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Fuel Property Evaluation of Wood Pellets from Rice Straw and Refuse-Derived Fuel Blends

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Abstract – *As the demand for renewable energy and effective waste management grows, this study investigates the potential of producing wood pellets from rice straw biomass blended with refuse-derived fuel (RDF). Six mixing ratios by weight of rice straw to RDF were tested: 100:0, 90:10, 80:20, 70:30, 60:40, and 50:50 (wt%). The RDF used comprised 48% plastic, 25% paper, 23% fabric, and 4% organic matter. Pellets were produced using a rotary flat die briquetting machine, and key properties—including higher heating value (HHV), durability, bulk density, equilibrium moisture content, and water absorption behavior—were evaluated. Results showed that increasing RDF content improved the HHV, reaching a maximum of 17.40 ± 1.06 MJ/kg at 50 wt% RDF. However, higher RDF proportions reduced durability (lowest at 93.34 ± 2.63%) and bulk density (545.09 ± 31.85 kg/m³). Equilibrium moisture content also decreased with more RDF, reaching a minimum of 12.87 ± 1.62% (dry basis). Notably, RDF addition enhanced water resistance by reducing pellet disintegration during immersion. These findings highlight a promising strategy for converting agricultural residues and municipal waste into high-quality solid biofuels with enhanced energy content, water resistance, and reduced moisture sensitivity. The integration of rice straw and RDF offers a sustainable solution for waste valorization, supporting both environmental protection and the development of decentralized renewable energy systems.*

Keywords – biomass pellets, fuel properties, refuse-derived fuel (RDF), rice straw.

1. INTRODUCTION

The increasing global demand for energy, coupled with the adverse environmental impacts of fossil fuel consumption, has intensified interest in renewable energy sources. Among these, biomass has emerged as a promising option due to its widespread availability and sustainable characteristics [1]. In countries like Thailand, which generate large quantities of agricultural residues such as rice straw, the potential for biomass energy production is substantial, as acknowledged in the national Alternative Energy Development Plan [2]. One effective method for utilizing biomass is pelletization, which improves fuel properties by increasing energy density, enhancing combustion efficiency, and simplifying transportation. However, conventional biomass pellets still face challenges including relatively low heating values and limited mechanical durability [3]–[4]. To address these limitations, researchers have explored the integration of high-energy-density materials such as refuse-derived fuel (RDF) - a heterogeneous mixture typically composed of plastics, paper, textiles, and organic matter [5]-[8]. Several studies support the benefits of adding RDF. Chotikhun *et al.* (2023) [9] produced fuel from a mixture of sawdust and refuse-derived fuel (RDF) waste. They found that blending sawdust with RDF at proportions ranging from 0% to 50% RDF increased the heating value from 19.40 MJ/kg to 22.09 MJ/kg, while moisture absorption decreased from 9.68% to 4.17%, respectively. Rezaei *et al.* (2020) [5] produced pellets from RDF, which consisted of plastic, paper, organic, and wood *materials*. Their study found that RDF with a high plastic content, specifically when the plastic proportion increased from 20% to 40%, resulted in the heating value rising from 23.6 MJ/kg to 29.8 MJ/kg. However, at the same time, the durability decreased from 92.25% to 50.96%, and the density of the pellets dropped from 1145.8 kg/m³ to 1040 kg/m³, respectively. Laosena *et al.* (2022) [10] studied the production and properties of pellets made from mixtures of rubberwood (Hevea brasiliensis) and refuse-derived fuel (RDF) waste at ratios of 100:0, 70:30, 60:40, and 50:50. They found that the mechanical durability ranged from 98–99%, and pellets with a ratio of 50% rubberwood and 50% RDF had a heating value 22.21% higher than pure rubberwood pellets, as well as the highest density and energy content among all samples. In addition to the aforementioned property tests, Yang *et al.* (2021) [11] studied refuse-derived fuel (RDF) as an approach for converting municipal waste, aiming to address the depletion of fossil fuels and improper waste management. By applying a gasification process, they found that using RDF instead of coal reduced CO2 emissions by up to 40% and decreased the amount of waste sent to landfill by more than 50%. Despite these advancements, existing literature has primarily focused on blending RDF with woody biomass. Limited attention has been given to the co-pelletization of RDF with agricultural residues, such as rice straw, which are

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both abundant and underutilized in Thailand. Therefore, this study aims to investigate the production of biomass pellets from rice straw blended with RDF at various ratios. Key properties, including higher heating value (HHV), bulk density, durability index, equilibrium moisture content (EMC), and water absorption behavior, are examined to assess the technical feasibility and performance of the resulting fuel. The findings are expected to support the development of efficient biomass-based energy systems while promoting sustainable waste management practices.

2. MATERIALS AND METHODS

2.1 Raw Materials Preparation

Rice straw collected from Nakhon Pathom province was utilized as a biomass feedstock for wood pellet production. The straw was size-reduced using a chopper equipped with a screen to ensure particle sizes smaller than 5 mm (as illustrated in Figure 1), and its moisture content was controlled within 10–15% (wet basis). Refuse-derived fuel (RDF) was composed of plastic, paper, fabric, and organic matter. All components were shredded to particle sizes below 5 mm and blended in the following proportions: 48% plastic, 25% paper, 23% fabric, and 4% organic matter. This blended waste composition was referred to as RDF, as shown in Figure 1. Subsequently, rice straw and RDF were mixed at six different weight ratios of rice straw to RDF: 100:0, 90:10, 80:20, 70:30, 60:40, and 50:50 (wt%). These mixtures were then used for pellet production.

Fig. 1. Rice straw and refuse-derived fuel (RDF) materials used in the study.

2.2 Wood Pellet Production

The pelletization process was conducted using a rotary flat die briquetting machine. A 10 kg sample of the prepared rice straw–RDF mixture was conditioned by adding 20–30% water by weight to achieve an appropriate moisture level for pellet production. The mixture was then fed into the pelletizing machine and compressed through a die with a diameter of 6 mm. The resulting wood pellets, which exited the machine at elevated temperatures, were subsequently air-cooled to dissipate heat and enhance their structural integrity. The overall production process is illustrated in Figure 2.

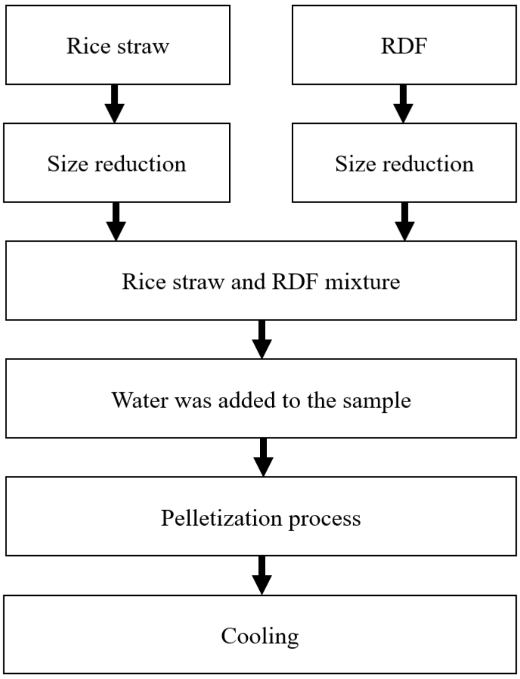

Fig. 2. Schematic representation of the wood pellet briquetting process.

2.3 Properties of Wood Pellets

The higher heating value (HHV) of the samples was determined using a Parr bomb calorimeter in accordance with ASTM D5865-07 [12].

The bulk density of the wood pellets was measured according to ASTM E873-82 [13]. The sample was placed into a box with dimensions of 0.305 × 0.305 × 0.305 m. The box was then lifted and dropped from a height of 1.5 inches, repeated 25 times to settle the material. After compaction, the weight of the pellet sample (m_{pellet}) and the volume occupied in the container (V_{pellet}) were recorded. Bulk density (ρ_{pellet}) was calculated using Equation (1).

$$\rho_{pellet} = \frac{m_{pellet}}{V_{pellet}} \quad (1)$$

The durability index of the pellets was evaluated following the Pellet Fuels Institute (PFI) standard [14]. A 0.5 kg pellet sample was placed in a durability testing machine equipped with a box measuring 0.300 × 0.300 × 0.125 m and an internal agitator. The box was rotated at a speed of 50 revolutions per minute (rpm) for 10 minutes to induce repeated impact of the pellets against the walls of the chamber. After testing, the sample was sieved through a 1/8-inch mesh screen. Fines and broken particles passed through the screen, while intact pellets remained on top. The retained pellets were weighed (m_{pellet}) and compared with the initial sample mass

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($m_{initial}$) to calculate the durability index (DI) using Equation (2).

$$DI = \frac{m_{pellet}}{m_{initial}} \times 100 \tag{2}$$

The equilibrium moisture content (EMC) of the samples was determined following the method adapted from Soponpongpipat *et al.* (2022) [4]. The samples were initially dried in a hot-air oven at 105 °C for 24 hours. After drying, they were cooled to room temperature in a desiccator chamber. The initial mass (m_i) was recorded, and the samples were subsequently placed in a humidity-controlled chamber maintained at 90% relative humidity (RH) and 30 °C. The sample weight was measured every 30 minutes using an analytical balance with a precision of 0.0001 g. Measurements continued until the weight remained constant, at which point the final mass (m_f) was recorded. The EMC was calculated using Equation (3).

$$EMC = \frac{(m_f - m_i)}{m_i} \times 100 \tag{3}$$

The water absorption behavior of the pellet samples was evaluated by immersing them in a glass tray filled with water. The physical changes of the pellets were monitored over time through photographic documentation to observe the extent of water uptake and structural disintegration.

3. RESULTS AND DISCUSSION

3.1 Physical Characteristics of the Pellets

The visual inspection of pellet surfaces revealed notable changes in physical appearance associated with increasing RDF content, as illustrated in Figure 3. Pellets produced solely from rice straw showed a compact, cohesive structure with smooth surfaces, indicative of effective natural binding among biomass particles. Upon incorporating RDF at 10%, 20%, and 30% by weight, the pellets retained satisfactory cohesion but exhibited minor surface cracks and roughness. This increase in surface irregularity is primarily attributed to the high plastic content in RDF (48%), which lacks inherent binding properties and interferes with the compaction process during pelletization. As the RDF ratio increased to 40% and 50%, the surface defects became more pronounced, with a greater number of visible cracks and a looser structural appearance. These visual changes reflect a decline in pellet integrity as RDF proportion rises. This is consistent with the findings of Rezaei *et al.* (2020) [5], who reported that pellets with a high plastic content generated more dust when subjected to shaking, indicating a rougher surface and a looser structure. This effect is attributed to the lack of inherent binding properties of plastics, which interferes with the natural bonding among biomass particles. In summary, increasing RDF content negatively affects the physical uniformity and cohesion of rice straw pellets, which may influence their handling and mechanical strength during storage and transport.

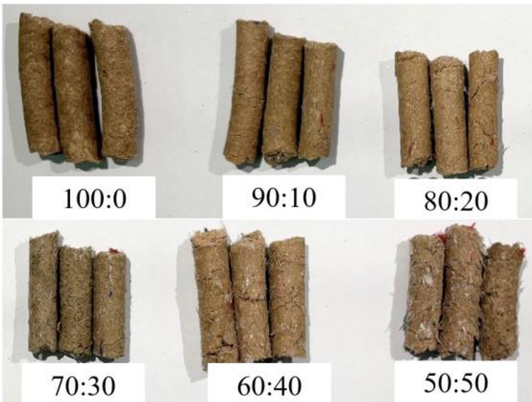

Fig. 3. Surface characteristics of pellets at varying rice straw: RDF ratios (100:0 to 50:50 by weight).

3.2 Higher Heating Value (HHV)

The higher heating value (HHV) is a critical parameter that reflects the energy content of fuel and determines its effectiveness in combustion applications. As illustrated in Figure 4, the HHVs of the wood pellets increased progressively with higher RDF content. Pellets produced solely from rice straw exhibited an HHV of 13.59 ± 1.18 MJ/kg, while those produced from pure RDF achieved a significantly higher value of 19.83 ± 1.22 MJ/kg. The blended samples with RDF proportions of 10%, 20%, 30%, 40%, and 50% yielded HHVs of 14.55 ± 0.29, 15.65 ± 0.67, 15.47 ± 1.43, 16.74 ± 0.73, and 17.40 ± 1.06 MJ/kg, respectively. The observed trend of increasing higher heating value (HHV) with a greater proportion of RDF can be attributed to the inherent properties of RDF components, particularly plastics and paper, which possess higher calorific values compared to lignocellulosic biomass. These components significantly enhance the overall energy content when incorporated into biomass-based fuels. This finding is consistent with the study by Laosena *et al.* (2022) [10] produced pellets from rubberwood blended with RDF and found that an increased proportion of RDF resulted in higher heating values of the pellets. Similarly, Chotikhun *et al.* (2023) [9], which reported that blending RDF with sawdust increased the calorific value of the resulting pellets. In conclusion, incorporating RDF into rice straw pellets presents a viable strategy for enhancing energy output. The positive correlation between RDF content and HHV supports the feasibility of producing high-performance biomass fuels by utilizing waste-derived materials, thereby contributing to both renewable energy development and waste valorization.

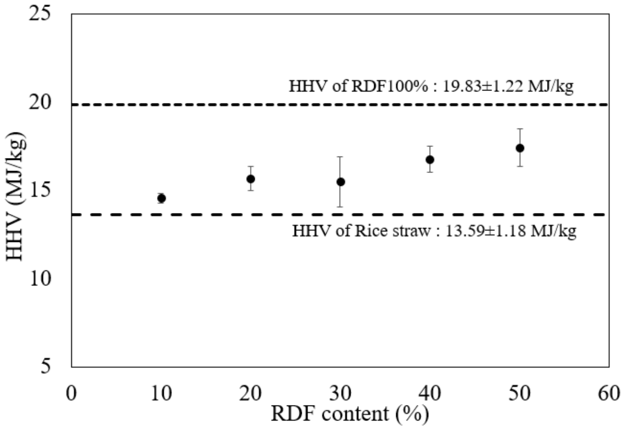

Fig. 4. Effect of RDF blending ratio on the higher heating value (HHV) of rice straw-based pellets.

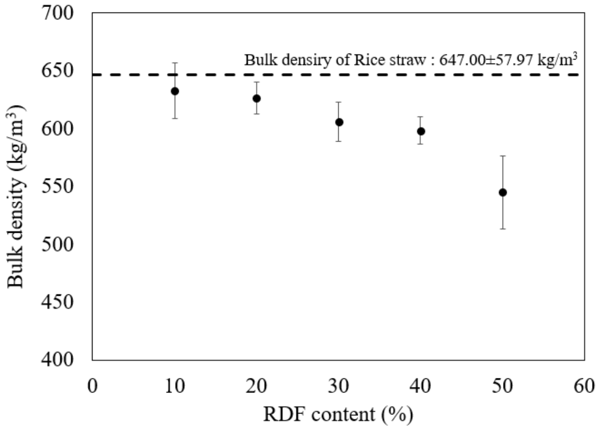

Fig. 5. Effect of RDF blending ratio on the bulk density of rice straw-based biomass pellets.

3.3 Bulk Density

Bulk density is an important parameter influencing the storage, handling, and transportation efficiency of solid biofuels. As shown in Figure 5, the bulk density of the wood pellets demonstrated a clear decreasing trend with increasing RDF content. Pure rice straw pellets recorded the highest bulk density at 647.00 ± 57.97 kg/m^3. When RDF was introduced at 10% to 50% by weight, the bulk density declined progressively to 632.99 ± 24.37, 626.55 ± 13.71, 605.99 ± 16.72, 598.63 ± 11.78, and 545.09 ± 31.85 kg/m^3, respectively. This reduction in bulk density is primarily attributed to the heterogeneous and less cohesive nature of RDF constituents—particularly plastic and fabric materials—which result in pellets with looser packing structure and higher porosity. The lower particle-to-particle bonding strength in RDF-blended mixtures leads to increased void space within the pellet matrix, thereby reducing its overall density. These observations align with findings reported by Laosena *et al.* (2022) [10], who noted a similar decline in density when RDF was added to rubberwood-based pellets. Furthermore, Rezaei *et al.* (2020) [5] found that increasing the plastic content in RDF from 20% to 40% significantly reduced the bulk density of the pellets. In summary, increasing the RDF proportion in rice straw blends compromises the structural compaction of the pellets, thereby lowering bulk density. While this may slightly impact fuel logistics and storage volume, the trade-off may be acceptable given the accompanying gains in energy content and waste reduction potential.

3.4 Durability Index

Durability is a key indicator of pellet quality, reflecting the mechanical resistance of pellets to fragmentation during handling, transportation, and storage. As presented in Figure 6, a declining trend in the durability index was observed with increasing RDF content. Pure rice straw pellets exhibited the highest durability at $99.41 \pm 1.08\%$. The inclusion of RDF at 10%, 20%, 30%, 40%, and 50% by weight resulted in reduced durability indices of $99.07 \pm 2.40\%$, $96.67 \pm 1.82\%$, $95.33 \pm 2.05\%$, $94.62 \pm 1.86\%$, and $93.34 \pm 2.63\%$, respectively. This reduction in durability can be attributed to the physical characteristics of RDF, which typically includes plastic, fabric, and paper—materials with poor binding capacity and structural cohesion. The weaker inter-particle bonding in RDF-blended pellets increases their susceptibility to chipping and breakage under mechanical stress, particularly during tumbling tests. Moreover, the observed decline in durability corresponds with the decrease in bulk density described in Section 3.3, suggesting that RDF reduces pellet compaction, thereby compromising structural integrity. This is consistent with the findings of Rezaei *et al.* (2020) [5], who reported that increasing the proportion of plastic in RDF from 20% to 40% resulted in a decrease in durability from 92.25% to 50.96%. Similarly, García *et al.* (2021) [15] also found that durability decreased as the proportion of RDF increased. In summary, although RDF contributes positively to the calorific value of biomass pellets, its increasing proportion leads to a measurable decline in durability. This trade-off highlights the need to optimize RDF blending ratios or incorporate binding additives to maintain pellet strength for practical applications.

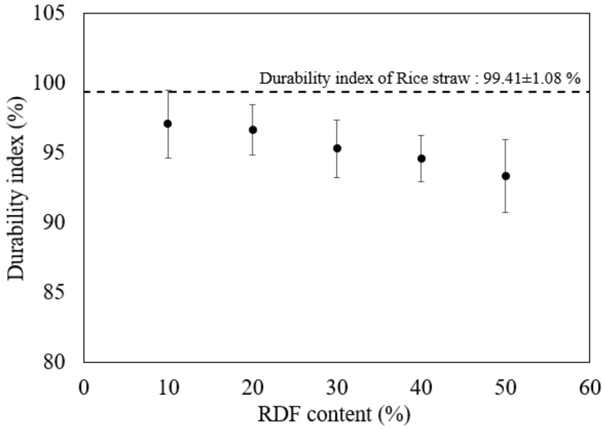

Fig. 6. Durability index of pellets at different rice straw: RDF blending ratios.

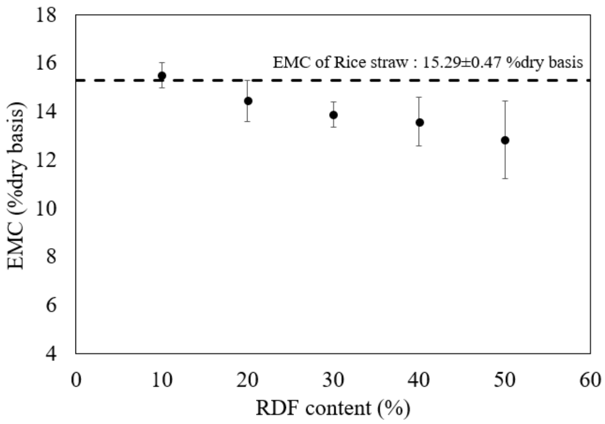

Fig. 7. Effect of RDF blending ratio on the equilibrium moisture content of rice straw-based biomass pellets.

3.5 Equilibrium Moisture Content (EMC)

Equilibrium moisture content (EMC) is a crucial parameter that affects fuel stability, storage performance, and combustion efficiency of biomass pellets. As shown in Figure 7, a decreasing trend in EMC was observed with increasing RDF content. The EMC of pure rice straw pellets was measured at $15.29 \pm 0.47\%$, while RDF-blended pellets with 10%, 20%, 30%, 40%, and 50% RDF exhibited EMC values of $15.52 \pm 0.52\%$, $14.45 \pm 0.85\%$, $13.89 \pm 0.51\%$, $13.59 \pm 1.02\%$, and $12.84 \pm 1.62\%$, respectively. The progressive reduction in EMC can be explained by the material composition of RDF, which includes a substantial proportion of plastic (48%). Plastics are inherently hydrophobic and do not absorb moisture readily. As the RDF proportion increases, the overall water uptake capacity of the blended pellets declines, resulting in lower equilibrium moisture levels. In contrast, lignocellulosic biomass like rice straw tends to be more hygroscopic due to its porous structure and high cellulose content. This is consistent with the study by Nyashina *et al.* (2025) [16], who investigated the blending of wood and cardboard by evaluating moisture absorption from ambient air. They found that as the proportion of cardboard waste in the wood mixture increased, the pellets became more water-resistant. In summary, the incorporation of RDF into rice straw pellets contributes to lowering EMC due to the hydrophobic nature of RDF components. This characteristic not only enhances the shelf-life and storability of the pellets but also benefits combustion efficiency by reducing the energy loss associated with moisture evaporation.

3.6 Water Absorption Behavior

Water resistance is a vital property for biomass pellets, particularly when considering storage and transportation under humid or accidental wet conditions. The results of the water immersion test, as illustrated in Figure 8, reveal a distinct improvement in the water resistance of pellets with increasing RDF content. Pellets composed solely of rice straw rapidly absorbed water, swelled, and disintegrated within the 5-hour immersion period, indicating poor structural integrity under moisture exposure. Conversely, RDF-blended pellets demonstrated significantly enhanced resistance to water-induced degradation. With higher RDF proportions, pellet samples retained their structural form more effectively and showed reduced swelling and disintegration. At RDF proportions of 10% and 20%, some degree of swelling and disintegration was still observed but was clearly less than that of the pure rice straw pellets. At RDF proportions of 30%, 40%, and 50%, the pellets showed minimal swelling and disintegration. This enhanced performance can be attributed to the hydrophobic nature of RDF components, particularly plastic, which constituted nearly half of the RDF blend. Plastic materials exhibit low water affinity, and when incorporated into biomass matrices, they introduce water-repellent characteristics that inhibit moisture penetration. Additionally, the results complement the trends observed in Section 3.5, where increasing RDF content led to a reduction in equilibrium moisture content, further supporting the hydrophobic behavior of RDF-blended pellets. In summary, blending RDF with rice straw effectively enhances the water resistance of biomass pellets. This improvement contributes not only to maintaining mechanical integrity during storage and handling but also to reducing the risk of biological degradation, thereby extending the shelf-life and practical usability of the fuel.

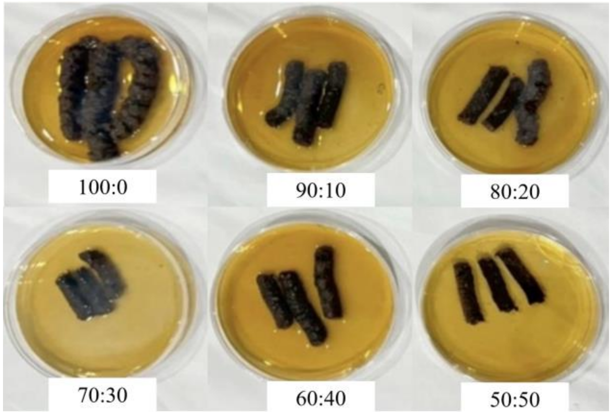

Fig. 8. Pellet disintegration behavior after 5-hour water immersion at different RDF blending ratios.

4. CONCLUSION

This study investigated the feasibility of producing densified biomass fuel from rice straw blended with refuse-derived fuel (RDF) at various mixing ratios. The results demonstrated that the integration of RDF into rice straw pellets is technically viable and beneficial for enhancing fuel performance. Specifically, increasing the proportion of RDF led to a significant improvement in higher heating value (HHV) and moisture resistance due to the hydrophobic nature of RDF components. Although a moderate reduction in bulk density and durability was observed with higher RDF content, all pellet formulations remained within the acceptable limits defined by the Pellet Fuels Institute (PFI) standards. Additionally, it was found that a 30% RDF blending ratio was the most suitable for pellet production, as it provided pellets with minimal disintegration, high heating value, high bulk density, good durability, low equilibrium moisture content, and excellent water resistance. These findings suggest that blending rice straw with RDF offers a practical and sustainable approach to valorizing both agricultural residues and municipal solid waste. The approach not only contributes to renewable energy development but also supports circular economy practices through waste-to-energy conversion.

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