Effect of Biomass Waste and CaO Blend Compositions on the Pelletizing Characteristics of Refuse-Derived Fuel (RDF)

Lusi Ernawati[1,*], Rizqy Romadhona Ginting[2], Rizka Lestari[3], Apip Amrullah[4], Obie Farobie[5], Pandji Prawisudha[6], Muhammad Raihan[7], Pangga Apriliawan[8]

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Abstract— **Refuse-Derived Fuel (RDF) is increasingly acknowledged as a sustainable method of managing municipal solid waste while simultaneously producing valuable energy. However, the quality and compactness of RDF as a fuel can vary substantially depending on the materials used to produce it. The incorporation of biomass waste and calcium oxide (CaO) significantly influences the pelletizing behavior of biopellets by altering their physical and thermal properties, which in turn determines their effectiveness and suitability as a fuel source. In this study, representative RDF pellets were prepared by blending four primary components: wood sawdust, organic waste, plastic waste, and a fixed proportion of CaO. The investigation focused on assessing the effects of varying biomass waste-to-organic waste ratios on the physicochemical characteristics, densification behavior, and proximate properties of typical RDF pellets. The experimental design included biomass-to-organic waste ratios of 1:1, 2:1, 3:1, 4:1, 5:1, and 6:1, while the proportions of plastic (20 wt%) and CaO (5 wt%) were held constant. The findings revealed that optimal RDF performance was achieved at biomass-to-organic waste ratios of 1:1 and 6:1, respectively. The resulting RDF pellets exhibited the following properties: ash content of 7.04 ± 8.78%, moisture content of 8.19 ± 8.82%, volatile matter ranging from 65.11 ± 66.19%, fixed carbon content of 13.95 ± 17.32%, calorific values between 4193 ± 4419 kcal·kg^{-1}, and bulk densities of 0.98 ± 1.18 kg·dm^{-3}. These results highlight the potential of RDF pellets as a promising alternative fuel source for boiler applications**.

Keywords— calcium oxide; municipal solid waste; refuse-derived fuel; waste-to-energy;

*Corresponding Author:lusiernawati@lecturer.itk.ac.id

I. Introduction

The rapid pace of urbanization and industrialization has led to a significant increase in the generation of municipal solid waste (MSW) and industrial waste worldwide [1,2]. Improper management of these wastes not only contributes to severe environmental pollution but also results in the loss of potentially valuable energy resources. To address these challenges, refuse-derived fuel (RDF) production has gained attention as a promising waste-to-energy strategy [3]. RDF is produced by processing MSW and industrial waste to extract high-calorific-value components, such as plastics, paper, and biomass residues, which are then converted into a homogeneous fuel suitable for energy recovery applications [4–6]. This approach not only facilitates the efficient harnessing of the energy potential embedded in waste materials but also significantly reduces the volume of waste directed to landfills [7,8].

The RDF production process typically involves drying, shredding, and separating recyclable and inert materials to enhance fuel quality and combustion efficiency [9]. These steps not only improve the calorific value and physical properties of the waste but also contribute to reducing greenhouse gas (GHG) emissions and dependence on fossil fuels [10–12]. RDF offers considerable advantages for industrial applications, including co-firing in cement kilns, power plants, and other energy-intensive industries [13,14]. Integrating RDF into existing energy systems aligns with the principles of a circular economy by transforming waste into a valuable resource [15,16]. While this process improves uniformity and lowers moisture content compared to untreated waste, the combustion of RDF still presents technical challenges. These challenges include variations in combustion behavior due to heterogeneous material composition and the release of chlorine compounds from plastic components [17,18]. To address these issues, the application of appropriate pre-treatment methods is essential for improving the physical and fuel characteristics of RDF, thereby enhancing its viability as a substitute for conventional fossil fuels.

Lusi Ernawati, Department of Chemical Engineering, Institut Teknologi Kalimantan, Balikpapan, 76127, Indonesia, Email: lusiernawati@lecturer.itk.ac.id
Rizqy Romadhona Ginting, Department of Chemical Engineering, Institut Teknologi Kalimantan, Balikpapan, 76127, Indonesia, Email: rizqy.romadhona@lecturer.itk.ac.id
Rizka Lestari, Department of Chemical Engineering, Institut Teknologi Kalimantan, Balikpapan, 76127, Indonesia, Email: rizka.lestari@lecturer.itk.ac.id
Apip Amrullah, Department of Mechanical Engineering, Lambung Mangkurat University, Banjarmasin, 70123, Indonesia, Email: apip.amrullah@ulm.ac.id
Obie Farobie, Department of Mechanical and Biosystem Engineering, IPB University, Bogor, 16680, Indonesia, Email: obiefarobie@apps.ipb.ac.id
Pandji Prawisudha, Faculty of Mechanical and Aerospace Engineering, Institute Technology of Bandung, Bandung, 40132, Indonesia, Email: pandji@itb.ac.id
Muhammad Raihan, Department of Chemical Engineering, Institut Teknologi Kalimantan, Balikpapan, 76127, Indonesia, Email: 05221068@student.itk.ac.id
Pangga Apriliawan, Department of Chemical Engineering, Institut Teknologi Kalimantan, Balikpapan, 76127, Indonesia, Email: 05221024@student.itk.ac.id

Furthermore, moisture content and particle size play a critical role in the effectiveness of RDF densification. As noted by Rezaei et al. [19], when the moisture level of the feedstock drops below 20%, the energy demand for pellet formation increases significantly. In contrast, excessive moisture levels can adversely affect the mechanical strength and durability of the resulting pellets. Sprenger et al. [20] reported that optimal RDF pellet production is achieved at a moisture content of approximately 15% and an ash content close to 20%. Moreover, studies have shown that integrating thermochemical treatments with densification processes can further enhance the quality of pellets produced from biomass waste [21,22].

In terms of RDF processing, decreasing the particle size and ensuring a more uniform distribution of char particles can reduce the energy demand during size reduction [23, 24]. However, a lower proportion of fine particles in RDF makes it harder for natural binders like lignin to hold the material together, necessitating the addition of external binding agents. This not only raises production costs [25] but also increases moisture absorption [26], which negatively affects the calorific value of the fuel.Unlike biomass, where lignin acts as a natural binder RDF lacks such binding agents, necessitating the use of artificial binders that maintain fuel quality and minimize cost.

Calcium oxide (CaO) plays a significant role as a binding agent in shaping the characteristics and performance of biopellet refuse-derived fuel (RDF). It affects several aspects, including combustion behavior, material properties, and gasification efficiency [27,28]. As a primary component in the ash formed during RDF combustion or gasification, CaO alters the chemical content of ash makeup, which can influence its reuse potential or disposal methods [29]. Moreover, CaO impacts the thermal properties of RDF-based materials. For instance, when RDF is integrated into ceramic mixtures like clay blocks [30], it can enhance thermal insulation, resulting in potential energy and cost savings [31,32]. Additionally, CaO also affects combustion dynamics and modifies the composition of the syngas produced during gasification, including reducing tar content an important factor for the optimal performance of gas engines [33]. However, the incorporation of CaO may also reduce the compressive strength of RDF pellets, which can pose challenges for their handling and storage [34]. Overall, the influence of CaO on RDF is complex, affecting its physical and thermal properties, combustion behavior, and structural integrity.

The present study aims to evaluate the effects of biomass waste and CaO blend compositions on the physical and chemical characterization, and the densification behavior representative of a typical Refuse-Derived Fuel (RDF). It focuses on evaluating how the solid waste composition and densification affect the production of durable and calorific of pellets. This setup enables a detailed analysis of the compaction behavior and mechanical strength of pellets produced from the RDF blend. This paper also highlights the potential of RDF in contributing to sustainable waste management and energy recovery systems, while addressing key technical and environmental considerations in its production and utilization.

II. Method

A. Material

Sawdust (a blend of meranti and bangkirai wood) combined with organic waste (such as fruit peels) acts as the primary biomass-based fuel. This mixture is characterized by high carbon content, low moisture, and excellent flammability. Plastic waste (mainly PE, PP, and PET) is used as a co-fuel in co-firing processes to boost the calorific value of RDF. While plastics have a high energy content, they need to be mixed with biomass and other organic materials for effective burning. The optimal formulation is determined by the desired calorific value performance. Typically, sawdust comprises 60 to 80%, while inorganic waste plastic (PE or PP) accounts for 20 to 40% of the mixture. It is important to ensure that the plastic content does not exceed 25% to preserve combustion stability and minimize emissions. In addition, CaO (Merck, p.a. 98.5%) and starch content should be kept below 5%, as higher levels may lead to pellet brittleness. Following the collection of organic and inorganic waste, the materials are subjected to a separation process to isolate the organic fraction. The organic waste is subsequently dried until its moisture content reaches approximately 11% by weight. Thereafter, the dried material undergoes comminution using a crusher and is sieved to obtain a uniform particle size within the range of 40 to 60 mesh.

B. Preparation

The sawdust to be dried is first sieved to achieve a uniform particle size. If an adsorbent such as CaO is used, it should be blended with the sawdust in a predetermined ratio prior to feeding it into the drying unit. Adjust key drying parameters, including the inlet air temperature of the rotary dryer (e.g., 90°C, 110°C, and 140°C), as needed. Determine the appropriate drying time and drum rotation speed based on the material's properties. Figure 1 shows the thermal dryer machine for solid waste drying. The drying process begins by activating the heating system (furnace) to generate hot air, which is then directed into a cylindrical, rotating drying chamber (rotary drum). Sawdust is continuously fed into the rotating drum to ensure uniform exposure to the hot air.

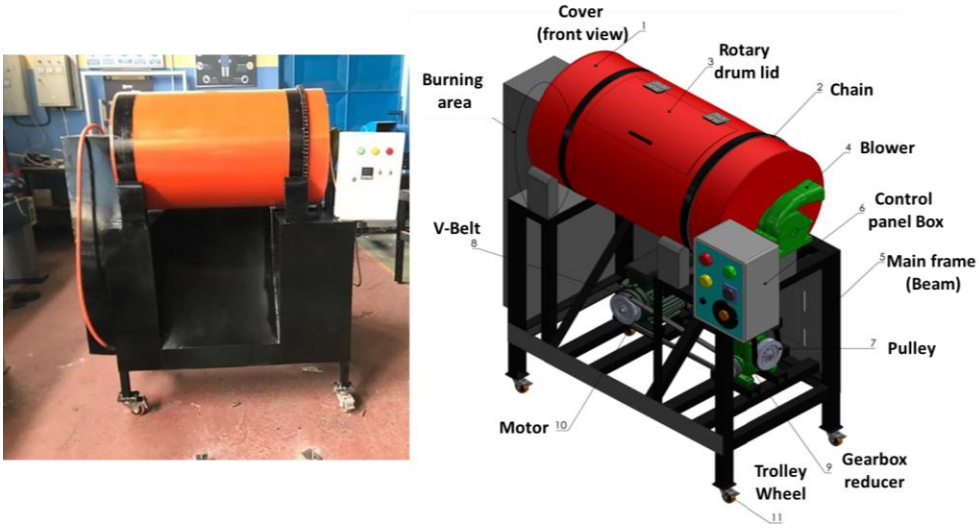

Figure. 1. Design of rotary thermal dryer machine for solid waste drying

Figure. 2. Design of pelletizer machine for making RDF pellets. The pelletizer uses rollers to compress RDF material into uniform pellets (typically 6-10 mm diameter).

During the drying process, periodic sampling was conducted (e.g., every 15 minutes) to measure the moisture content. Continuously monitor temperature, airflow rate, and drum speed to maintain process stability. Upon achieving the target moisture content, the dried sawdust is collected from the discharge end of the drum. This material is then suitable for subsequent pelletization. Refuse-derived fuel (RDF) pellets comprise a heterogeneous mixture of materials, resulting in highly variable physical and chemical properties that are challenging to predict. Pelletization serves as an effective approach to mitigate this variability, particularly in energy applications such as combustion (Figure 2).

C. Characterization

The prepared samples underwent a series of characterizations to evaluate their properties. Scanning electron microscopy (SEM, The Phenom Pro-X) was utilized to investigate the surface morphology at an accelerating voltage of 15 kV. Energy-dispersive X-ray spectroscopy (EDX, FEI Inspect-S50) was employed to examine the chemical composition of the RDF pellets sample. The crystallographic structure of the samples was examined using X-ray diffraction (XRD) with a Bruker D8 Advance diffractometer (Germany). The thermal stability of RDF sample was characterized using TGA analyzer (Linseiss, Type: STA PT 1600). The samples were further analyzed through proximate analysis (PT. GEOSERVICES, Balikpapan) to assess how moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon (FC) influence the gross calorific value. Proximate analysis was conducted according to ASTM standard, including moisture content (ASTM-D 3173), ash content (ASTM D 3174), volatile matter (ASTM D 3175), fixed carbon (ASTM D 3172), and calorific value (ASTM D 5865). The experimental determination of the weight-based particle size distribution of pellet RDF was performed through classification by both size and material type. Each size fraction, as well as the material within each size fraction, was weighed. The entire manual sorting process took five days, with the weighing conducted on the fifth day. Throughout this period, the sample was stored at ambient temperature conditions, which facilitated the reduction of its initial moisture content.

III. RESULTS AND DISCUSSION

The scanning electron microscope (SEM)

observations present images labeled Figure 3(a) through 3(f), illustrating the variations in surface morphology of RDF pellet samples. These differences correspond to the mixed compositions, which incorporate varying of sawdust combined by organic waste and CaO blend composition as outlined in Table 1.

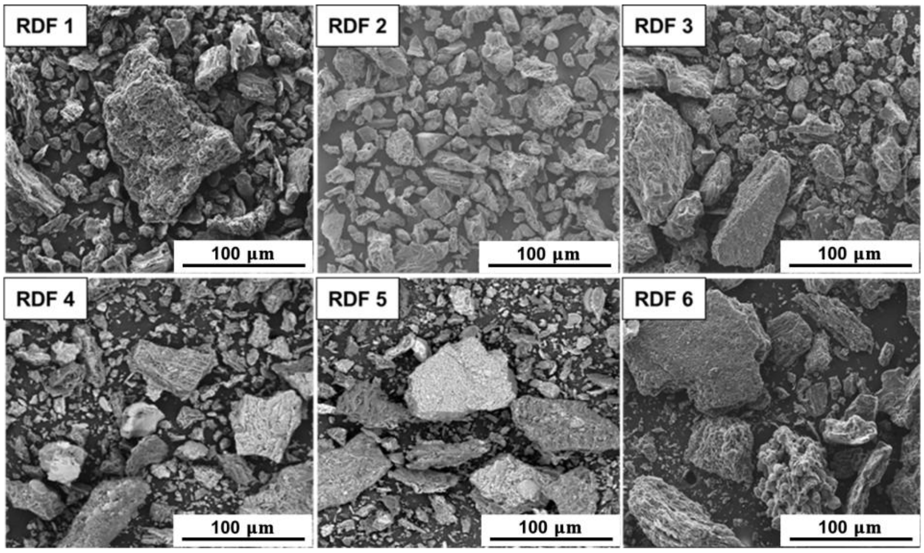

Figure. 3. The morphological characteristics of RDF pellets under variations of biomass waste and CaO blend compositions were analyzed through SEM testing.

From the low-magnification SEM images reveal the presence of aggregates approximately 100 µm in size. High sawdust content as shown in Figure 3 (RDF-4, RDF-5, RDF-6), shows a large aggregates and porous structures. In contrast, mixed compositions containing low sawdust content (RDF-1, RDF-2, RDF-3) reduce porosity but can improve calorific value and structural stability. A balanced ratio of sawdust and other materials (RDF-1 and RDF-5) offers potential optimization between porosity and mechanical strength. RDF-1 and RDF-2 containing a lower sawdust content results in large, dense particles with a relatively smooth surface, indicating the absence of natural wood structure. The surface pores appear small and closed, suggesting high density but low surface reactivity [35]. This composition tends to lower combustion and adsorption efficiency when used as RDF [36].

In contrast, samples containing higher amounts of sawdust display a more intricate and uneven porous structure, which mirrors the cellulose framework characteristic of carbonized wood [37]. The rough surface with interconnected micropores supports more efficient adsorption and combustion, indicating natural activation from the sawdust texture. RDF-3 and RDF-4 samples with a medium sawdust composition, shows more uniform and finely fragmented particles. The slightly porous surface suggests an optimal mixture of sawdust and other materials, likely resulting in pellet RDF that balance mechanical integrity and combustion performance [38]. RDF-5 and RDF-6 samples illustrate a disproportionate mixture of wood sawdust and organic waste, leading to cracked and fragmented particles. This suggests possible decomposition or chemical degradation during the activation process [39].

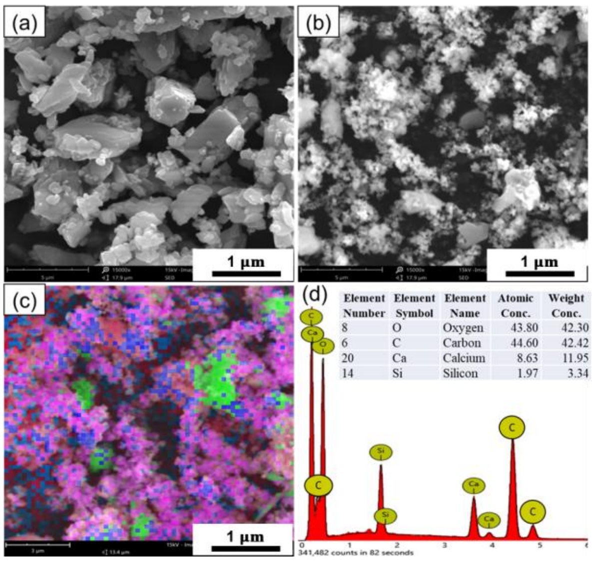

Figure. 4. (a) SEM micrograph of CaO powder, (b) SEM micrograph of RDF-1 pellet with CaO of 5 wt% addition, (c) EDX mapping of RDF-1 pellet, (d) EDX elemental composition of RDF-1 pellet.

The irregular surface morphology suggests the presence of residual organic material, which may lead to the formation of an amorphous structure characterized by high reactivity but diminished mechanical strength. In mixtures of sawdust and plastic waste, the surface morphology shows denser regions, likely caused by plastic melting. This phenomenon tends to seal or fill pores, resulting in lower porosity and reduced combustion reaction rates. While this composition enhances heat generation, it may compromise surface reactivity. For the sawdust and CaO mixture, coarse grains and particle aggregations are observed, likely due to the reaction between CaO and carbon. The surface appears rougher and denser, with signs of recrystallization or aggregation. This composition has the potential to improve thermal stability and enhance the ash properties of the RDF pellets [40]. Figure 4. (a) SEM micrograph of CaO powder at high magnification showing irregularly shaped particles with angular morphology and varying sizes. The particles exhibit rough surfaces, indicative of their highly reactive nature. (b) SEM micrograph of RDF-1 pellet containing 5 wt% CaO, showing a compacted matrix with CaO particles distributed within the RDF structure. The presence of fine and coarse particles suggests heterogeneity in the RDF matrix. (c) EDX elemental mapping of RDF-1 pellet highlighting the distribution of key elements: oxygen (red), carbon (purple), calcium (green), and silicon (blue). The map confirms the presence of CaO particles dispersed throughout the RDF matrix, with regions of high calcium concentration observed as green clusters. (d) EDX spectrum and quantitative elemental analysis of RDF-1 pellet, revealing that carbon (42.44 wt%) and oxygen (42.30 wt%) are the dominant elements, followed by calcium (11.95 wt%) and silicon (3.34 wt%). These results indicate the successful incorporation of CaO into the RDF pellet and the presence of minor silicon likely originating from inorganic components in the RDF feedstock. Furthermore, the incorporation of calcium oxide (CaO) into Refuse Derived Fuel (RDF) pellets offers some advantages, particularly in enhancing hygienization and supporting gasification processes. Acting as a structural additive, CaO improves the mechanical properties of the pellets and helps reduce fire risks during storage [41]. Additionally, it can affect the moisture content of RDF, thereby increasing its storage stability.

Figure. 5. Visual appearance of RDF pellets under variation of biomass waste and CaO blend compositions.

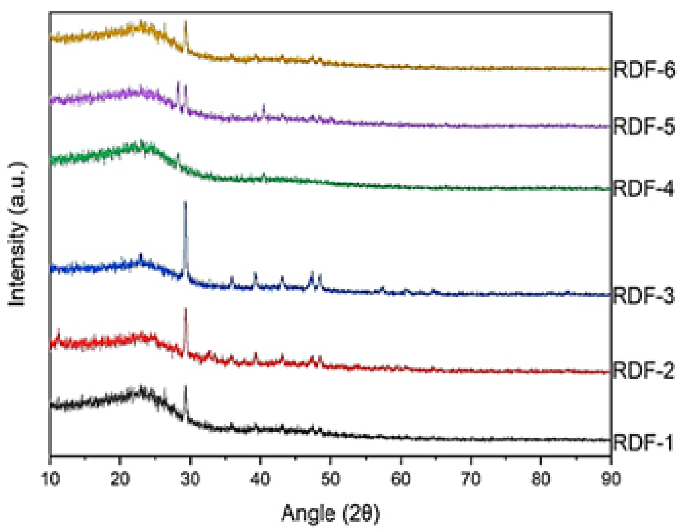

Figure. 6. X-ray diffraction results for the RDF pellets under variation of biomass waste and CaO blend compositions.

Figure 5 illustrates six types of RDF pellets, highlighting how the color of the wood pellets varies according to biomass waste and CaO-blend compositions. The RDF pellet diameters ranged between 6.21 mm and 6.61 mm. RDF pellets produced by combining biomass waste (sawdust and organic waste) exhibit slightly larger diameters than those made solely from pure sawdust. In terms of length, the pellets containing 75% biomass waste (sawdust and organic waste), 20% plastic waste, and 5% CaO showed the greatest length at 47.51 mm. Although increasing the plastic waste content resulted in shorter pellet lengths, they remained longer than the pure sawdust pellets, which measured 41.29 mm. The XRD results for RDF samples are depicted in Figure 6, where displays sharp diffraction peaks at 2θ (26.6°; 29.4°; and 37°), corresponding to crystalline phases such as silica, calcium carbonate, and calcium oxide [42]. Additionally, a broad sloping background is observed, indicative of amorphous organic phases like cellulose and lignin [43]. This composition suggests that the RDF pellets possess a high calorific value potential due to the predominance of organic compounds, while the presence of mineral phases contributes to a moderate to high ash content, depending on the proportion of inorganic material [44].

The Thermogravimetric analysis (TGA) graph illustrates the mass loss curves as a function of decomposition temperature for six RDF pellet samples with different biomass waste and CaO blend compositions. The observed mass loss reflects the evaporation and release of volatile compounds, as well as the thermal decomposition behavior of the materials. TGA analysis revealed mass losses of in the range between 35 to 80 wt% for RDF-1, RDF-2, RDF-3, RDF-4, RDF-5 and RDF-6, respectively, indicating that approximately 25% char remained at the end of the process. Unlike coal and petroleum coke combustion, where fuel constituents decompose in the solid phase during char combustion, RDF combustion exhibits decomposition primarily in the gas phase at earlier stages [45]. This behavior is attributed to RDF's low fixed carbon content and high volatile matter fraction [46].

Figure 7 shows the thermogravimetric analysis of RDF samples. RDF-1 exhibits a slow and steady mass loss, leaving the smallest residue at high temperatures (~700 °C). This suggests a high sawdust content, as wood components like hemicellulose and cellulose decompose completely at elevated temperatures. RDF-2 shows the most rapid and significant mass loss below 400 °C, resulting in a low final residue. The medium to high wood composition indicates excellent thermal reactivity, making it well-suited for energy production. RDF-3 shows the slowest rate of mass loss and the highest final residue (40%). This suggests a high proportion of inorganic materials (e.g. CaO) and possibly plastics. The low sawdust content contributes to higher heat resistance but results in greater residual mass.

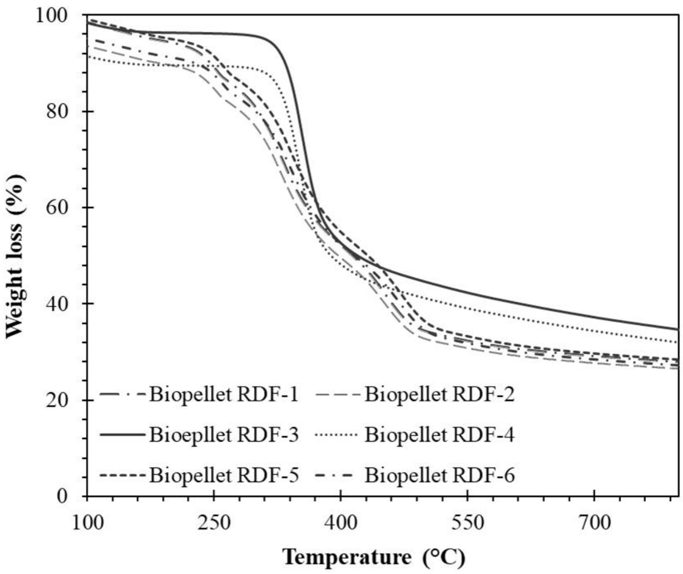

Figure. 7. The thermogravimetric analysis of RDF pellets under variations of biomass waste and CaO blend compositions.

RDF-4 sample shows the decomposition rate relatively quickly but still leaves a moderate residue (~35%). This indicates a medium sawdust content blended with other organic materials, such as kitchen waste or small amounts of plastic. RDF-5 sample shows a decomposition pattern similar to RDF-1 and RDF-2, with dominant mass loss occurring between 300 to 500 °C. This behavior suggests a high lignin content, characteristic of hardwoods or other biomass materials. RDF-6 shows the curve closely resembles that of RDF-5 but with slightly more residual mass. Its composition likely consists of sawdust mixed with other materials in moderate proportions.

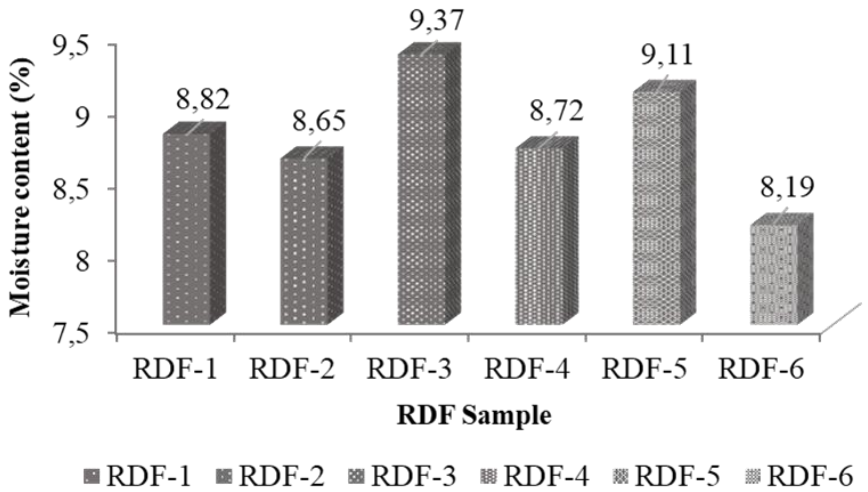

Figure. 8. Graph of correlation between pellet RDF composition and water content. The various composition of biomass waste and CaO blend composition is outlined in Table 1.

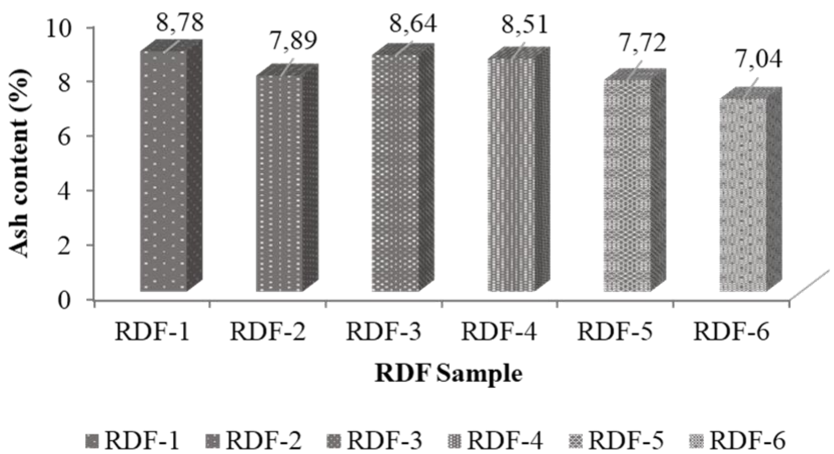

Figure. 9. Graph of correlation between pellet RDF compositions and ash content. The various composition of biomass waste and CaO blend composition is outlined in Table 1.

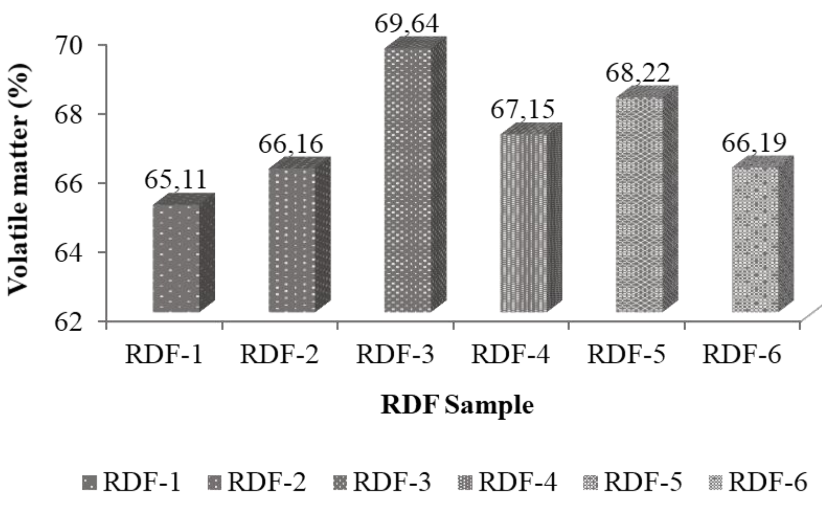

Figure. 10. Graph of correlation between pellet RDF composition and volatile matter. The various composition of biomass waste and CaO blend compositions is outlined in Table 1.

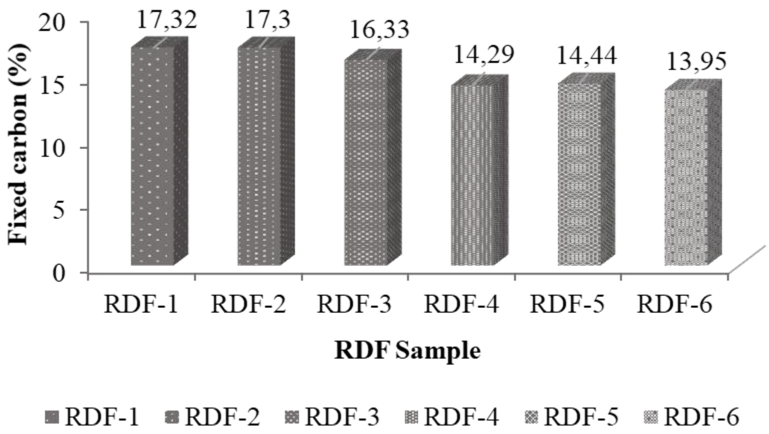

Figure. 11. Graph of correlation between pellet RDF compositions and fixed carbon. The various composition of solid waste and CaO blend composition is outlined in Table 1.

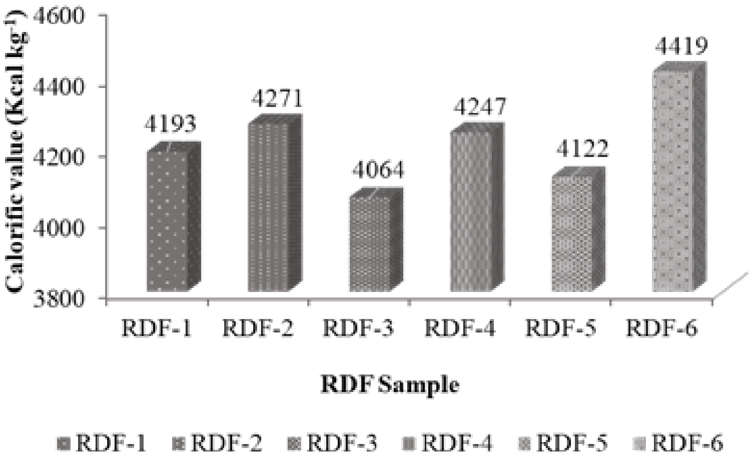

Figure. 12. Graph of correlation between pellet RDF compositions and calorific value. The various composition of biomass waste and CaO blend composition is outlined in Table 1.

The results for moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon (FC) influence the gross calorific value are presented in Table 2 and Figure 8. Moisture content is a critical parameter for assessing the quality of RDF pellet, as it directly influences their calorific value, ignition ease, combustibility, and the amount of smoke generated during combustion. According to Obernberger et al. (2004), a high moisture content lowers the calorific value, reducing energy conversion efficiency and overall performance, since a portion of the energy is expended to evaporate the water [47]. Excessive moisture also inhibits sustained combustion. Conversely, low moisture content enhances efficiency, improves combustion continuity, and supports better fuel performance [48]. Moisture content significantly impacts the combustion behavior of RDF pellets. It affects internal temperature changes due to the endothermic evaporation process and the energy required to raise the fuel to combustion temperatures [49]. During the burning process, water within the pellets absorbs heat for vaporization, which reduces their effective calorific value. This energy loss leads to lower combustion temperatures and can impair the reaction. As noted by Rahman (2011), RDF pellets with high water content not only exhibit reduced calorific value but also face difficulties in ignition and tend to produce excessive smoke [50]. According to the standard SNI 8966-2021, the moisture content of RDF pellets must not exceed 10%. The RDF pellets tested in this study exhibited a moisture content of 8.6%, meeting the specified standard [51]. Lower moisture content generally indicates higher quality of RDF pellet. As noted by Lehtikangas (2001), the average moisture content of commercial pellet products ranges between 10–12% [52]. The relatively low moisture content achieved in this study is attributed to extended drying times during preparation. Similar to briquettes, RDF pellets are produced through a compaction process. High compaction pressure can also contribute to reduced moisture content by compressing and filling the pores structure of materials, thereby limiting water retention [53].

The residue left after fuel combustion is referred to as ash. Ash consists of non-combustible materials that do not contain carbon or contribute to the calorific value [54]. Figure 9 shows the correlation between pellet RDF and ash content. In biomass, ash primarily comprises minerals such as calcium, potassium, magnesium, and silica, which can influence the combustion process and energy output [55]. A higher ash content in fuel reduces its calorific value, while lower ash content enhances energy efficiency. Ash forms from mineral compounds bound within the carbon structure of biomass during combustion and also acts as an impurity in the fuel [56]. To determine ash content, the fuel is typically heated to 450–500 °C for approximately one hour, leaving behind only the non-flammable residue. As noted by Obernberger et al. (2004), elevated ash levels in biomass fuels can contribute significantly to pollution and operational challenges during combustion [57]. The highest ash content was observed in the RDF-1 pellet, with a composition of sawdust and organic waste (1:1), reaching 8.78%. In contrast, the lowest ash content was found in RDF-6, with a composition of (6:1), at 7.04%. This trend indicates that increasing the proportion of material in the RDF pellets leads to lower ash content. This is because the pellet has a lower concentration of non-combustible substances, making it easier to burn and evaporate. Consequently, combustion produces minimal residue, resulting in reduced ash formation [58].

Volatile matter is a substance found in fuel such as methane, hydrocarbons, hydrogen, carbon monoxide, nitrogen, and unburned gases. Volatile matter (VM) is determined by placing the fuel in a furnace at a temperature of 900±15°C for 15 minutes [59]. The materials that will evaporate when the pellets are dried at a controlled temperature. These volatile materials determine the combustion ability of a fuel. Fuel with a high volatile matter content means that most of its calorific value will be released as combustion vapor [57]. The highest volatile matter content is found in RDF-3 pellet sample, with a sawdust and organic waste composition of (1:3) at 69.64%, while the lowest volatile matter content is found in RDF-1 pellet with a sawdust and organic waste composition (1:1) at 65.11% as shown in Figure 10. A reduced volatile matter content indicates improved quality of the RDF pellets. High volatile matter content will produce a lot of smoke when pellets are burned. Volatile matter levels are also affected by the drying process. Prolonged drying of RDF pellets reduces both their moisture content and volatile matter content [60].

Figure 11 shows the correlation between pellet RDF compositions and fixed carbon. The carbon content of a solid fuel is a key determinant of its energy potential. Fixed carbon refers to the fraction of carbon remaining in the fuel after the release of volatile matter during combustion. Measuring fixed carbon provides insight into the amount of solid material capable of burning after volatile components have been released. Carbon content is a critical parameter for fuel quality, as higher fixed carbon levels correspond to higher calorific values, thereby enhancing fuel performance [61]. Several factors influence the carbon content. For example, a higher starch binder content can lead to increased ash formation, which subsequently reduces the carbon fraction. Moreover, the drying process plays a critical role, extended drying reduces moisture content, thereby enhancing the calorific value and increasing the fixed carbon content. In this study, the highest fixed carbon content (17.32%) was observed in pellet RDF-1 and RDF-2 pellets composed of sawdust and organic waste of (1:1 and 1:2). Conversely, the lowest fixed carbon content (13.95%) was recorded in RDF-6 pellet composed of sawdust and organic waste of (6:1).

Calorific value refers to the amount of heat generated per unit weight during the combustion of a fuel. It is the primary parameter for assessing the quality of RDF pellets. Defined as the heat released from burning a specific mass of fuel, the calorific value accounts for the formation of ash, CO_2, SO_2, nitrogen, and water (excluding water vaporized as steam). A higher calorific value indicates superior fuel quality. The calorific value is closely related to the fixed carbon content of the RDF pellets, as higher fixed carbon levels generally result in greater energy output [62]. Figure 12 shows the correlation between pellet RDF compositions and calorific value. In this study, the highest calorific value was recorded in RDF-6 pellets made from sawdust and organic waste at (6:1) ratio, reaching 4419 kcal/kg. Conversely, the lowest calorific value was observed in RDF-1 pellets with biomass and organic waste composition of (1:1), measuring 4064 kcal/kg. The proximate analysis results for the RDF pellets are summarized in the Table 2. The result shows that RDF-1 pellet exhibits relatively high ash content, indicating a significant proportion of inorganic materials. The heating value is moderate, consistent with its relatively high fixed carbon content. However, the elevated moisture content could reduce combustion efficiency. RDF-2 demonstrates a high calorific value and low ash content, making it an excellent fuel candidate. The medium-to-high sawdust content, combined with low moisture and high FC, suggests good combustion efficiency and energy potential. While, for RDF-3, despite it has a high volatile matter, the heating value is low due to elevated moisture and ash content, which compromise efficiency. This composition likely contains a higher proportion of non-biomass materials (e.g., plastics, wet organics) or reduced sawdust content. RDF-4 shows a high calorific value even with low FC, possibly due to the presence of highly volatile solid fuels such as plastics. However, ash and moisture levels remain considerable, which may impact residual combustion. RDF-5 shows the content of relatively high volatile matter and moisture, enabling rapid ignition but potentially lowering combustion efficiency. RDF-6 exhibits the highest calorific value despite presenting the lowest fixed carbon content. This phenomenon can be attributed to its elevated plastic composition, as plastics are characterized by high energy density even at low fixed carbon levels. Furthermore, the reduced ash and moisture contents contribute to enhanced combustion efficiency and improved storage stability [63].

Densification enhances the density of raw materials by 2 to 3 times (as shown in figure 13). This increase in density leads to a reduction in the volume of raw materials, thereby improving storage and transportation efficiency and minimizing the risk of damage. Several factors affect bulk density, including moisture content, particle size, CaO concentration, and the morphology of the raw material [64]. Achieving the ideal moisture level and particle size optimizes lignin activation during densification. Materials with high lignin content, such as wood sawdust and organic waste, exhibit superior compaction performance. The morphology of wood sawdust, characterized by its lower porosity, further supports effective densification. As a result, the density of RDF pellets typically ranges between 0.92 to 1.18 kg/dm³. Both the density and calorific value of these pellets determine the energy content per unit volume. High-density RDF pellets generate more energy compared to those with lower density. The densification process increases the heating value by approximately 1 to 2 times. Additionally, incorporating wood sawdust into RDF pellets enhances their density and, consequently, the energy produced. This improvement in energy content per volume unit directly contributes to the overall efficiency of RDF pellets.

TABLE 1.
THE VARIOUS OF BIOMASS WASTE AND CAO BLEND COMPOSITIONS FOR EACH RDF PELLETS

RDF compositions	RDF-1	RDF-2	RDF-3	RDF-4	RDF-5	RDF-6
	(g)	(g)	(g)	(g)	(g)	(g)
Wood sawdust (a blend of meranti and bangkirai)	213	283	340	354	366	386
Organic waste (fruits peel)	212	142	85	71	59	64
Mixed Plastic waste (PE, PP, and PET)	25	25	25	25	25	25
Calcium oxide (CaO)	25	25	25	25	25	25
Tapioca starch	25	25	25	25	25	0
Total of weight (g)	500	500	500	500	500	500

TABLE 2.
THE RESULT OF PROXIMATE ANALYSIS OF RDF PELLETS

Parameter value	RDF sample					
	RDF-1	RDF-2	RDF-3	RDF-4	RDF-5	RDF-6
Diameter (mm)	6.21	6.33	6.27	6.51	6.44	6.61
Length (mm)	47.51	46.21	45.73	42.44	41.29	41.15
Density (kg/dm^3)	0,98	1,15	0,92	1,08	1,10	1,18
Volatile matter (%)	65,11	66,16	69,64	67,15	68,22	66,19
Moisture content (%)	8,82	8,65	9,37	8,72	9,11	8,19
Ash content (%)	8,78	7,89	8,64	8,51	7,72	7,04
Fixed carbon (%)	17,32	17,3	16,33	14,29	14,44	13,95
Calorific value (Kcal/kg)	4193	4271	4064	4247	4122	4419

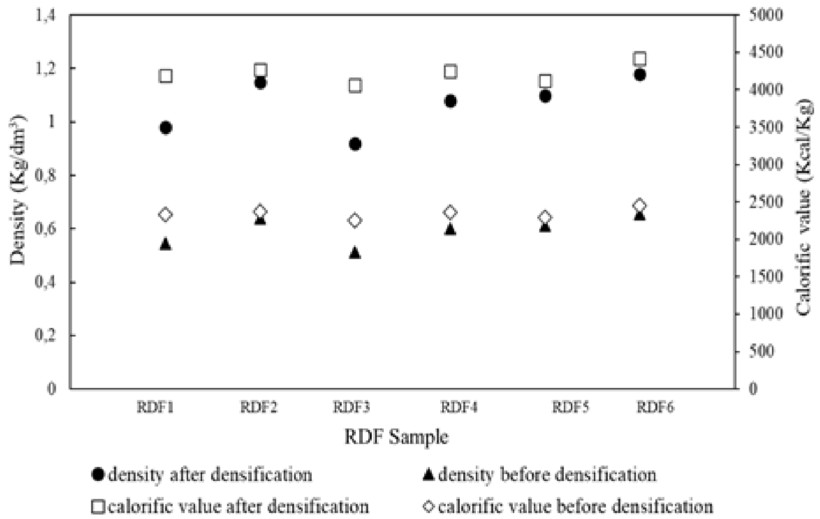

Figure. 13. Correlation between density and calorific value of RDF pellets before and after densification

IV. CONCLUSION

The study demonstrates that the composition of biomass waste and CaO blends significantly influences the pelletizing characteristics and fuel properties of RDF pellet. Optimized blending ratios improve the physical attributes such as density and calorific value of the RDF pellets. The inclusion of CaO as an additive plays a critical role in reducing emissions by promoting the capture of acidic gases and improving ash melting behavior. However, excessive CaO content can negatively impact pellet strength and energy content due to its non-combustible nature. Therefore, a balanced formulation between biomass waste and CaO is essential to produce high-quality, eco-friendly RDF pellet that meets energy and environmental standards. These findings highlight the potential of biomass waste and CaO blends as a sustainable solid fuel alternative and provide a scientific basis for scaling up RDF production in waste-to-energy initiatives. It can be concluded that high-quality RDF pellets for energy recovery can be successfully fabricated by incorporating various proportions of RDF in the formulations. This study presents a promising approach for energy recovery from waste, emphasizing its economic and environmental benefits in addressing the global rise in energy demand and the continuous growth of waste generation, contributing toward a more sustainable society.

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