

III. RENEWABLE AND ALTERNATIVE ENERGY SOURCES AND BIOFUELS

VALORIZATION OF TARO (*Colocasia esculenta* L.) AGRICULTURAL WASTE INTO ENERGY DENSE BRIQUETTES: A SUSTAINABLE FUEL QUALITY ASSESSMENT

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Abstract. This study investigates the potential of taro (*Colocasia esculenta* L.) peel, a significant agricultural waste, as a raw material for high-quality solid fuel briquettes. To optimize characteristics, briquettes were pre-treated by oven-drying (90°C-120°C, 30-60 min) and assessed via proximate analysis, DSC, and Ignition Rate testing. Results confirmed successful property upgrades, identifying 120°C for 45 minutes as optimal for energy concentration. This condition yielded the highest Fixed Carbon (55.08%) and total thermal output (1,689.176 J/g by DSC), plus the maximum Ignition Rate (0.0008778 g/second), confirming superior combustion kinetics. The 120°C variant's superior energy content and confirmed thermal stability (onset 206.840°C) establish it as the most promising fuel. Findings validate the technical feasibility of transforming taro peel waste into an energy-dense solid fuel, demonstrating a viable strategy for sustainable waste management and renewable energy generation.

Keywords: Taro Peel Waste, Solid Fuel Briquettes, Valorization, Fixed Carbon, Thermal Stability, Ignition Rate, DSC

INTRODUCTION

The increasing global energy demand, coupled with urgent climate change concerns, necessitates a rapid shift toward sustainable and renewable energy sources. Biomass is a critical component of this transition, offering a carbon-neutral alternative to fossil fuels. In agrarian economies, the sustainable utilization of vast quantities of agricultural waste is not merely a matter of energy policy but also a critical component of waste management and circular economy initiatives.

Taro (*Colocasia esculenta* L.) is a vital staple crop worldwide, particularly in tropical regions. It is a plant that originated in Southeast Asia. During population migrations in the first century, its cultivation spread across China, Japan, and several Pacific Ocean islands. It is known by various names globally, including Old Cocoyam, "Dash(e)en," and "Eddo(e)," as well as localized names such as *Abalong* (Philippines), *Taioba* (Brazil), *Arvi* (India), and *Satoimo* (Japan). Taro is a very popular food in Indonesia, with high production concentrated in the Papua and Java regions (specifically Bogor, Sumedang, and Malang) [1]. Its processing generates substantial amounts of taro peel residue, which is typically discarded, contributing to environmental pollution and resource inefficiency. The direct use of raw agricultural waste as fuel is impractical due to inherent limitations, including

high moisture content, low energy density, and poor handling characteristics.

To transform this low-utility waste into a viable fuel, briquetting is recognized as an effective densification process that converts loose, heterogeneous biomass into uniform, high-density solid fuel. Briquettes are typically formed into cylindrical logs using high mechanical pressure without the addition of chemicals or binders [2]. Based on National Standardization Agency of Indonesia (SNI) 01-6235-2000, high-quality briquettes must possess a maximum ash content of 8%, a maximum moisture content of 8%, and a maximum mass loss upon heating at 90°C of 15% [3].

Various studies have been conducted on utilizing agricultural waste to produce briquettes as alternative fuels, primarily focusing on physical and thermal properties. Research has frequently employed thermal analysis techniques, such as Differential Scanning Calorimetry (DSC), to characterize biomass fuels. L. A. Nikolaeva and T. M. Solovev [4] investigated the thermal properties of fuel briquettes using the DSC method. Their study analysed the thermal degradation of bitumen, brown coal, oil sludge, and wood (pine) in an oxidizing atmosphere (air). They determined the stages, temperature ranges, and maximum temperatures of thermal degradation on the DSC curves during heating from 40°C to 600°C at a rate of 20°C/min.



The process of thermal breakdown and the thermal impacts of bound moisture evaporation were successfully identified. A comparative calorific analysis of coconut shells and durian fruit peel was researched using DSC [5]. The study recommended using coconut shell with a 10% mass of starch, achieving an optimum temperature of 578.97°C with an enthalpy value of 0.42 J/g. Bemgba Bevan Nyakuma et al. [6] performed a comparative analysis of the calorific fuel properties of Empty Fruit Bunch (EFB) Fiber and Briquette. They concluded that briquette pyrolysis was more efficient due to its lower moisture content, calorific requirement, and specific heat capacity. Conversely, EFB pyrolysis exhibited a lower ignition temperature and a tendency to yield more pyrolysis products.

Other studies focused on the physical and mechanical integrity of the finished briquettes: V. R. Birwatkar et al [7] researched the physical and thermal properties of biomass briquettes made from a mixed raw biomass of Mango leaves, Subabul leaves, and Sawdust. They discovered that the average energy density ratio was 2.71. Specifically, combination T-3 demonstrated the highest quality, showing values for shatter resistance, resistance to water penetration, and energy density ratio of 95.83%, 95.13%, and 2.79, respectively. Test results indicated that briquettes made with combination T-3 were the highest-quality fuel across all tested combinations.

While the conversion of various agricultural residues into briquettes has been studied, specific data concerning the optimal thermal pre-treatment parameters for taro peel and its consequential effects on fuel quality, particularly the ability to maximize the concentration of Fixed Carbon, remain scarce. This study addresses this gap by aiming to evaluate and optimize the production of energy-dense briquettes from taro peel as agricultural waste. The specific objectives are to determine the most effective thermal pre-treatment conditions (varying temperature and duration) for preparing taro peel feedstock, to thoroughly characterize the fuel properties of the resulting briquettes through proximate analysis (Moisture Content, Ash, Volatile Matter, and Fixed Carbon) and to validate the maximum energy concentration and thermal stability using advanced methods, specifically Differential Scanning Calorimetry (DSC) and Ignition Rate analysis. The findings are expected to contribute specific technical data supporting the valorization of

taro peel waste as a competitive, sustainable solid biofuel.

MATERIAL AND METHOD

Materials and Preparation

The raw material, taro peel (*Colocasia esculenta* L.), was sourced as agricultural waste from a taro chips processing facility in Bogor, West Java. The taro peel used in this research can be seen in Figure 1. The collected peels were initially prepared by sun-drying for three days to reduce inherent moisture. Tapioca flour (30 grams per batch) served as the binding agent, mixed with 200 mL of distilled water. Equipment used for processing included a furnace, a milling machine, a sieving apparatus, a hotplate, a stirring rod, and a briquetting molding machine. For subsequent analysis, instruments included an analytical balance, oven, desiccator and a Differential Scanning Calorimeter (DSC) instrument.



Fig. 1. Taro peels

Briquette Manufacturing Process

The manufacturing process involved three main stages: carbonization, mixing, and compaction. First, the dried taro peel feedstock was subjected to controlled carbonization in a furnace at 390°C for approximately 2 hours, with regular stirring to ensure uniform charring into charcoal. Taro peel charcoal can be seen in Figure 2.

The carbonization process, also known as charring, is an essential pretreatment step carried out on the taro peel feedstock before it is converted into briquettes. This process involves the thermal decomposition of the organic raw material, the taro peel, into a stable, carbon-rich solid (biochar) through pyrolysis in an oxygen-limited environment. To execute this, the taro peel is placed inside a closed-wall reactor or chamber, such as a charring pit or a steel tank. Once ignited, the chamber is sealed to restrict significant airflow. This oxygen deprivation induces incomplete combustion, forcing the material

to decompose thermally. The process is carefully monitored (e.g., by observing the flue gases) to ensure efficient charring and prevent excessive ash formation, resulting in biochar with increased fixed carbon content and energy density, which are crucial for producing high-quality, uniform briquettes.

According to Kurniawan and Marsono (2008) [8], the purpose of burning fuel is to convert it into charcoal which contains energy that can still be used as fuel. According to the carbonization concept, biomass is burned without oxygen, releasing only the volatile materials while retaining the carbon. Charcoal production is significantly influenced by the carbonization temperature. Carbonization temperature, size, material type, and carbonization time are all factors that affect carbonization. The amount of carbon created decreases with increasing carbonization temperature, and the material being carbonized will break more quickly throughout if it is smaller, ensuring perfect carbonization [9]. The resulting char was then finely ground and sieved. The results of grinding and sieving taro peel charcoal powder can be seen in Figure 3.

Second, a sticky binder solution was prepared by heating the tapioca mixture. The charcoal powder was mixed thoroughly with the binder until a homogeneous, cohesive dough was formed. Third, the mixture was placed into the briquetting mold and compacted. The compacted briquette results can be seen in Figure 4. The wet briquettes were then subjected to thermal pre-treatment via oven-drying varying temperature (90°C, 105°C, and 120°C) and duration (30, 45, 60 minutes) to determine the optimal conditions for fuel quality.



Fig. 2. Taro peel charcoal

Fuel Quality Characterization

The final briquette samples were subjected to comprehensive fuel quality characterization, performed largely based on the ASTM D-1762-84

(2021) standard [10], and assessed for their mechanical and thermal properties.



Fig. 3. Taro peel charcoal powder



Fig. 4. Taro peel briquette product

Proximate Analysis

Proximate analysis quantified the basic components of the fuel:

1. **Water Content:** Determined by mass loss after drying at 105°C until constant weight. Calculation of water content uses the following formula:

$$\text{Water Content (\%)} = \frac{B - C}{B - A} \times 100\%$$

Note:

A = Weight of empty cup (g)

B = Weight of filled cup (g)

C = Weight of filled cup after heating (g)

2. **Volatile Matter:** Determined by mass loss after heating the moisture-free sample in a furnace at 950°C for 7 minutes. Calculation of Volatile matter using the formula:

$$\text{Volatile matter (\%)} = \frac{W2 - W0}{W1 - W0} \times 100\%$$

Note:

W0 = weight of empty cup (g)

W1 = weight of cup + sample before heating (g)

W2 = weight of cup + sample after heating (g)

- Ash Content:** Determined by mass loss after heating the volatile residue at 950°C for 3 to 4 hours until constant weight. Ash content is calculated using the formula:

$$W2 - W0$$

$$\text{Ash Content} = \frac{\quad}{W1 - W0} \times 100\%$$

$$W1 - W0$$

Note:

W0 = weight of empty cup (g)

W1 = weight of cup + sample before burning (g)

W2 = weight of cup + sample after burning (g)

- Fixed Carbon (FC):** Calculated by difference: FC (%) = 100% - (Moisture + Volatile Matter + Ash).

Thermal Properties Analysis (DSC)

The thermal stability and energy release properties were analyzed using a Differential Scanning Calorimeter (DSC) instrument (Setline DSC) (Figure 5). Samples (max 25 mg) were placed in a crucible and heated to record the heat flow. This analysis quantified the Total Heat Release (Enthalpy) and the Onset Temperature of thermal decomposition.

Combustion Performance (Ignition Rate)

The Ignition Rate (IR) and total combustion time were determined manually using a briquette furnace. The initial mass of each sample was recorded. The sample was burned until fully reduced to ash, and the total combustion time was measured with a stopwatch. The ignition rate testing can be seen in Figure 6.

RESULTS AND DISCUSSION

The goal of valorizing taro peel waste into an energy-dense solid fuel was assessed by analyzing the influence of systematic thermal pre-treatment on the briquette's composition, thermal stability, and

combustion kinetics. The fuel characteristics were significantly influenced by the variation in heating



Fig. 5. Differential Scanning Calorimeter (DSC) Instrument



Fig. 6. Ignition Rate Testing temperature and duration, establishing a clear hierarchy of fuel quality.

Proximate Analysis and Impurity Management

The proximate analysis (Table 1) revealed that all briquette samples successfully met the national standard for moisture content (8%), ranging from 3.47% to 5.93%. The 105°C for 45 minutes condition proved optimal for impurity control,

yielding the lowest moisture content (3.59%) and the lowest ash content (8.17%). This successful reduction of inert material is essential for increasing net combustion efficiency and minimizing residual waste.

The proportion of combustible components, such as Volatile Matter (VM) and Fixed Carbon (FC) was inversely related to the heating intensity. The maximum FC content of 55.08% was achieved under the 120°C for 45 minutes condition. This significant increase in FC relative to the raw material demonstrates that the mild thermal

treatment successfully concentrated the stable, high-energy carbon matrix by converting or driving off some lower-energy volatile components (VM reduced to 28.43% for this variant). A fundamental principle of biomass fuel quality states that high concentrations of Fixed Carbon (FC) are dependent upon the minimization of inert material and moisture [11]. The observed relationship confirms this principle: the lowest measured values for moisture and ash content directly correlate with the highest fixed carbon percentages [12].

Table 1. Fuel Quality Characterization of Taro Peel Briquettes

Heating Temperature (°C)	Heating Time (minutes)	Moisture Content (%)	Ash Content (%)	Fixed Carbon (%)	Ignition Rate (g/second)
No Heating	-	4.99	11.52	53.65	0.0007813
90	30	4.91	11.65	49.03	0.0007710
90	45	5.56	11.56	43.95	0.0007986
90	60	5.93	11.42	53.43	0.0008203
105	30	3.47	8.56	46.94	0.0006724
105	45	3.59	8.17	52.26	0.0007133
105	60	3.88	12.36	38.34	0.0004570
120	30	5.23	11.31	48.09	0.0007537
120	45	5.17	11.31	55.08	0.0008778
120	60	5.45	11.74	45.55	0.0007814

Thermal Activity and Energy Concentration (DSC)

One method of thermal analysis is the measurement of calories, which quantifies the amount of heat produced by a phase transition or an element's chemical reaction. Both techniques have the potential to significantly alter a substance's temperature by releasing or absorbing heat. Thus, during the phase transition, the difference in heat flow between two samples at the same temperature is measured using the calorific value measurement method [13]. A common technique for assessing the quality of semi-crystalline polymers is DSC analysis, which defines the phase transition temperature, specific heat, and pre-heating and cooling stages [14]. Additionally, it measures semi-

crystalline thermoplastics [15] and looks at phase transitions or thermal degradation [16]. To ascertain heat capacity, the sample is heated at a particular temperature scan rate. The DSC thermogram was used to determine the temperature effects of the glass transition. The DSC approach may identify characteristics in wood and fuels as well as the temperature ranges at which physical-chemical changes take place [4].

The Differential Scanning Calorimetry (DSC) analysis served as the definitive quantitative proof of energy concentration. The DSC thermogram (Figure 7) for the optimal 120°C, 45 min variant showed an extremely strong exothermic peak. This sample exhibited the maximum total heat release (1,689.176 J/g), which is nearly double the thermal output of the

low-impurity 105°C variant (908.362 J/g). This dramatic increase in J/g directly validates the superior energy density achieved by maximizing the Fixed Carbon content. The DSC recorded an Onset Temperature of 206.840°C for the high-FC variant.

This elevated onset point, compared to the 182.993°C of the 105°C sample, confirms improved thermal stability, a desirable feature for safer handling and storage, as a result of the reduced reactive volatile content.

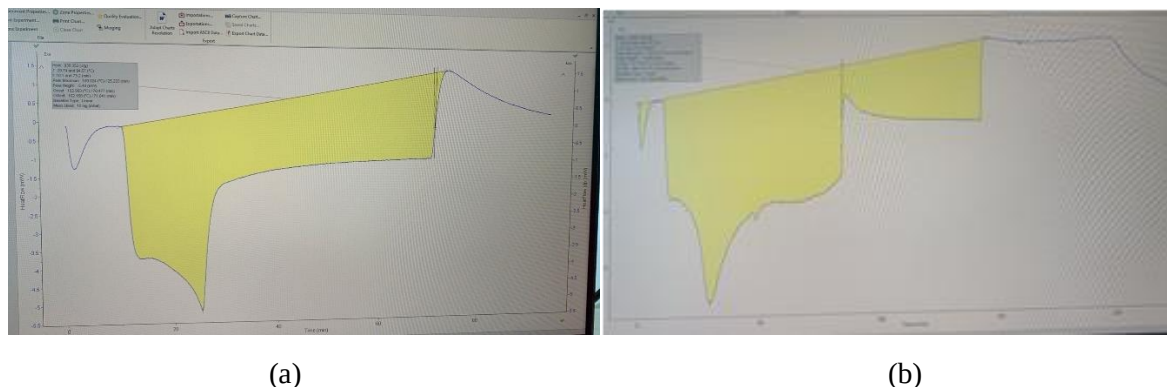


Fig. 7. DSC Thermogram of the Active Thermal Properties Test on Briquettes with Pre-treatment at
a) 105°C for 45 Minutes and (b) 120°C for 45 Minutes

Combustion Performance and Optimal Selection

The Ignition Rate (IR) test (Table 1) provided insight into the practical combustion kinetics. The maximum IR (0.0008778 g/second) was achieved by the same energy-optimal variant (120°C, 45 min). This finding is crucial because it demonstrates that the process simultaneously maximized energy content (Fixed Carbon and DSC) and optimized combustion performance (high IR). This variant offers a superior combination of traits, which are high energy concentration for sustained heat release, good thermal stability, and fast initiation of the burning process. In conclusion, the 120°C for 45 minutes condition successfully produced a briquette with the highest Fixed Carbon content and maximum measurable thermal output (DSC), decisively proving the success of the taro peel valorization process.

CONCLUSIONS

Based on the comprehensive fuel quality assessment, this study confirms the successful valorization of taro peel agricultural waste into an energy-dense, high-quality solid biofuel. The thermal pre-treatment condition of 120°C for 45 minutes was unequivocally established as the optimal process for maximizing fuel energy content. This variant achieved the highest Fixed Carbon

content (55.08%) and demonstrated the maximum heat release (1,689.176 J/g) via DSC analysis, confirming a significant concentration of combustible material. The optimal variant also exhibited the highest Ignition Rate (0.0008778 g/second), validating its superior combustion kinetics. The high Fixed Carbon combined with fast ignition makes this briquette an excellent, high-performance solid fuel. While meeting national standards for moisture content across all samples, the optimal high-FC variant demonstrated good thermal stability with an onset decomposition temperature of 206.840°C. This stability, coupled with the low impurity content achieved across the trials, confirms the briquette's suitability for controlled use and safe storage. In summary, the taro peel briquettes produced under optimized conditions offer an effective and sustainable solution for managing agricultural residue while simultaneously providing a valuable, energy-dense product to the renewable energy sector.

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