and Rusirawan, 2025; Nasution, 2024). Furthermore, biomass waste had been widely evaluated as a sustainable alternative energy source in various contexts for electricity generation and emissions reduction efforts, particularly in rural areas and the energy industry (Sulasminingsih et al., 2023).

The results of the Tukey HSD post hoc test on the calorific value showed significant differences among several RDF compositions. Based on the analysis, the comparison between composition A and composition B yielded a significance value of 0.021 (p < 0.05) with an average difference of 220.848 kcal/kg, indicating a significant difference between the two compositions. The calorific value of composition A was significantly

higher than that of composition B. This could be explained by the high proportion of veneer waste in composition A, which contained significant amounts of lignin and fixed carbon, thereby increasing the energy density and thermal efficiency of the RDF fuel.

Meanwhile, the comparison between composition A and composition C showed a significance value of 0.107 (p > 0.05) with an average difference of 158,242 kcal/kg, indicating that the difference between the two was not statistically significant. Similarly, the comparison between composition B and composition C showed a significance value of 0.671 (p > 0.05) with an average difference of 62,607 kcal/kg, indicating no significant difference between the two. Thus, only compositions A and B showed a significant difference in calorific value, while composition C fell in the middle with a calorific value which was not significantly different from the other two compositions. Overall, these results indicated that composition A had the highest thermal performance, confirming the important role of the veneer biomass fraction in improving the energy quality of RDF through its denser and higher-energy lignocellulose content. (Table 4).

Variations in RDF composition significantly impacted the physical, chemical, and thermal properties of the resulting fuel. Morphological observations using SEM analysis indicated that RDF with a higher proportion of veneer (composition A) had a denser and more homogeneous surface structure compared to compositions B and C. This density was related to the high content of lignin and fixed carbon in wood-based biomass, which played a role in strengthening interparticle bonds and reducing material porosity. Lignin, as an aromatic polymer, contributed to increased structural strength and

calorific value due to its high-energy carbon bonds (Hidayat et al., 2020; Telmo and Lousada, 2011).

Conversely, RDF with a higher proportion of EFB and palm fronds (compositions B and C) exhibited a more porous and non-uniform morphology. This structure was due to the looser nature of EFB fibers and their high hemicellulose and moisture content, resulting in weaker interparticle bonds and lower density. The resulting RDF density ranged from 0.58–0.65 g/cm³. This was consistent with the findings of Shojaeiarani et al. (2019), who reported that decreasing density and increasing porosity in solid fuels could reduce combustion stability and energy density per unit volume.

EDX analysis results showed that the entire RDF composition was dominated by carbon (83–89%) and oxygen (8–10%), reflecting the lignocellulosic nature of the RDF feedstock. Higher carbon content in composition A directly correlated with increased calorific value (7,170.36 kcal/kg). This aligned with the findings of Jiang et al. (2020), who reported that higher fixed carbon and lignin content in biomass increased the gross calorific value of solid fuels due to the more thermally stable aromatic structure of lignin. High carbon content indicated a greater proportion of organic fractions and lower ash, which generally contributed to better combustion efficiency.

In addition to the primary elements carbon and oxygen, EDX results also detected moderate amounts of minerals such as K and Ca. Research on biomass combustion characteristics indicated that the presence of alkali metals (e.g., K) and alkaline earth metals (e.g., Ca) could influence combustion properties such as ignition time, volatile combustion duration, and char combustion through complex thermochemical interactions. For

Table 4. Tukey's follow-up test of calorific value in RDF chunks of compositions A, B, and C

(I) Group		Mean difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower bound	Upper bound
Composition A	Composition B	220.848*	72,515	0.021	32.49	409.20
	Composition C	158,242	72,515	0.107	-30.11	346.60
Composition B	Composition A	-220. 848*	72,515	0.021	-409. 20	-32.49
	Composition C	-62, 607	72,515	0.671	-250. 96	125.75
Composition C	Composition A	-158, 242	72,515	0.107	-346. 60	30.11
	Composition B	62,607	72,515	0.671	-125, 75	250,96
*The mean difference is significant at the 0.05 level.						

example, a study by Carvalho et al. (2017) showed that increasing the concentration of K in biomass particles could accelerate the volatile combustion process and reduce the ignition delay time, while Ca also played a role in the combustion phase in a kinetically different manner. This effect stemmed from the mineral's catalysis of devolatilization and char oxidation during the combustion of organic matter. Therefore, the presence of K and Ca, even in moderate amounts, could contribute to increasing the thermal reactivity of RDF and influence its overall combustion characteristics, although the specific effects might depend on the concentration and form of the minerals in the biomass matrix.

XRD analysis corroborated other findings related to RDF properties, where higher plastic fractions indicated a more amorphous structure and altered physical and thermal behaviour. Amorphization, or decreased crystallinity, was often associated with increased heat transfer and accelerated devolatilization during combustion, which could improve the thermal reactivity of solid fuels. Studies on palletisation of RDF with varying plastic fractions had shown that increasing the proportion of plastic in the fuel composition significantly increased the heating value, although the density and mechanical strength of the pellets could vary depending on the temperature treatment and the fractions of other components (Rezaei et al., 2020). Furthermore, research on wood plastic pellets combining biomass (sawdust) and RDF had shown that the plastic mixture could produce pellets with a higher heating value than pure biomass pellets, while also affecting the physical properties of the pellets (Chotikhun et al., 2023). These findings supported the concept that the plastic fraction not only contributed as a high-calorie energy source but also modified the fuel microstructure, thereby influencing the thermal characteristics and combustion performance of RDF in industrial applications.

The RDF moisture content in this study ranged from 5.96–7.10%. Composition A had the lowest moisture content, which positively impacted the heating value and combustion efficiency. According to Matúš et al. (2015), increasing the moisture content above 10% could lower the heating value and slowed the combustion rate. Therefore, drying the material before the RDF moulding process was an important factor in increasing the heating value.

Moisture content played a crucial role in determining the thermal performance of RDF because water absorbed some of the combustion energy for evaporation, thus reducing energy efficiency. Composition A exhibited the lowest moisture content (±6%), which contributed to a higher heating value and a stable combustion process. Research by Halim and Muhammad (2025) showed that the Higher Heating Value (HHV) of RDF increased significantly with decreasing moisture content, with each 1% decrease in moisture content significantly increasing energy efficiency. Their follow-up study also confirmed that RDF with a moisture content below 10% resulted in more efficient combustion because the latent energy of evaporation was minimized.

These findings were consistent with the research by Shojaeiarani et al. (2019), who reported that high moisture content in solid biofuels reduced the net heating value and inhibits the combustion process due to increased energy requirements for evaporation. Therefore, pre-drying was a critical step in RDF production to ensure efficient, stable, and environmentally friendly combustion characteristics. Controlling the moisture content below 10% not only increased the heating value but also helped reduce emissions and solid residues during combustion, making RDF more suitable for industrial applications such as co-firing in the energy and cement sectors (Abd Halim and Muhammad, 2025).

The ash content of RDF in this study ranged between 11–13%, indicating the presence of moderate amounts of inorganic minerals. This value was still within the limits generally considered optimal for solid fuels because it was not too high to produce excessive ash residue which could interfere with the combustion process and kiln operation. Excessive biomass ash could add unreactive mineral components or reduce thermal efficiency if the proportion exceeded a certain limit (e.g., above 15%, depending on the biomass type and combustion system), making it important to consider the chemical composition of ash in RDF evaluation.

Research by Tosti et al. (2021) evaluated the properties of biomass ash produced from various fuel types and heat conversion technologies for its potential as a substitute for clinker in cement production. This study demonstrated that biomass ash with a combination of key components (e.g., a CaO/SiO_2 ratio close to that of traditional

clinker feedstock) was likely to react functionally in the formation of clinker minerals such as C_3S and C_2S when heated in a kiln. Their burnability modelling and analysis indicated that ash quality, determined by chemical composition, particle size, and major oxide ratio, significantly influenced its substitution potential in clinker without significantly disrupting the sintering reaction. Therefore, biomass ash at moderate levels, as found in the RDF in this study, could be considered as having potential for integration into co-firing systems or cement feedstock substitution if its chemical composition met the required technical criteria.

Differences in RDF compositions demonstrated that the balance of biomass types and other material fractions directly determined the physical and chemical properties and energy quality of solid fuels. RDF was a heterogeneous fuel whose calorific energy was influenced by the proportion of high-energy-content components such as plastic, paper, and lignocellulosic fibers (rice husks, veneers), as well as its biogenic content. Therefore, compositional variations resulted in varying calorific values and densities (Rezaei et al., 2020). RDF containing high-energy material fractions generally exhibited higher calorific values and higher energy densities, while fractions with an open fiber structure tended to increase the fuel's porosity and initial ignition speed (Rezaei et al., 2020; Chavando et al., 2022).

Research on RDF pelletization also explained that variations in mass fractionation among plastic, paper, organic waste, and wood produced RDF products with significantly different physical characteristics such as bulk density, mechanical strength, and calorific value, all of which were highly dependent on the composition of the source material (Rezaei et al., 2020). These differences indicated that RDF formulations must be tailored to specific application objectives, such as stable combustion in co-firing kilns or industrial boilers. Furthermore, the literature indicated that RDF compositional heterogeneity remained a major challenge in improving energy quality and performance consistency, especially when produced from blends of various waste types (Santos et al., 2023; Chavando et al., 2022).

Therefore, RDF formulations which considered the proportions of biomass components with respect to energy content, microstructure, biogenicity, and volatile fractions which facilitated ignition could produce fuels with high energy efficiency, good combustion stability, and suitable thermal properties for specific industrial applications. This made RDF composition design not simply a blending process, but a strategy for achieving optimal fuel performance in the energy and cement sectors through a fuel engineering approach (Rezaei et al., 2020; Santos et al., 2023).

From a practical perspective, all tested RDF compositions had calorific values above 7.000 kcal/kg, far exceeding the minimum RDF standard for co-firing applications in the cement industry (4.300 kcal/kg) (Fitrianingrum and Surjasatyo, 2023). This indicated that RDF based on veneer waste, EFB, and palm fronds had the potential to replace up to 30% of coal requirements in the cement production process without reducing kiln efficiency. The use of this type of RDF was also in line with Indonesia's clean energy transition roadmap and global decarbonization policies promoted by the International Energy Agency (IEA, 2024).

The calorific value and physical properties of RDF in this study were consistent with the results reported by Rosales-Serna et al. (2024); Shojaeiarani et al. (2019); Telmo and Lousada (2011) confirmed that densification and moisture control processes could improve the quality of biomass-based solid fuels. However, this study provided a novel contribution by combining veneer waste and palm oil waste—a combination which had not been widely studied before. The resulting RDF had higher energy performance than RDF based on domestic or textile waste (Gathut and Dahlan, 2024). This finding strengthened the potential of Indonesian tropical biomass as a sustainable alternative energy source for the cement industry in Southeast Asia.

Overall, the relationship among biomass composition, carbon content, and microstructural characteristics directly influenced RDF performance. The optimal composition (A: 45% veneer, 25% OPEFB, 20% palm fronds, and 10% plastic) was shown to produce the highest calorific value and a more stable structure, making it the most potential for industrial-scale RDF production. These results not only confirmed the suitability of local biomass waste as an RDF feedstock but also demonstrated its contribution to achieving renewable energy targets and sustainable waste management in the industrial sector.

CONCLUSION

The results of this study indicate that the morphological characteristics and elemental composition of RDF based on veneer waste, EFB, and oil palm fronds are predominantly lignocellulosic with good porosity and high carbon content, as confirmed by SEM and EDX analysis, with a carbon content of more than 80% and the presence of minor minerals which support thermal stability. These findings confirm that all three types of biomass are suitable for use as RDF raw materials. The most optimal RDF formulation was obtained with composition A (45% veneer, 25% EFB, 20% fronds, 10% plastic), which produced the highest calorific value of 7,170.36 kcal/kg, exceeding the minimum standard for RDF co-firing in the cement industry (4.300 kcal/kg) and other compositions. Therefore, formulation A is recommended as the best composition for industrial-scale RDF production due to its most efficient thermal performance and potential to support local biomass waste management and the sustainable energy transition towards renewable energy utilization.

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