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Effect of Biomass Feedstock Granulometry on Thermophysical Characteristics of Charcoal Briquettes via Screw Extrusion

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Abstract. The present study investigates the impact of particle size variation (10, 18, 20, and 35 mesh) on the physical and thermal properties of charcoal briquettes from coconut shells manufactured with a screw-based extruder machine. The briquette manufacturing process involves crushing, mixing, molding, and drying. Assessments were conducted to ascertain friability, compressive strength, density, calorific value, volatile matter, ash content, fixed carbon, and water content. Comparable assessments were also performed on commercially available export-grade briquettes designated as b_5. The results of this investigation demonstrate that all briquette samples generated conform to the SNI 01-6235-2000 standard for water, ash, and calorific value, and adhere to international standards for fixed carbon, density, and compressive strength. The b_4 specimen (35 mesh) demonstrated the best performance, exhibiting a friability of 0% in the unburned condition and 7.04% in the burned condition. Compared to b_5, the b_4 specimen exhibited notable enhancement, demonstrating a 100% increase in friability in the unburned condition and a 53.22% improvement in the burned condition. This study emphasizes the significance of smaller particle sizes in improving briquettes' mechanical strength and combustion efficiency. It presents the importance of renewable energy technology and sustainable waste management.

Keywords: biomass densification techniques, coconut shell charcoal briquette, screw extrusion biomass processing, renewable solid fuel performance, biomass densification techniques

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1. Introduction

Coconut is a significant commodity mainly utilized for its meat, although other components, including the husk and shell, can be transformed into products with added value and byproducts [1]. In 2022, Indonesia produced around 2,822,000 tons of coconut [2]. With this composition, it is estimated that the coconut shell waste generated reaches 342,360 tons per year. This amount is quite significant and can cause environmental impacts if not managed properly. Consequently, designing solutions for the sustainable management of coconut shell material is becoming increasingly imperative. This can be accomplished by adopting a circular economy model that encourages the effective reutilization of waste and the utilization of sustainable technology to convert coconut shells into high-value products [1,2].

Charcoal briquettes are an alternative utilization of coconut shell waste that is considered efficient and of high economic value. In addition to reducing the accumulation of organic waste, especially coconut shells, the briquetting process also produces a solid fuel product that can be used as a renewable energy source [3]. Briquettes are solid biomass produced by compressing organic and inorganic materials and have been widely applied as an environmentally friendly alternative fuel. Excellent characteristics of briquettes include the ability to produce high heat, low smoke emissions, relatively long flame time, and renewability [4]. These advantages make briquettes a potential solution to replace conventional fuels such as firewood and coal, both in household needs and the small-scale industrial sector. Therefore, the development and optimization of briquettes from coconut shell waste is a strategic step in supporting the clean energy transition and sustainable waste management [3].

Charcoal briquettes have emerged as a prevalent alternative energy source in numerous countries. Briquettes are frequently utilized as fuel for shisha, a traditional water pipe designed for smoking flavored tobacco, in the Middle East [2]. In the meantime, briquettes are extensively employed as fuel for cooking and barbequing operations in the United States, Europe, Australia, and Japan [5]. Indonesia is a prominent exporter of charcoal briquettes, with a calorific value ranging from 6,000 to 7,200 cal/g, rendering them highly competitive on the international market. The synergy of superior product quality and ample raw material availability generates substantial prospects for expanding export markets. Increasing global demand propels advancements in production methodologies and quality enhancements to create more efficient, eco-friendly, and sustainable products [3].

The quality of briquettes is predominantly determined by the characteristics of the raw materials, including biomass type, particle size, and water content. Furthermore, the operational parameters that control the densification process, including temperature and pressure, significantly influence the quality of the produced briquettes [6]. Aal et al. [7] suggested reduced particle sizes to produce high-quality briquettes. This can diminish the interstitial space between particles and forge more robust connections during the compression process. The size of raw material particles significantly influences the effectiveness and consistency of the briquette production process. The physical and chemical characteristics of the resultant briquettes are significantly influenced. Numerous studies indicate that changes in particle size directly impact essential properties such as water content, ash content, volatile matter content, fixed carbon content, heating value, density, compressive strength, brittleness, and combustion rate [8–11]. Differences in particle size led to changes in the microstructure, porosity, and density of the briquettes, which collectively affect the combustion efficiency and mechanical durability of the products during storage and use [8]. Several studies have investigated the effect of particle size in raw materials on the quality of the resultant briquettes. Nonetheless, investigations on the quality of briquettes manufactured with a screw extruder machine utilizing different particle sizes of coconut shell charcoal powder are still limited. Therefore, the present study aims to examine the effect of particle size of coconut shell charcoal on the quality of briquettes generated by a screw extrusion machine.

The quality of the manufactured briquettes will be assessed according to many characteristics, including fixed carbon content, heating value, ash content, water content, compressive strength, volatile matter content, density, and brittleness. It can potentially enhance briquette quality as an efficient and eco-friendly alternative fuel, while providing manufacturers with practical information on determining the optimal particle size to maximize briquette performance and durability.

2. Methods

2.1. Materials

The coconut shell-based charcoal utilized in this study was sourced from a local vendor in Patebon, Kendal Regency, Central Java. The raw material then underwent a process of pulverization and screening using a sieve with mesh sizes of 10, 18, 20, and 35 to obtain a variety of particle sizes to be analyzed. The mesh sizes were selected based on preliminary trials and industry recommendations to optimize the particle size for briquette production. As an adhesive, tapioca starch was used, which is an organic adhesive with a relatively affordable price and easily obtained commercially. Tapioca starch has high hygroscopic properties, so it can absorb water optimally, supporting the process of forming homogeneous and dense briquettes. In addition, the application of tapioca flour as a binder is known to increase the compressive strength of briquettes while reducing the level of brittleness, thereby extending the shelf life and increasing the mechanical resistance of the product [12].

2.2. Specimen Preparation

The coconut shell charcoal powder, which has been filtered through multiple mesh sizes, is mixed with binder and water utilizing a mixer equipment. The water used in this study was 32%, while the binder utilized was 5% by weight. The specimen labels employed in this study are b_1, b_2, b_3, and b_4, which represent coconut shell charcoal powder filtered through mesh sizes 10, 18, 20, and 35, respectively. The product resulting from the mixing process was subsequently blended using a screw extruder machine, with three repetitions implemented to guarantee a uniform mixture of raw material, water, and adhesive. The process of briquette production using the screw extruder machine was carried out at a rotational speed of 1650 rpm. The briquettes were manually cut to dimensions of 2.5 cm × 2.5 cm × 2.5 cm. The drying procedure took place in an oven set at 100°C for a duration of 3 hours, aimed at removing excess moisture and improving the product's physical integrity.

2.3. Testing

The present study involves a variety of tests designed to evaluate the impact of particle size on the quality of briquettes from coconut shell charcoal. The tests performed include compressive strength, density, calorific value, volatile matter, ash content, brittleness, fixed carbon content, and water content. In addition, similar tests were implemented on commercial briquettes of export quality, named b_5 specimen. This study examines the volatile matter, water content, and ash content, with each parameter analyzed according to ASTM D3175-02, ASTM D3173-03, and ASTM D3174-04 standards. The fixed carbon content is determined per ASTM D3172-89, and the calorific value is assessed using the ASTM D240 method to quantify the heat energy released during combustion. The briquette's density is determined by ASTM B311-93 and ASTM D440-07 R02 standards. The assessment of compressive strength is performed through mechanical properties testing using a a universal testing instrument, with a loading rate of 2–4 kg/cm² per second. A drop test is conducted by releasing the briquette from an elevated height of 1.83 meters against a rigid surface, following ASTM D440-07 R02 standards, to assess the friability and size stability of the briquette. Each test is systematically conducted three times to ensure the reliability of the results and minimize measurement bias. The collected data is subsequently averaged and subjected to descriptive-comparative analysis to establish a foundation for assessing the briquettes of coconut shell charcoal quality and performance with applicable global criteria.

3. Results and Discussion

Figure 1 illustrates the effect of modifications in raw material particle size on the water content of coconut shell charcoal briquettes. The findings from the test indicate that the water content in samples b_1, b_2, b_3, and b_4 are 1.54%, 1.66%, 1.74%, and 2.59%, respectively. The observed values are continuously inferior to the water content of commercial briquettes (b_5), recorded at 4.97%, signifying an effectively conducted drying and production process in the present study. The decrease in water content for specimens b_1, b_2, b_3, and b_4 relative to specimen b_5 was 69.01%, 66.60%, 64.99%, and 47.89%, respectively. The significant decrease in water content signifies an enhancement in briquette quality, especially regarding durability and resistance to water. The size of the particles substantially influences water content, with smaller particles generating more water content. This is because the briquette density is increased due to the presence of finer particulates, which block the evaporation of water during the drying process [11]. Specimen b_1, characterized by a particle size of 10 mesh (the largest size in this study), demonstrated the lowest water content. All briquette samples evaluated met the requirements of the Indonesian National Standard (SNI) No. 01-6235-2000, which specifies a maximum content of water of 8%.

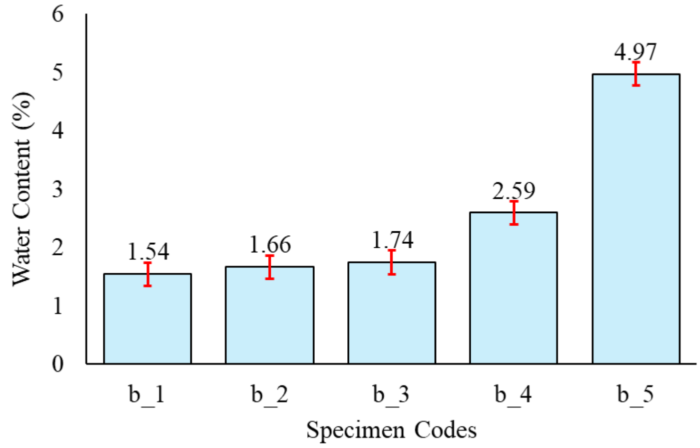

Figure 1. Influence of particle size of raw materials on the water content of briquette specimens.

The raw material particle size influence on the ash content of coconut shell charcoal briquettes is depicted in Figure 2. The ash content values for b_1, b_2, b_3, and b_4 were 2.30%, 1.98%, 2.04%, and 1.99%, respectively. The values were consistently higher than the ash content of commercial briquettes (b_5), measured at 1.87%. The findings from this study indicate that the raw material's particle size substantially influences the briquettes' ash content. A reduction in particle size leads to less ash content in the resultant briquettes.

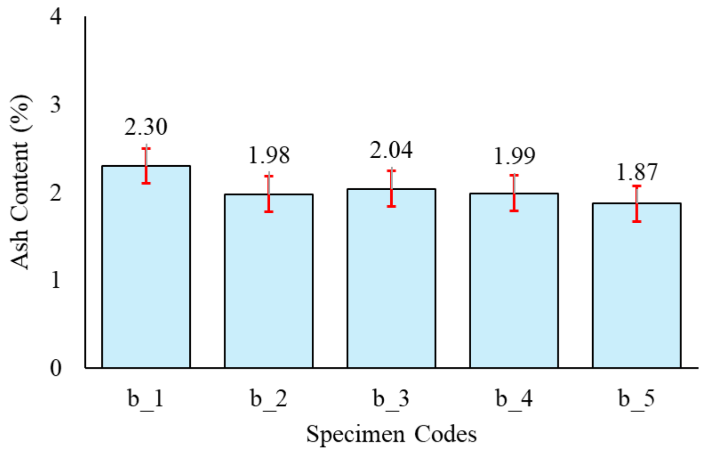

Figure 2. Influence of particle size of raw materials on the ash content of briquette specimens.

Yirijor et al. [13] discovered that briquettes composed of fine charcoal particles generally exhibit reduced ash content compared to those made from coarse particles. This results from the reduced particle size, facilitating a more uniform and thorough combustion process, producing less ash residue than coarse particles. This enhancement in quality improves the overall combustion efficiency and the thermal value of the briquettes by facilitating more effective oxygen diffusion and greater heat transfer. Although the ash content of this research sample was slightly higher than that of commercial briquettes, recorded at 1.87%, all tested specimens still met the maximum ash content limit of 8% in accordance with the Indonesian National Standard (SNI) Number 01-6235-2000. Furthermore, the findings of this study are consistent with the criteria for briquettes produced in previous research, which indicate that the ash content in briquettes using mocaf adhesive ranges from 1.54% to 2.3%. Briquettes made with cassava flour adhesive have an ash content between 1.01% and 2.06% [2].

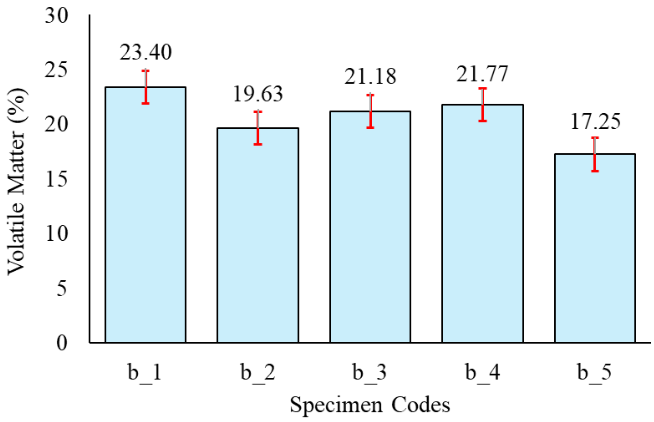

Figure 3. Influence of particle size of raw materials on the volatile matter of briquette specimens.

Volatile matter is a component of organic compounds in briquettes that easily evaporate during the combustion process and is an important indicator in determining the thermal efficiency and flame quality of solid fuels. The volatile matter content also reflects the extent to which the carbonization process successfully removes volatile compounds from the feedstock. The volatile matter content in samples b_1, b_2, b_3, and b_4 are 23.40%, 19.63%, 21.18%, and 21.77%, respectively (Figure 3). In general, smaller particle sizes result in higher water content. This is due to the increased density and homogeneity of the briquette structure, which inhibits the release of volatile compounds during drying and carbonization [14]. The findings of the present study were consistently higher than the volatile matter of commercial briquettes (b_5), measured at 17.25%. However, the highest volatile matter content was found in specimen b_1 (largest particle size), which is thought to be due to a less-than-optimal carbonization process. Irregular heat distribution during carbonization can lead to incomplete decomposition of volatile compounds [15]. Specimen b_2 exhibited the lowest volatile matter content, measuring 19.63%. This value is higher than that of the commercial briquette, which is 17.25%, and it surpasses the maximum limit established by the Indonesian National Standard (SNI 01-6235-2000), which is set at 15%. However, the volatile substance content found in all specimens complies with international norms, with Japan permitting a range of 15-30% and the United States allowing a range of 19-28%.

Fixed carbon is an important component in briquettes that reflects the amount of solid carbon remaining after volatile compounds have evaporated and ash has formed. This parameter serves as a key indicator in assessing the energy quality and combustion stability of solid fuel. High values of fixed carbon content indicate better combustion efficiency as well as longer flame times. The fixed carbon content in samples b_1, b_2, b_3, and b_4 are 74.31%, 78.39%, 76.78%, and 76.24%, respectively (Figure 4). Particle size of raw material variations appears to affect the fixed carbon content, where finer particle sizes generally lead to a decrease in fixed carbon content. This is due to the increase in volatile matter content, which is negatively correlated to the fixed carbon fraction [16].

The fixed carbon content of all specimens was slightly lower than that of commercial briquettes (b_5), which have a fixed carbon content of 80.88%. However, the test findings indicated that the thermal performance of the specimens generated in this investigation was approximately comparable to industry standards. Furthermore, all specimens generated in this study match with international standards, specifically the Japanese standard, which establishes the fixed carbon concentration ranges from 60% to 80%.

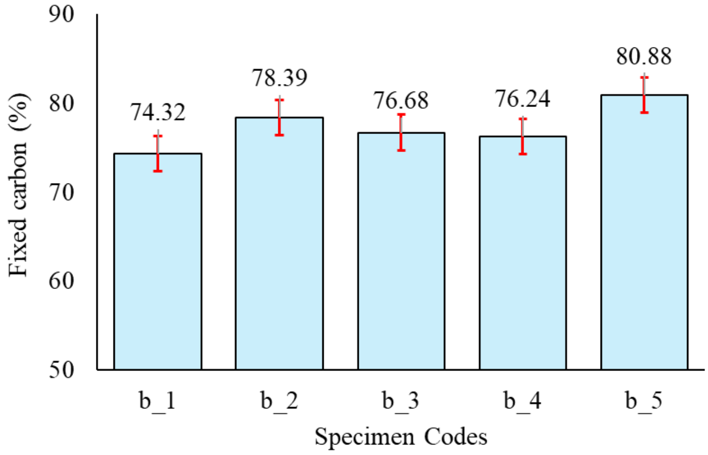

Figure 4. Influence of particle size of raw materials on the carbon of briquette specimens.

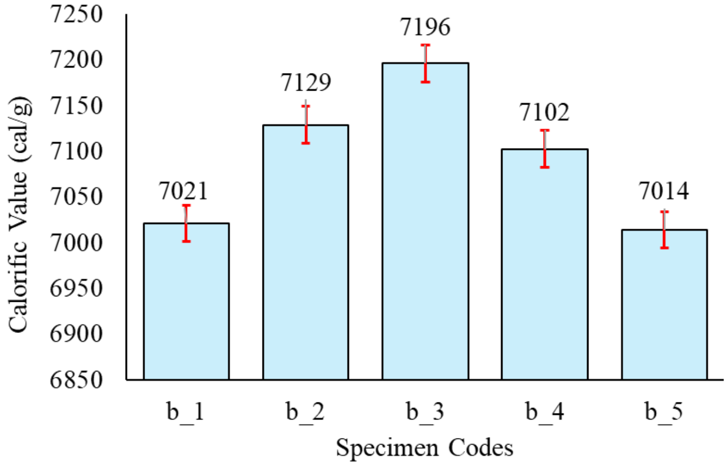

Figure 5. Influence of particle size of raw materials on the calorific value of briquette specimens.

Figure 5 presents the influence of particle size variation on the calorific value of coconut shell charcoal briquettes. The study's findings reveal that the calorific values of samples b_1, b_2, b_3, and b_4 are 7021 cal/g, 7129 cal/g, 7196 cal/g, and 7102 cal/g, respectively. The results consistently indicate calorific values superior to the commercial briquette (b_5), which has a calorific value of 7014 cal/g. The difference in calorific value is quite striking in specimen b_1, which recorded the lowest value. This is thought to be related to the combination of high ash and volatile matter content and low fixed carbon content in these specimens, as explained in previous studies that the content of moisture, ash, volatile matter and fixed carbon significantly affects the calorific value of a briquette [17]. In contrast, the highest heating value was obtained in specimen b_3 with 60 mesh particle size, which amounted to 7195.89 cal/g, indicating the superior thermal performance. All briquette samples in this study had heating values above the minimum standard set by the Indonesian National Standard (SNI) Number 01-6235-2000, which is 5000 cal/g. In fact, all specimens showed higher values than commercial briquettes with a calorific value of 7014 cal/g, indicating that the briquettes produced in this study have high potential to be applied as an efficient and competitive alternative fuel in domestic and global markets.

Figure 6 shows the impact of particle size variation on the density of briquette specimens. The test findings indicate that the density value of each specimen is b_1 at 0.56 g/cm³, b_2 at 0.64 g/cm³, b_3 at 0.63 g/cm³, and b_4 at 0.61 g/cm³. The results consistently showed a lower density compared to commercial briquettes (b_5), which had a density of 0.90 g/cm^3. Density is an important parameter in the evaluation of briquette quality, as it indicates the level of density between particles in the solid briquette structure. High density generally contributes to increased mechanical strength, combustion efficiency, and longer flame duration. According to Antwi-Boasiako and Acheampong [18], as well as Mitchual et al. [19], the density of briquettes is substantially determined by the particle size of the primary material, with finer ground materials yielding briquettes of higher density. Finer particle raw materials offer a larger surface area for bonding, forming briquettes with enhanced density.

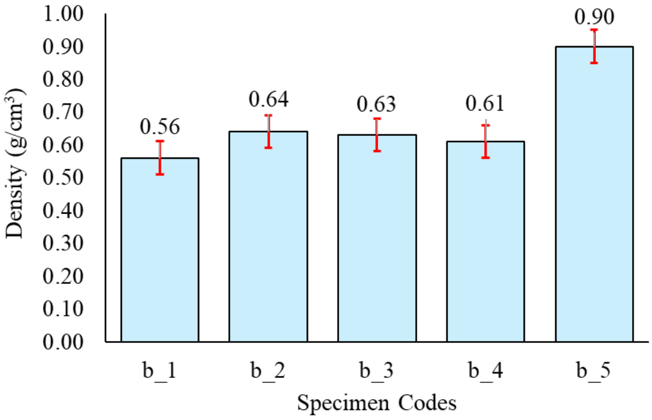

Figure 6. Influence of particle size of raw materials on the density of briquette specimens.

Specimen b_2 recorded the highest density value of 0.64 g/cm³, which is also the minimum limit for briquette density standards based on UK criteria. However, this value is still lower than the density of commercial briquettes (b_5), which reaches 0.90 g/cm³. Although all specimens have not reached the optimal density level of industrial briquettes, the results of this study show that coconut shell charcoal briquettes still meet international minimum quality standards and are still suitable for use as an economical and environmentally friendly alternative fuel. This study's findings indicate that all briquette specimens' density satisfies the minimum density criterion established by the British standard, at 0.48 g/cm³ [2].

Figure 7 shows the impact of raw material particle size on the compressive strength of briquette specimens. The test results show that the compressive strength values (N/mm²) of each specimen are as follows: b_1 of 4.52, b_2 of 1.99, b_3 of 4.37, and b_4 of 4.50. Particle size variation was found to affect the compressive strength of the briquettes, where specimen b_1 with the largest particle size produced the highest compressive strength, while the lowest value was recorded for specimen b_2.

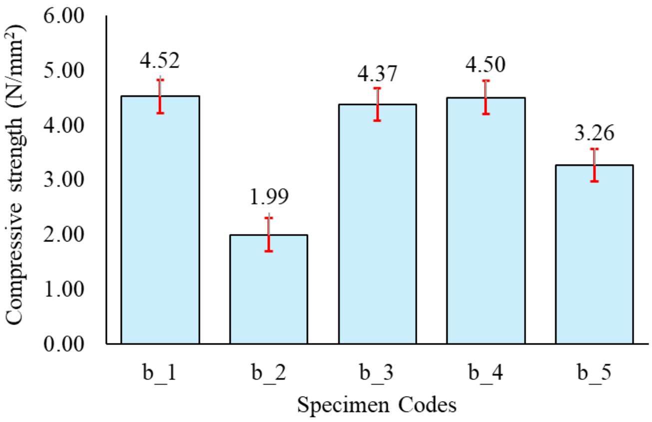

Figure 7. Influence of raw material particle size on the compressive strength of briquette specimens.

Overall, all specimens showed better mechanical performance than commercial briquettes (b_5), which have a compressive strength of 3.26 N/mm². Furthermore, all specimens successfully met the minimum standard of compressive strength based on British criteria, which is 1.99 N/mm². This indicates that the briquettes obtained in the study have sufficient structural resistance for practical use. Besides particle size, the compressive strength of charcoal briquettes is also influenced by several other factors, such as density, dryness, and surface textures [20]. Higher density can increase the binding force between particles, while optimal dryness helps avoid structural weakness due to excessive water content. Therefore, to produce consistently high-quality briquettes, thorough control of production parameters is necessary. These findings indicate that coconut shell charcoal briquettes not only have competitive energy value but also meet the mechanical requirements for distribution and commercial applications.

A brittleness test was conducted to assess the briquettes' resistance to impact as well as their size stability, both in unburned condition, and burned completely condition (Table 1). The test findings demonstrate that, under non-combustion settings, the friability values for samples b_1, b_2, and b_3 are each 0.32%, whilst b_4 attains 0%. The size stability for b_1 to b_3 is documented at 99.68%, whilst b_4 attains 100%. These results exceed those of the commercial briquette specimen (b_5), which exhibits a friability rating of 0.71% and a size stability of 99.29%. Specimen b_4, exhibiting the smallest particle size, displayed superior performance, aligning with prior studies indicating that smaller particles improve density and structural integrity [21–22].

Table 1. Effect of particle size variation on the brittleness value and dimensional stability of briquettes

Specimen Codes	Unburn condition		Burned completely condition	
	Dimensional Stability (%)	Friability (%)	Dimensional Stability (%)	Friability (%)
b_1	99.68	0.32	92.90	7.10
b_2	99.68	0.32	79.25	20.75
b_3	99.68	0.32	79.73	20.27
b_4	100	0	92.96	7.04
b_5	99.29	0.71	84.95	15.05

The friability markedly escalates under combustion conditions, attaining 7.10% for b_1, 20.75% for b_2, 20.27% for b_3, and 7.04% for b_4. The size stability during combustion conditions was measured at 92.90% for b_1, 79.25% for b_2, 79.73% for b_3, and 92.96% for b_4. Specimen b_4 demonstrated superior performance in both situations, bolstered by elevated particle density. Besides particle size, water content is crucial in assessing briquette friability. Overall, these results surpass the commercial briquette specimen (b_5), which exhibits a friability value of 15.05% and a size stability of 84.95%. The present study's findings demonstrate that during burning conditions, the friability value of specimen b_4 improved by 53.23% compared to the commercial product. Furthermore, the dimensional stability of specimen b_4 was enhanced by 9.45% compared to specimen b_5 under the same conditions. According to applicable standards, the brittleness value of briquettes should not exceed 4% [23–25]. All specimens in the unburned condition demonstrated a brittleness value of less than 4%, conforming to international standards and considered appropriate for practical applications. However, all specimens exceeded the threshold defined by international standards in the entirely burned condition. This indicates a requirement for further optimization of the production process parameters to improve the thermal and structural resistance of the briquettes.

4. **Conclusion**

The present study emphasizes the substantial influence of particle size on the performance of briquettes manufactured via screw extrusion. Particle size variations (10, 18, 20, and 35 mesh) affected the physical and thermal attributes of the briquettes, with smaller particle sizes increasing mechanical strength, diminishing brittleness, and enhancing combustion efficiency.

Briquettes composed of 35 mesh particles (specimen b_4) not only satisfied both Indonesian and international standards for water content, ash content, calorific value, and compressive strength, but also surpassed commercial briquettes in terms of brittleness and dimensional stability. The compressive strength, calorific value, fixed carbon, volatile matter, water content, dimensional stability, ash content, density, and friability for specimen b_4 were 24.50 MPa, 7102 cal/g, 76.24%, 21.77%, 2.59%, 99.29%, 1.99%, 0.61 g/cm^3, and 0.71%, respectively. Specimen b_4 exhibited a 100% enhancement in friability under unburned conditions and a 53.22% enhancement under burned conditions compared to the commercial briquette (b_5). These results emphasize the importance of particle size optimization in improving charcoal briquettes' performance and durability. The research identifies optimized briquettes as a highly effective renewable energy source with potential worldwide uses.

Furthermore, besides enhancing product quality, the study indicates that better briquette manufacture may significantly benefit decentralized energy systems. These findings endorse the scalability of locally generated energy solutions by improving the efficacy of renewable fuels like coconut shell charcoal. Decentralized energy systems, particularly in rural or off-grid regions, could gain from economical, efficient, and eco-friendly biomass briquettes as a feasible alternative energy source. Enhancing production processes offers potential for advancing thermal and structural qualities, expediting the global shift towards sustainable and clean energy solutions.

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