Characterization of Torrefied Briquettes from Agricultural Residues of the DOST-Natural Textile Fiber Innovation Hub

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Abstract- This research assessed the torrefied biomass briquettes of pineapple leaves fiber, banana pseudostem fiber, and water hyacinth as a sustainable alternative solid fuel. Biomass residues from the DOST-Natural Textile Fiber Innovation Hub were torrefied at 240°C, 260°C, 280°C, and 300°C for 30 minutes using an experimental quantitative research design and densified with cassava starch binder. The briquettes were characterized for physical integrity, water boiling performance, bulk density, moisture content, calorific value and economic feasibility. Results indicated that higher torrefaction temperature decreased moisture content and improved combustion characteristics and energy value where the highest calorific value (21,676 kJ/kg) was obtained at 280°C and fastest boiling time (11 min 29s) was obtained at 300°C. The 280°C briquette had the best overall compromise between structural integrity, energy performance and fuel quality of all the treatments. The economic analysis revealed a production cost of ₱72.38/kg, selling price of ₱109/kg, monthly return on investment of 21.82%, payback period of 5 months, and benefit–cost ratio of 1.51. Briquettes of torrefied biomass were found to be technically feasible and economically viable with 280°C as the most suitable torrefaction temperature. (Torrefaction, Biomass Briquettes, Agricultural Residues)

I. INTRODUCTION

The continued use of fossil fuels has led to depletion of resources, greenhouse gas emissions and environmental degradation which necessitates the search for sustainable energy options [1]. Coal is still the primary energy source in the Philippines and the use of renewable and locally available resources is increasingly important to meet the energy security and environmental issues [2,3]. Biomass energy, especially from agricultural residues, is a promising solution due to its abundance, renewability and potential to reduce waste-related environmental impacts [4,5]. Within the course of the year, a considerable amount of crop by-products such as banana, pineapple and other crop residues are generated within the country but are often underutilized or disposed of improperly [6]. These materials can be converted into briquettes to enhance their fuel properties and usability [7]. Torrefaction is a further step to enhance biomass quality by increasing energy density, reducing moisture content and enhancing combustion performance [8]. Consequently, torrefied biomass briquettes have become a feasible and sustainable substitute for traditional solid fuels.

II. LITERATURE REVIEW

Biomass Briquettes as Renewable Fuel: Biomass briquettes are manufactured solid fuels produced by compressing agricultural residues such as stalks, husks, fibers and leaves into dense and compacted blocks. This densification increases their energy density, storage stability and handling efficiency, thus making them more suitable for use as fuels than loose residues [9]. Properly produced agro-waste briquettes not only offer improved calorific values but also contribute to waste management by converting low-value residues into usable energy carriers [10]. The briquetting process thus contributes to the sustainable energy strategies by adding value to agricultural by-products and by reducing the dependence on fossil fuels or wood fuel [11].

Torrefaction Process: Torrefaction is a mild thermal treatment of biomass in limited or near-zero oxygen conditions (200–300 °C). The pretreatment improves the energy density, hydrophobicity and grindability of biomass for solid biofuel production. During torrefaction, the hemicellulose is extensively decomposed, the cellulose is partially decomposed, and the lignin is relatively stable, resulting in structural changes that improve the combustion behavior. In order to improve the overall fuel quality of the briquetted product, Chen et al. [12] reported that moisture and volatile matter decreases and fixed carbon and heating value increases with torrefaction.

Agricultural Residues as Feedstock: Pineapple Leaf Fiber (PALF), water hyacinth (Eichhornia crassipes) and banana pseudostem are lignocellulosic agricultural residues. These are known to be good candidates for briquette production and thermal upgrading. Research on banana residues has revealed that whole-tree waste materials (pseudostem, leaves, peels) can be transformed into densified fuels possessing satisfactory heating values and mechanical strength, contingent upon appropriate processing and densification methods; Ahmad et al. [13] manufactured briquettes from banana tree waste and observed enhanced combustion performance and structural stability following drying and size reduction. Similarly, research mixing banana residues with other wastes (pineapple peel, water hyacinth) found that mixing strategies can improve fuel properties and handling characteristics compared with single-feedstock briquettes.

Cassava Starch as Binder: Binders are essential in briquetting as they improve particle cohesion and mechanical integrity, reducing breakage during handling and transport while enhancing combustion performance. They act as a bridge between biomass particles, forming interparticle adhesion that maintains the shape and strength of briquettes even after drying. Starch-based binders are frequently recommended for agricultural residues due to their strong adhesive properties, renewable nature, and clean combustion behavior [9]. Recent studies have shown that natural starches, particularly cassava starch, consistently deliver high compressive strength and low ash content when used with lignocellulosic wastes [14]. Local experiments conducted in the Philippines also reported that cassava starch increased the density and mechanical strength of banana-leaf briquettes without significantly increasing ash content, validating its suitability for fibrous feedstocks such as pineapple leaves, banana pseudostems, and water hyacinths [14].

Local Studies: Local research efforts in the Philippines have focused on transforming agricultural residues into renewable fuel sources through briquetting. The Department of Science and Technology–Forest Products Research and Development Institute (DOST–FPRDI) has played a major role in developing charcoal briquette technologies utilizing coconut shells, sawdust, and agro-industrial wastes to promote rural energy self-sufficiency and small enterprise development [5]. Meanwhile, the University of the Philippines Los Baños (UPLB) conducted an experimental study on banana leaf–derived biochar briquettes and found that the use of cassava starch as a binder increased density, compressive strength, and combustion efficiency while maintaining low ash content [14]. These local studies highlight the viability of locally available biomass materials and binders in producing sustainable briquettes that can serve as clean alternatives to traditional charcoal and firewood fuels.

International Studies: International research has provided valuable insights into optimizing briquette quality and performance from various biomass resources. Kpalo et al. (2020) [1] reviewed the technical and cost benefit analysis of biomass briquetting, emphasizing its contribution to renewable energy development. Studies such as Osei et al. (2024) [15] demonstrated that coconut shell charcoal briquettes exhibit high calorific value and stable combustion suitable for domestic and industrial applications. Mibulo et al. (2023) [16] produced briquettes from banana peels, pineapple peels, and water hyacinth, showing that these residues can yield acceptable fuel properties. Similarly, Ahmad et al. (2018) [13] observed that banana tree waste can be compacted into dense, energy-efficient briquettes, while Rezania et al. (2016) [17] confirmed that water hyacinth can be converted into viable briquettes when properly dried and processed.

III. METHODOLOGY

This study employed an experimental quantitative research design to evaluate the effects of different torrefaction temperatures on the characteristics of biomass briquettes produced from agricultural residues. The research focused on determining the physical, combustion, and energy-related properties of torrefied briquettes manufactured from a combination of pineapple leaf fiber (PALF), banana pseudostem fiber residues (BPSFR), and water hyacinth fiber residues (WHFR). Four torrefaction temperatures (240°C, 260°C, 280°C, and 300°C) were investigated to identify the optimum thermal condition for briquette production. The resulting briquettes were evaluated through performance assessment, water boiling tests, and laboratory analyses, and were subsequently compared with a commercially available briquette.

Raw Material Preparation

Agricultural residues consisting of pineapple leaf fiber, banana pseudostem fiber, and water hyacinth fiber were obtained from the DOST–Natural Textile Fiber Innovation Hub. Prior to processing, the collected materials were cleaned to remove impurities and were air-dried under ambient conditions to reduce moisture content and improve sample stability [18]. After drying, the materials were weighed and prepared for thermal treatment. The total collected biomass consisted of approximately 60.12 kg of pineapple leaf fiber, 102.12 kg of banana pseudostem fiber residues, and 170.87 kg of water hyacinth fiber residues.

Torrefaction Process

The prepared biomass materials were subjected to torrefaction using an electric oven under limited oxygen conditions [12]. Samples were torrefied at four temperature levels: 240°C, 260°C, 280°C, and 300°C. Each treatment was maintained for a residence time of 30 minutes. Before and after torrefaction, the biomass samples were weighed to determine mass changes resulting from thermal degradation. Following treatment, the torrefied materials were cooled in sealed containers to minimize oxidation and moisture reabsorption. This procedure was conducted to improve the fuel properties of the biomass through moisture reduction, increased carbon concentration, and enhanced energy density [19].

Briquette Production

The torrefied biomass samples were mechanically shredded using a food processor blender and subsequently sieved to obtain a uniform particle size [20]. A cassava starch binder was prepared by mixing cassava starch and hot water at a ratio of 1:3. The biomass mixture consisted of equal proportions of pineapple leaf fiber, banana pseudostem fiber, and water hyacinth fiber (1:1:1), with cassava starch binder comprising 10% of the total mixture [9].

Fig. 1. Briquetting of torrefied biomass

Figure 1 illustrates the blended material was thoroughly mixed to achieve homogeneity and was then compressed using a screw-type briquetting machine to produce cylindrical briquettes. The briquettes were designed with an outer diameter of 54 mm, a height of 54 mm, and a central hole to improve airflow during combustion [21]. After briquetting, the samples were air-dried and sun-dried until a constant mass was achieved [12].

Performance Evaluation

The produced briquettes were evaluated using a structured performance checklist covering five categories: physical and structural integrity, visual and material quality, handling and storage suitability, combustion-related performance, and overall acceptability. Fifteen evaluation criteria were rated using a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). Customer Satisfaction Score (CSAT) analysis was employed to determine the acceptability of the briquettes produced at each torrefaction temperature. The reliability of the evaluation instrument was assessed using Cronbach's alpha to determine internal consistency [22].

Water Boiling Test

A Water Boiling Test (WBT) was conducted to assess the practical combustion performance of the briquettes. For each trial, 100 g of briquette fuel was combusted in a charcoal stove to heat 250 mL of water. Water temperature was recorded at two-minute intervals using a digital thermometer until boiling was achieved. The total boiling time was measured using a stopwatch. The test served as an indicator of combustion efficiency and suitability for household heating applications [23].

Laboratory Analysis

The physical and energy-related properties of the briquettes were determined through laboratory testing. Moisture content was analyzed in accordance with ISO 11722:2013, while calorific value was determined using a bomb calorimeter following ASTM D5865/D5865M-2022 standards [24]. Bulk density was calculated from the measured mass and volume of the briquettes using geometric relationships for hollow cylinders [25].

$$v = \pi(R^2 - r^2)h \quad (1)$$

$$\rho = \frac{m}{v} \quad (2)$$

These analyses were performed to evaluate fuel quality and compare the torrefied briquettes with a commercially available briquette product.

Data Analysis

Descriptive statistical methods were used to summarize and compare the results obtained from the performance checklist, water boiling test, bulk density determination, moisture content analysis, and calorific value testing. The performance ratings were interpreted using mean scores and Customer Satisfaction Scores (CSAT), while laboratory results were compared across the four torrefaction temperatures and against a commercial briquette. The temperature condition that exhibited the most favorable combination of physical integrity, combustion performance, and energy characteristics was identified as the optimal torrefaction condition for briquette production.

IV. RESULT

Table 1. Reliability Test: Cronbach's Alpha Interpretation

Cronbach's a	Internal Consistency
0.90 and above	Excellent
0.80-0.89	Good
0.70-0.79	Acceptable
0.60-0.69	Questionable
0.50-0.59	Poor
below 0.50	Unacceptable

From the computed results, Cronbach's alpha value at 240°C is 0.83, which is interpreted as having "Good" internal consistency. At 260°C, the obtained value is 0.81, also indicating "Good" reliability. Similarly, the alpha value at 280°C is 0.82, reflecting a "Good" level of internal consistency among the survey items. Furthermore, at 300°C, the computed Cronbach's alpha value is 0.83, which is likewise interpreted as "Good," indicating that the survey instrument maintained a consistent level of reliability across all temperature conditions.

Fig. 2. Overall result of the CSAT Score of torrefied briquettes produced at four different torrefaction temperatures

Figure 2 illustrates the overall responses from the respondents. The overall result of the CSAT scores for the torrefied briquettes produced at four different torrefaction temperatures showed generally high levels of customer satisfaction and acceptability among the respondents. Among all samples, the briquettes torrefied at 280°C obtained the highest CSAT score of 98.4%, indicating the highest level of overall satisfaction and user acceptance. This was followed by the 300°C variant with a CSAT score of 96%, and the 240°C variant with 89.46%, both reflecting very positive evaluations from the respondents. Meanwhile, the briquettes torrefied at

260°C recorded the lowest CSAT score of 72.67%, although the rating still indicates a favorable level of acceptability.

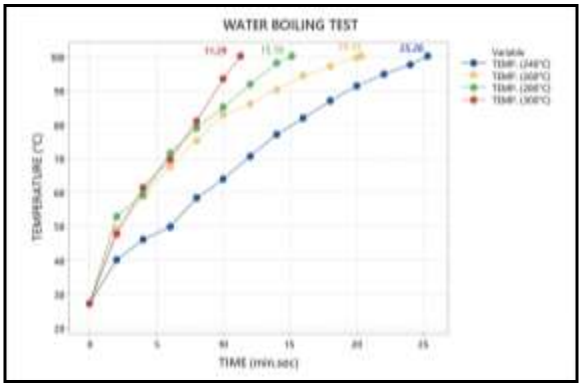


Fig. 3. Average time and water temperature profiles of torrefied briquettes at various temperature

Figure 3 presents the average time–temperature profiles of water heated using briquettes torrefied at 240 °C, 260 °C, 280 °C, and 300 °C. The graph illustrates the rate of temperature increase over time, highlighting the differences in heating behavior among the briquette samples. Briquettes produced at higher torrefaction temperatures exhibited steeper heating curves and reached the boiling point more rapidly compared to those treated at lower temperatures.

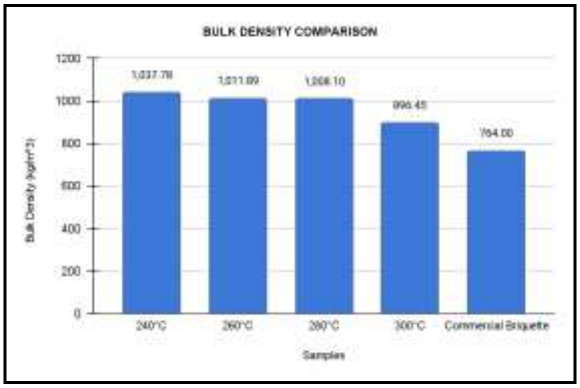


Fig. 4. Comparison of Bulk Density of Torrefied Briquettes and Commercial Briquette

Figure 4 presents a comparison of bulk density for torrefied briquettes produced at 240 °C, 260 °C, 280 °C, and 300 °C against a commercial briquette. The results indicate a clear decreasing trend in bulk density as torrefaction temperature increases. Briquettes treated at 240 °C recorded the highest bulk density (1037.78 kg/m³), followed by 260 °C (1011.89 kg/m³) and 280 °C (1008.10 kg/m³), while the 300 °C samples exhibited a significant reduction (896.45 kg/m³), closely approaching the commercial briquette density of 764 kg/m³.

Table 2. Moisture Content and Calorific Value of Torrefied Briquettes Laboratory Results

Sample	Method	Test/Analysis		Result				
				240°C	260°C	280°C	300°C	Raw Biomass
Biomass	ISO 11722:2013	Residual Moisture, % mass fraction		6.9	6.4	5.3	4.0	12.7
	PTM D5865/D 5865M:2022NS AS	Gross Calorific Value	cal/g	4,536	4,709	5,177	4,969	3,331
			BTU/lb	8,112	8,621	9,339	8,945	5,995

Table 2 presents the consolidated results from the Department of Energy (DOE) laboratory analysis, comparing the raw biomass against the briquettes torrefied at four different temperature levels (240°C, 260°C, 280°C, and 300°C). The data indicates a clear trend where increasing the torrefaction temperature significantly enhances the fuel properties of the biomass.

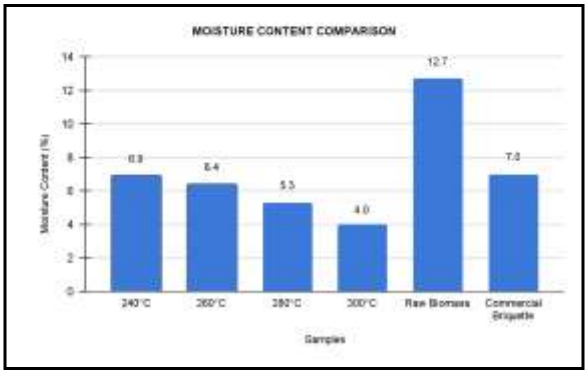


Fig. 5. Comparison of Residual Moisture Content with Commercial Briquette

The residual moisture content of the torrefied briquettes demonstrated the effectiveness of the torrefaction process in enhancing drying and hydrophobic properties. Raw biomass exhibited the highest moisture content (12.7%), reflecting its natural hygroscopic nature due to abundant hydroxyl groups in hemicellulose and cellulose [26]. After torrefaction, moisture content decreased progressively with increasing temperature, ranging from 6.9% at 240 °C to 4.0% at 300 °C. This trend aligned with literature, which reported that thermal degradation of hemicellulose reduces bound water and decreases moisture affinity [6,16]. Compared with the commercial briquette (7%), all torrefied samples performed equally well or better, particularly at 280 °C (5.3%) and 300 °C (4.0%), indicating improved hydrophobicity and storage stability [27].

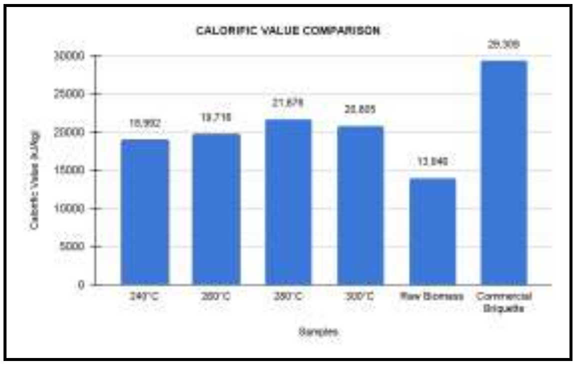
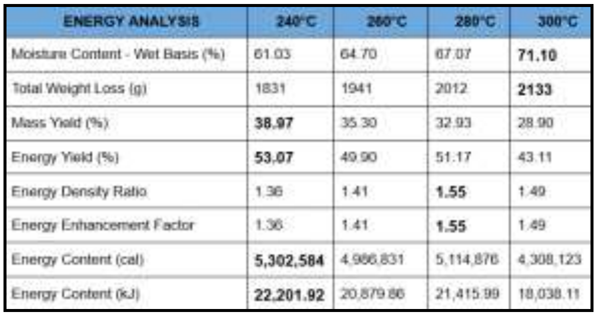


Fig. 6. Comparison of calorific value with commercial briquette

The calorific value results highlight the energy upgrading effect of torrefaction. Raw biomass recorded the lowest heating value (13,946 kJ/kg), reflecting its high oxygen and moisture content typical of untreated lignocellulosic materials [8]. Torrefaction progressively increased the calorific value from 18,992 kJ/kg at 240 °C to a peak of 21,676 kJ/kg at 280 °C, due to carbon enrichment and the reduction of oxygenated compounds via hemicellulose degradation and devolatilization [6,28,27]. At 300 °C, a slight decrease to 20,805 kJ/kg was observed, indicating that excessive torrefaction may cause disproportionate mass and energy loss despite higher carbonization severity [18,29]. Compared with the commercial briquette (29,309 kJ/kg), which likely exhibits higher fixed carbon content, the 280 °C torrefied briquette showed substantial improvement over raw biomass, confirming that moderate torrefaction effectively enhances fuel quality while maintaining structural stability [16,30].

Table 3. Summary Results of Comparative Energy Analysis



ENERGY ANALYSIS	240°C	260°C	280°C	300°C
Moisture Content - Wet Basis (%)	61.03	64.70	67.07	**71.10**
Total Weight Loss (g)	1831	1941	2012	**2133**
Mass Yield (%)	**38.97**	35.30	32.93	28.90
Energy Yield (%)	**53.07**	49.90	51.17	43.11
Energy Density Ratio	1.36	1.41	**1.55**	1.49
Energy Enhancement Factor	1.36	1.41	**1.55**	1.49
Energy Content (cal)	**5,302,584**	4,986,831	5,114,876	4,308,123
Energy Content (kJ)	**22,201.92**	20,879.86	21,415.99	18,038.11

Table 3 presents the energy performance of torrefied briquettes at four torrefaction temperatures. As torrefaction temperature increased from 240 °C to 300 °C, moisture content rose from 61.03% to 71.10%, while total weight loss increased from 1831 g to 2133 g, and mass yield decreased from 38.97% to 28.90%. These trends reflect intensified devolatilization and thermal degradation of hemicellulose and partial cellulose at higher torrefaction severity [8,27].

Energy densification improved with temperature, as indicated by the energy density ratio, which peaked at 1.55 for 280 °C, reflecting effective carbon enrichment and oxygen reduction [5,16]. At 300 °C, the ratio slightly declined (1.49), suggesting that excessive torrefaction reduces energy retention efficiency due to volatile loss [18,29]. Energy yield also declined with temperature, from 53.07% at 240 °C to 43.11% at 300 °C, showing the trade-off between fuel upgrading and material loss.

The 280 °C treatment maintained a relatively high energy content (5,114,876 cal; 21,415.99 kJ) while achieving the highest energy density ratio, indicating an optimal balance between energy retention and fuel quality. Compared with raw biomass (9,993,000 cal; 41,840.70 kJ), torrefied samples show lower total energy due to mass loss, but higher energy concentration per unit mass, confirming that torrefaction acts as an energy upgrading process rather than increasing total energy [5,7]. Overall, 280 °C is identified as the most favorable torrefaction temperature for maximizing energy densification while maintaining acceptable energy yield.

Table 4. Summary of Financial Analysis for Torrefied Briquette Production

Parameters	Amount
Total Project Cost	Php 52,803
Total Operating Cost	Php 72.38/kg
Selling Price of Torrefied Briquettes	Php 109/kg
Break-Even Analysis	2,500 bags/year
Monthly Revenue	Php 34,295.76
Monthly Production Cost	Php 22,773.64
Operating cost per day	Php 948.98
Monthly Return on Investment (ROI)	21.82%
Payback Period	5 months
Cost–Benefit Analysis	1.51

Table 4 presents a comprehensive summary of the key financial parameters for the production of torrefied briquettes. The total project cost is ₱52,803, while the operating cost per kilogram is ₱72.38, with a selling price of ₱109 per kilogram. The break-even analysis shows that the project needs to sell approximately 2,500 bags per year to cover all costs. On a monthly basis, the projected revenue is ₱34,295.76, with a monthly production cost of ₱22,773.64. The project demonstrates a monthly return on investment (ROI) of 21.82% and a payback period of 5 months, indicating that the initial investment can be recovered within a short timeframe. Finally, the cost–benefit analysis ratio of 1.51 confirms that the benefits significantly exceed the costs, showing that the project is economically viable and has strong potential for profitability.

V. CONCLUSION

The study successfully demonstrated that torrefaction significantly affects the physical, combustion, and fuel properties of biomass briquettes, with performance varying depending on temperature. Across the evaluated treatments, briquettes torrefied at 280°C consistently showed the most balanced results in terms of structural integrity, calorific value, energy density ratio, and combustion performance, indicating that moderate torrefaction provides the most optimal condition among the tested temperatures.

The economic evaluation showed that the production system required a relatively high initial investment, primarily due to the cost of the briquette machine and torrefaction oven. Operating costs were mainly driven by labor and electricity, while other cost components contribute minimally. The computed selling price was sufficient to recover production costs with a reasonable margin, and financial indicators such as break-even point, return on investment, payback period, and benefit–cost ratio indicated that the project is economically feasible under the given assumptions.

Overall, the study concluded that torrefied biomass briquettes are technically and economically viable as an alternative solid fuel. However, performance was highly dependent on torrefaction temperature, with 280°C identified as the most optimal condition based on the combined evaluation of physical, thermal, combustion, and economic results.

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