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Production and Characterization of RDF Pellets from Food and Paper Waste as a Renewable Energy Source

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ABSTRACT

This study investigates the production of refuse-derived fuel (RDF) pellets from a blend of food waste, specifically banana peels and paper waste. The goal is to develop a renewable energy source from commonly discarded materials. RDF pellets, formed by compacting various types of organic waste into dense, cylindrical forms suitable for combustion, are the focus of this research. This study produced RDF pellets using a hydraulic pressure of 5 kPa, with food waste-to-paper waste ratios of 30:70, 50:50, and 70:30. The resulting pellets were then analyzed for their physicochemical and morphological properties. Among the tested formulations, the 70:30 ratio yielded the most favourable results, achieving a high heating value (HHV) of 19.92 MJ/kg. Increasing the proportion of banana peels enhanced the pellet density and compactness, indicating a strong influence of composition on fuel quality. Scanning Electron Microscopy (SEM) analysis revealed a more homogeneous and tightly bound internal structure in pellets with higher banana peel content, correlating with improved mechanical strength and energy density. These findings underscore the potential of integrating food and paper waste for RDF production, supporting both sustainable energy generation and effective waste management strategies.

Keywords: Food Waste, Pelletization, Refused-derived Fuel, Renewable Energy.

1. INTRODUCTION

The escalating volume of municipal solid waste (MSW) in Malaysia is a pressing environmental concern, especially as landfill space is rapidly depleting [1]. Among the array of strategies to tackle this issue, the production of Refuse-Derived Fuel (RDF) pellets has emerged as a promising solution [2]. RDF, a renewable fuel derived from combustible components of MSW, including food waste, paper, plastics, and other organic residues, offers a dual benefit. It alleviates the strain on landfills and provides an alternative to fossil fuels in energy generation. RDF pellets are gaining momentum in both large-scale industrial settings, such as cement kilns and power plants, and in small-scale or household applications, particularly in regions with limited access to conventional energy sources [3].

1.1 Background and Motivation

Malaysia generates approximately 39,000 tons of MSW daily, with food and paper waste as the major contributors [4]. Despite ongoing recycling efforts, the recycling rate remains relatively low, necessitating the exploration of alternative waste-to-energy solutions. In this context, food waste, particularly banana peels, holds significant promise due to its high organic content and

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abundance [5]. In Malaysia and many tropical countries, bananas are one of the most widely consumed fruits, and banana peels constitute a major fraction of household and market food waste streams [6]. Compared to other common food wastes such as vegetable residues or fruit pulp, banana peels have been reported to contain higher calorific values (15–20 MJ/kg), lower ash content, and a rich lignocellulosic composition that enhances compaction during pelletization [7]. Similarly, paper residues, which are plentifully generated and often non-recyclable, serve as excellent co-feedstock for RDF pellets production. The use of these materials not only supports waste reduction but also aligns with national sustainability goals, including SDG 7 (Affordable and Clean Energy) and the National Energy Transition Roadmap (NETR) [8].

1.2 Research Aim and Scope

This study aims to produce and characterize RDF pellets from a mixture of banana peel waste and paper residues, with the goal of identifying the optimal formulation for high-quality fuel. Banana peels, often discarded as food waste, are investigated as a key biomass source due to their favorable thermal properties. A review article notes that the energy content of dry banana peel is estimated to be 18.89 MJ/kg, making it a viable feedstock for renewable energy production through thermal processes such as direct combustion or briquetting [9]. The research scope includes fuel property evaluation, such as calorific value, moisture content, and ash content, as well as combustion performance relevant to RDF applications. The potential impact of this research on waste management and energy generation is significant, making it a crucial area of study.

1.3 Characterization Techniques

To gain a deeper understanding of the fuel characteristics, morphology analysis using Scanning Electron Microscopy (SEM) is employed to examine the surface morphology and structural features of the RDF pellets. SEM allows for the visualization of particle bonding, porosity, and compactness factors that directly influence pellet strength, combustion stability, and energy release. These microstructural insights are essential for assessing the performance and feasibility of RDF pellets for real-world use in both domestic and industrial settings [10].

2. MATERIAL AND METHODS

The development of RDF pellets for this study was carried out by four main stages, which are preparation of raw materials, mixing process, pelletizing, and lastly, properties analysis. In this study, the production and analysis of the RDF pellets from food and paper waste were done at the Faculty of Mechanical Engineering & Technology (FMET) and the Faculty of Chemical Engineering & Technology (FCET), Universiti Malaysia Perlis (UniMAP).

2.1 Materials

The first step in producing RDF pellets is to gather the food waste (banana residue) from the nearby stall and paper waste from the main office of FMET. The banana residues were cleaned using water to remove any impurities and dried in the sun for 3 – 4 days. This cleaning process is crucial to ensure the quality of the RDF pellets. The paper waste was shredded into smaller pieces of 1 mm.

2.2 Apparatus and Experimental Procedure

The first stage of this research begins with the preparation of materials. The dried banana peels are subjected to carbonization in a furnace at a controlled temperature of 100°C. The carbonized banana peels, as shown in Figure 1, are then ground into finer particles and sieved into a size of

$500\mu m$. Moving on to the second stage, the mixing process, the banana peel and paper waste are combined in varying ratios of 30:70, 50:50, and 70:30. The mixture is then compacted using a SPECAC manual hydraulic press (Figure 2) at pressures of 5kPa. Finally, the RDF pellets produced (Figure 3) undergo rigorous parameter testing and meticulous data analysis, ensuring the validity of the research's findings.

Figure 1: Carbonized banana peels.

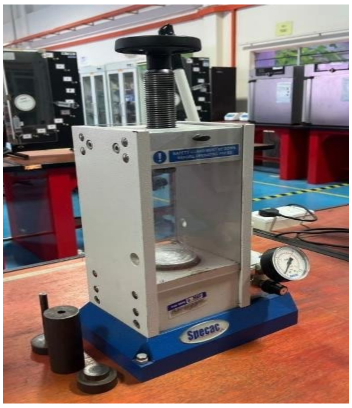


Figure 2: SPECAC hydraulic press.

Figure 3: RDF pellets.

2.3 Analysis

The physicochemical properties of the RDF pellets were assessed through physical, proximate, combustion, and morphology analyzes. Physical analysis was used to measure the RDF pellets' density, while proximate analysis was carried out to determine their ash content, volatile matter, and fixed carbon. The amount of energy density was evaluated through combustion analysis. Morphology analysis was conducted using Scanning Electron Microscopy (SEM) to examine the surface structure and compactness of the pellets, which influence combustion efficiency and mechanical integrity. Each analysis was repeated three times to ensure the precision and reliability of the obtained results.

2.3.1 Physical Analysis

The effect of the carbonization and mixed ratio process on the physical of the RDF pellets produced was determined based on the density of the RDF pellets produced. Density was determined from the ratio of the mass over the volume of the RDF pellets. Equation 1 shows the formula for calculating the density.

Density, ρ= mass/volume, (g/cm^3) (1)

2.3.2 Proximate Analysis

In this analysis, the compositions of ash, volatile matter, fixed carbon, and moisture are analyzed. The moisture content (MC) was obtained by using the oven drying technique and calculated by using Equation 2 where W_w is the wet weight of the sample and W_d is the weight of the dried sample.

$$MC\ (\%) = (W_w - W_d) / (W_d) \times 100 \quad (2)$$

The ash content (AC) was determined according to ASTM E1755-01 (2007), which required the solid fuel to be burned at 575°C for 4 hours in the furnace, and the balance is weighted by using an analytical balance. The percentages of content calculated using Equation 3.

$$AC\ (\%) = (\text{Weight ash}) / (\text{Weight sample}) \times 100 \quad (3)$$

The volatile matter (VM) involves vaporization of the material. In the furnace, 2 g of the RDF sample was heated in a partially closed crucible to about 550 °C for 10 minutes according to the ASTM 872-82 (2006) inside the furnace. Then, the crucible and its content were cooled in desiccators. The weight loss was recorded as a percentage of the volatile matter. The percentage of volatile matter was calculated using Equation 4, where W_i is the initial weight of the sample and W_f is the final weight of the sample.

$$VM\ (\%) = (W_i - W_f) / (W_i) \times 100 \quad (4)$$

Finally, the fixed carbon (FC) is the solid combustion product that remains after a coal particle is heated and the volatile component is driven off, and its calculation is presented in Equation 5.

$$FC\ (\%) = 100\ \% - (MC + AC + VM) \quad (5)$$

2.3.3 Combustion Analysis

The calorific value (CV) of RDF pellets was determined and analyzed using an Oxygen Bomb Calorimeter. This measurement is performed to determine the heat or energy released by the fuel during complete combustion. The measured values are typically displayed in units of MJ/kg.

2.3.4 Morphology Analysis

The morphology of the pellets was tested using a Scanning Electron Microscope (SEM). The analysis aims to compare the surface morphology of the solid fuel made from different torrefaction treatments and particle sizes.

3. RESULTS AND DISCUSSION

3.1 Physicochemical Properties

The effects of mixed ratios on the properties of the RDF pellets were assessed through physicochemical properties analysis, which includes physical, proximate, and high heating value analysis.

3.1.1 Physical Analysis

In this study, the physical property, particularly the density of RDF pellets produced from different banana peel to paper waste ratios, was measured to assess the effect of raw material composition on pellet quality and suitability as a renewable fuel source. Table 1 shows the effect of mixed ratio on the density of the RDF pellets produced.

Table 1: Effect of mixed ratio on the density of the RDF pellets.

Ratio	**30:70**	**50:50**	**70:30**
Density (kg/cm^3)	2.20	2.63	3.10

From the results in Table 1, the highest density (3.10 kg/cm^3) was recorded for the 70:30 banana peel to paper waste ratio, indicating better compaction and binding at higher banana peel content. In contrast, the lowest density (2.20 kg/cm^3) was observed in the 30:70 mixture, suggesting that higher paper content may reduce pellet compactness. This trend highlights the influence of the banana peel's fibrous and cohesive nature in enhancing pellet densification, which is crucial for improving handling, storage, and combustion performance of RDF [11].

3.1.2 Proximate Analysis

Proximate analysis determines the moisture content, ash content, volatile matter, and fixed carbon of RDF pellets, which are key indicators of fuel quality and combustion behaviours. Table 2 summarizes these parameters for pellets produced from different banana peel to paper waste ratios (30:70, 50:50, and 70:30), highlighting the effect of composition on fuel properties.

Table 2: Effect of mixed ratio on the MC, AC, VM, and FC of the RDF pellets.

Composition (%)	30:70	50:50	70:30
Moisture Content (MC)	13.00	13.00	13.00
Ash Content (AC)	14.45	14.67	18.13
Volatile Matter (VM)	14.23	15.41	17.92
Fixed Carbon (FC)	58.32	56.92	50.95

Based on the results in Table 2, the moisture content (MC) remained consistent at 13% across all samples, indicating effective moisture control during the pelletizing process and ensuring comparability between samples. The ash content (AC) increased with a higher proportion of banana peels, from 14.45% in the 30:70 mixture to 18.13% in the 70:30 mixture. This trend suggests that banana peels contain more inorganic material, which could lead to greater ash generation during combustion [12]. High ash content may pose challenges such as slagging or fouling in combustion systems, particularly in industrial applications.

Volatile matter (VM) showed a progressive increase from 14.23% to 17.92% as the banana peel ratio increased. This indicates a greater presence of easily combustible components in banana peels, potentially enhancing ignition and combustion reactivity. In contrast, the fixed carbon (FC) content exhibited a decreasing trend with increased banana peel content, dropping from 58.32% in the 30:70 mixture to 50.95% in the 70:30 mixture. Higher fixed carbon values are generally associated with longer and more stable combustion [13], which suggests that a higher paper content may contribute to improved burn duration and energy stability.

These results demonstrate a trade-off between fuel reactivity and combustion stability. The 70:30 mixture, with higher volatile matter, may be more suitable for applications requiring rapid energy release, while the 30:70 and 50:50 blends, with higher fixed carbon, offer better sustained combustion [14]. Overall, the 50:50 ratio presents a balanced composition, combining moderate ash production with favourable volatile and carbon contents, making it a potentially optimal formulation for RDF pellet production.

3.1.3 Combustion Analysis

Combustion analysis evaluates the energy potential of RDF pellets by determining their calorific value. This parameter reflects the amount of energy released during burning, which is crucial for assessing fuel performance. Table 3 presents the calorific values (CV) for pellets produced from different banana peel to paper waste ratios.

Table 3: Effect of mixed ratio on the calorific value (CV) of the RDF pellets.

Ratio	CV (MJ/kg)
30:70	17.82
50:50	19.03
70:30	19.92

According to the findings presented in Table 3, the calorific value (CV) of RDF pellets increased with a higher proportion of banana peels, ranging from 17.82 MJ/kg for the 30:70 blend to 19.92 MJ/kg for the 70:30 blend. This trend indicates that banana peels possess a higher energy content than paper waste, attributed to their greater volatile matter and organic composition [15]. Proximate analysis further corroborates this observation, as the 70:30 mixture demonstrated higher volatile matter (17.92%) and lower fixed carbon (50.95%), which are associated with enhanced fuel reactivity and elevated calorific values. Conversely, the 30:70 blend, characterized by a higher fixed carbon content (58.32%), shows improved combustion stability. The 50:50 blend strikes a balanced profile, featuring adequate volatile matter (15.41%) alongside moderate fixed carbon (56.92%), making it suitable for various combustion applications [16].

The SEM micrographs support these conclusions: the 30:70 blend exhibited loose structures with voids, indicating weaker compaction and lower combustion efficiency, while both the 50:50 and 70:30 blends revealed denser and more uniform surfaces, reflecting stronger particle bonding, enhanced durability, and improved combustion behavior. Notably, the calorific values obtained are comparable to those of other solid fuels, such as rice husk briquettes (13.4 MJ/kg) [17] and rice husk–banana residue pellets (16.4 MJ/kg) [18], with all samples exceeding the DIN 51731 minimum standard (>17.5 MJ/kg).

These results have significant industrial and environmental implications: the 70:30 blend shows considerable potential as a renewable alternative to coal in energy-intensive sectors, while the 50:50 blend presents a practical solution for smaller-scale heating systems. By valorizing banana peels and paper waste, RDF pellets not only divert a substantial amount of municipal solid waste from landfills and reduce methane emissions but also contribute to Malaysia's Sustainable Development Goal 7 (Affordable and Clean Energy) and the National Energy Transition Roadmap (NETR), thereby reinforcing the transition toward a circular economy [19][20][21].

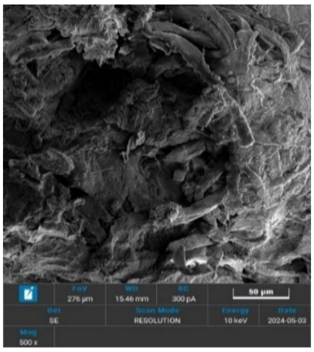
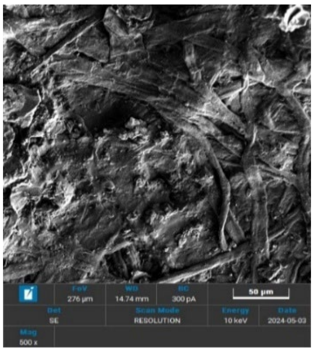
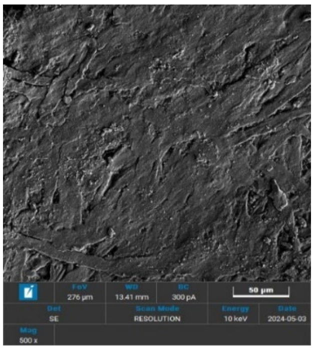
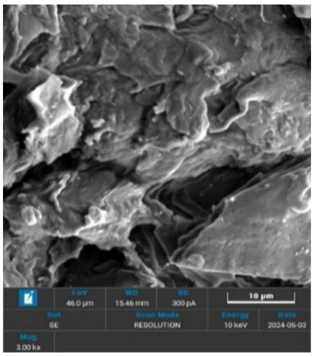
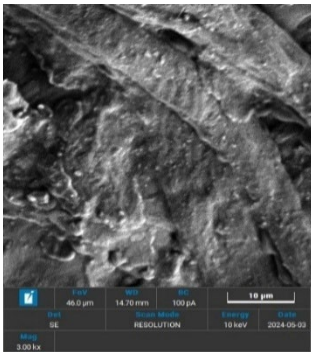
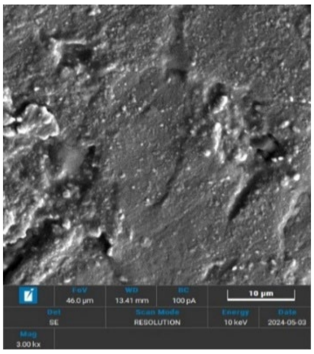
3.1.4 Morphology Analysis

Morphology analysis using Scanning Electron Microscopy (SEM) examines the surface structure, bonding, and porosity of RDF pellets. These microstructural features influence pellet strength and combustion behaviour. Table 4 shows the SEM micrographs of RDF pellets at X500 and X5000 magnifications for different banana peel to paper waste ratios (30:70, 50:50, 70:30).

From Figure 4, the SEM micrographs at X500 magnification showed a clear progression in surface morphology among the RDF pellets, corresponding to their calorific values (CV). The 30:70 blend exhibited a loose and uneven surface with visible voids, indicating weaker compaction, which aligns with its lowest CV of 17.82 MJ/kg. At X5000 magnification, fragmented particles and irregular gaps further suggested poor densification and reduced energy potential. In contrast, the 50:50 blend displayed a more uniform and compact surface at X500, while the X5000 images revealed smoother particle interfaces with minimal micro-voids. This enhanced structural cohesion corresponds to its moderate CV of 19.03 MJ/kg.

The 70:30 blend presented the densest and smoothest surface at X500. The tightly fused microstructures and minimal inter-particle gaps observed at X5000 likely support higher volatile release and combustion efficiency, paralleling its highest CV of 19.92 MJ/kg. These observations highlight that better pellet compaction and reduced porosity enhance volumetric energy density [22], and consistent microstructural properties correlate with higher calorific content [23].

Table 4: Effect of mixed ratio on the RDF pellets morphology.

	30:70	**50:50**	**70:30**
X500			
X5000			

4. CONCLUSION

This study demonstrates that blending banana peels and paper waste into RDF pellets leads to significant improvements in fuel quality, which are strongly influenced by the ratio of the feedstock used. Proximate analysis indicated that increasing the proportion of banana peels generally enhances volatile matter content while reducing ash content, both of which are favorable for combustion efficiency [24]. Consequently, the calorific value increased from 17.82 MJ/kg in a 30:70 blend to 19.92 MJ/kg in a 70:30 blend, reflecting the higher organic and energy-rich composition of banana peels [22].

SEM micrographs at X500 and X5000 magnifications confirmed that the morphological changes correspond to these chemical benefits. The 30:70 pellets exhibited a loose, uneven surface with visible voids, indicating lower compaction and reduced energy density. In contrast, the 50:50 blend displayed improved particle bonding between the banana peel fibers and paper particles, suggesting a balanced structure that enhances both mechanical durability and combustion performance. The 70:30 blend had the densest and smoothest surface with minimal voids, likely contributing to reduced heat loss during combustion and a higher calorific value [25].

Overall, the combination of proximate analysis, calorific performance, and microstructural evidence indicates that the feedstock composition is a critical design parameter for RDF pellets. While the 70:30 blend maximizes energy yield, the 50:50 ratio offers a balanced compromise between structural integrity and energy recovery. These insights can guide the optimization of waste-to-energy systems that utilize mixed organic and paper-based waste streams.

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