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Analysis of Higher Heating Value (HHV) Briquettes from Vitex Pinnata Charcoal to Enhance Energy and Economic Value in Tapuk Village to Support Sustainable Development Goals (SDGs) Completed with Bibliometric Analysis

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ABSTRACT

This study aimed to determine the calorific performance of halaban (Vitex pinnata) charcoal briquettes and to identify an operating window that village producers can reliably apply. This study was also completed with a bibliometric analysis. Charcoal powder from local producers was molded with starch binder under varied pressing intensities, dried, and characterized by proximate analysis and bomb calorimetry following relevant standards. The lower pressing intensity with a modest starch proportion delivered the highest heating value alongside low moisture, low ash, and sustained fixed carbon. This configuration outperformed higher compaction because reduced densification preserved pore pathways, improved drying, limited volatile dilution, and maintained the carbon-rich fraction, whereas excessive compaction trapped residual water and marginally suppressed fixed carbon despite stronger mechanics. The recommended setting supports cleaner, more stable combustion, shorter cooking times, and higher sale value for standardized briquettes, enabling down-streaming for rural livelihoods and contributing to accessible renewable energy when paired with quality control, training, and simple drying management at the producer scale. This study supports current issues in sustainable development goals (SDGs).

1. Introduction

Many reports regarding the conversion of biomass for the production of briquettes have been well-documented [1, 2]. In general, when the biomass is converted into briquettes, the quality of the briquettes is influenced by several interrelated factors such as compression pressure, particle size, and moisture content during the densification process. Increasing pressure typically improves density

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and mechanical strength up to an optimum point; however, excessive pressure can reduce internal porosity, impede drying, and impair combustion performance [3, 4]. Research on tropical wood briquettes has revealed strong correlations between density, durability, and calorific value, showing that an effective balance of thermal and mechanical properties is essential [5]. Additionally, consistency in process parameters such as moisture and volatile matter is crucial for ensuring reliable briquette quality [6]. Moisture and volatile matter tend to reduce energy, while fixed carbon content contributes significantly to energy output during combustion [7].

Various studies have established predictive models for HHV based on proximate analysis to facilitate rapid energy assessment [8-10]. Higher heating value (HHV), also known as calorific value (CV), is a critical parameter for evaluating the energy performance of solid fuels, including biomass briquettes. Table 1 summarizes the higher heating value (HHV) of briquettes produced from various biomass sources reported in previous studies. The comparison shows that thermal performance varies depending on feedstock type, pretreatment, binder proportion, moisture level, and carbon content.

Table 1
Comparison of Higher Heating Values of Biomass Briquettes from Previous Studies

Raw materials	Process	HHV (MJ/kg)	Analysis	Ref.
Water hyacinth	Formed & tested with a bomb calorimeter	14.55	GCV/HHV (bomb calorimeter)	[11]
Rice husk	Moisture 14% terbaik	17.688	HHV	[12]
Rice husk	Formulasi binder tinggi (50%)	13.67	HHV	[11]
Corn cob	Various formulations	15 until 20	HHV	[13]
Rubber wood residue)	Pressure and binder variations	19.57	HHV	[14]
Bamboo	Pressure and binder variations	21.26	HHV	[14]
Palm kernel shells	Carbonization → briquettes	20.27	GCV/HHV	[15]
Coconut shell	Carbonization → briquettes; binder variations	26.8 until 31.5	GCV/HHV	[16]

Halaban wood (Vitex pinnata), which is widely found in parts of Southeast Asia, has been reported in previous studies mainly from medicinal, antimicrobial, and phytochemical perspectives [17–21]. However, its potential as a solid biofuel feedstock, particularly in the form of charcoal briquettes, remains less explored. This gap indicates the need to evaluate Vitex pinnata charcoal from an energy-performance perspective, especially through proximate analysis and higher heating value (HHV) measurement.

This study explores the conversion of abundant Vitex pinnata charcoal residues in Tapuk Village into high-quality briquettes to enhance both energy performance and economic value. By standardizing these residues into briquettes, local producers could transform waste into valuable fuel products, increase household income, and contribute to cleaner domestic energy solutions.

Based on local market observations in Tapuk Village, halaban charcoal is commonly sold to middlemen for approximately Rp. 3,300 to 4,500 per kilogram. This value is considerably lower than the potential market price of processed charcoal and standardized briquette products, indicating an opportunity to increase producer income through value-added briquetting. This discrepancy underscores the opportunity for value-added processing through briquetting. From a technical perspective, briquetting enhances density and structural integrity while improving energy quality when moisture and volatile matter are minimized and fixed carbon is optimized [3-5]. Transforming raw charcoal into high-HHV briquettes improves energy yield and price competitiveness, benefiting households and microenterprises [8, 22]. At the macro level, this approach supports Indonesia's renewable energy and clean cooking targets, while addressing constraints related to access, affordability, and technology adoption [23-25]. When supported by reliable feedstock logistics and producer coordination, standardized briquettes offer a viable, sustainable fuel solution [22].

The development of halaban charcoal briquettes serves two key objectives: (i) to increase the economic value of village producers through standardized downstream processing, and (ii) to support the energy transition by replacing fossil-based fuels with solid renewable fuels that are feasible for household and micro, small, and medium enterprises (MSMEs) use.

This study aims to evaluate the proximate properties and higher heating value (HHV) of Vitex pinnata charcoal briquettes produced from local charcoal residues in Tapuk Village and to identify the most favorable pressing condition for improving their energy performance. This descriptive-qualitative study involves proximate testing and calorimetric analysis under varying compression pressures with a fixed starch binder. The novelty lies in (i) extending Vitex pinnata research into the bioenergy domain via briquette characterization, (ii) determining the optimal relationship between compression pressure and HHV, and (iii) integrating ASTM laboratory protocols with economic feasibility analysis at the village level to inform practical briquette production. This study supports the Sustainable Development Goals (SDGs).

2. Methodology

This study employed a single-factor laboratory experimental design to evaluate the effect of pressing pressure on the proximate properties and higher heating value (HHV) of Vitex pinnata charcoal briquettes. The study used Vitex pinnata charcoal residue obtained from local charcoal producers in Tapuk Village, Indonesia. Pressing pressure was selected as the independent variable, while moisture content, ash content, volatile matter, fixed carbon, and HHV were used as the main response variables. The tapioca starch binder concentration was kept constant in all treatments to ensure that differences in briquette properties were mainly attributable to variations in pressing pressure. Figure 1 shows the research framework and experimental variables used in this study.

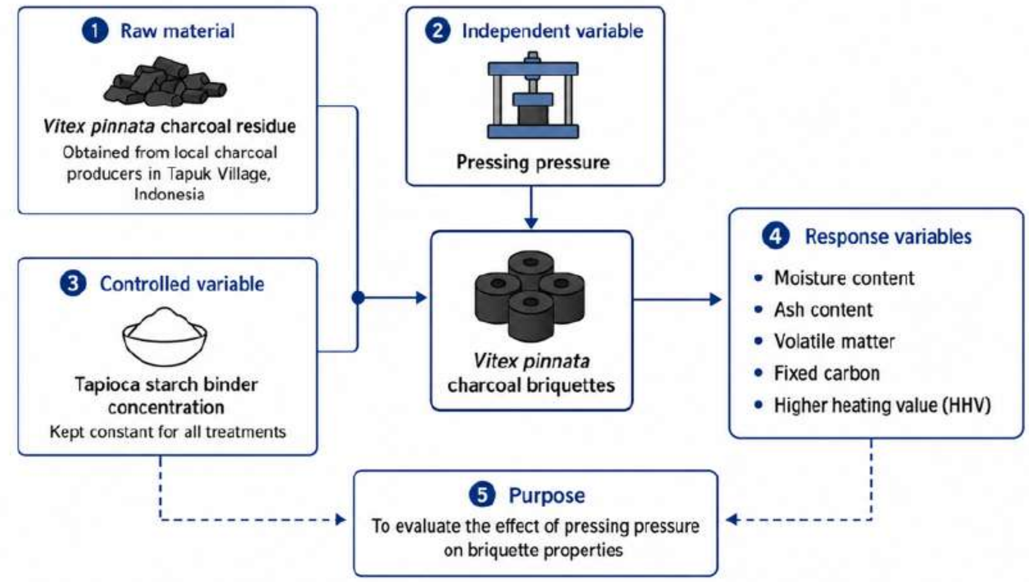


Fig. 1. The study farmwork and experimental variables

The briquette production procedure consisted of five main stages: raw material preparation, binder preparation, briquette molding, drying, and laboratory characterization. First, the Vitex pinnata charcoal residue was ground and sieved to obtain charcoal powder with a particle size of 70 mesh. The use of uniform particle size was intended to improve mixture homogeneity and reduce variation during briquette formation. The charcoal powder was then pre-dried in an oven at 100°C for 60 min to reduce residual moisture before being mixed with the binder.

The tapioca starch binder was prepared separately and then added to the charcoal powder. The tapioca starch binder was added at a fixed mass fraction of 7% relative to the total mass of the briquette mixture. Thus, each briquette formulation consisted of 93 wt.% charcoal powder and 7 wt.% tapioca starch binder. The mixture was stirred until a homogeneous briquette dough was obtained.

The prepared mixture was molded into cylindrical briquettes using a hydraulic pressing machine. Three pressing pressure levels were applied, namely 1 ton, 2.5 tons, and 3 tons. These pressure variations were used to examine the influence of compaction level on the thermal quality of Vitex pinnata charcoal briquettes. After pressing, the molded briquettes were dried in an oven at 100°C until constant mass was achieved. This final drying stage was carried out to minimize residual moisture before laboratory testing, since moisture content strongly affects calorific value and combustion performance.

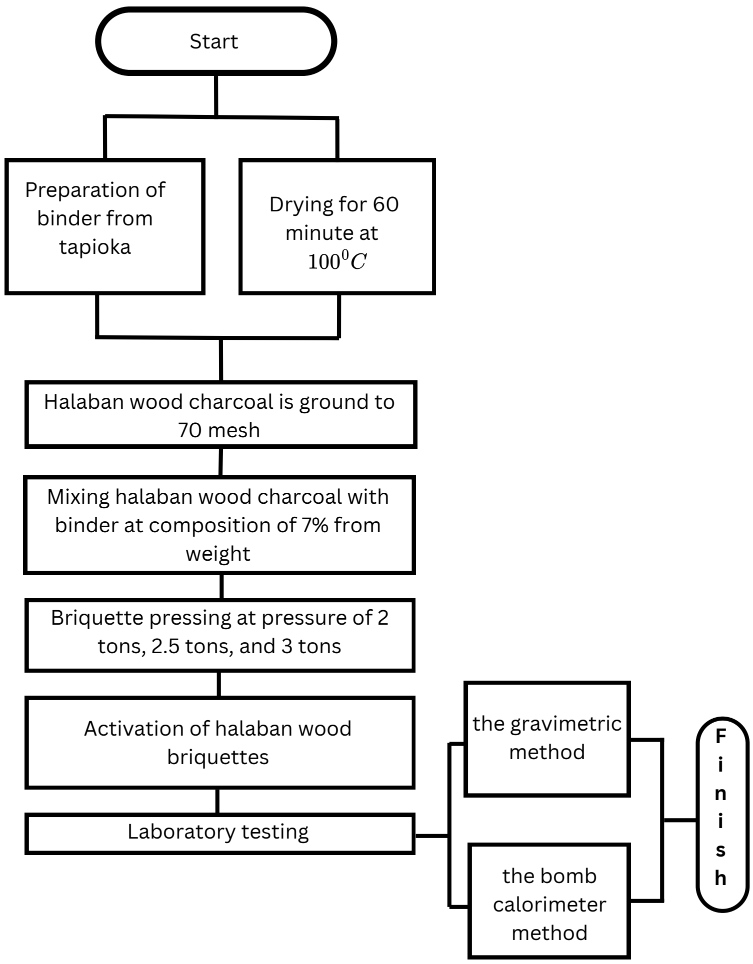


Fig. 2. Briquette processing steps and laboratory tests

The dried briquette samples were then subjected to laboratory characterization. Proximate analysis was conducted using the gravimetric method to determine moisture content, ash content, volatile matter, and fixed carbon. Moisture content, ash content, and volatile matter were determined according to ASTM D3173, ASTM D3174, and ASTM D3175, respectively. Fixed carbon was calculated by difference from the proximate analysis results. The higher heating value of the briquettes was measured using a bomb calorimeter in accordance with ASTM D5865. The obtained data were compared across the three pressing pressure treatments to identify the most favorable briquetting condition for producing high-HHV Vitex pinnata charcoal briquettes. The process of data acquisition is illustrated in Fig. 2.

3. Results
3.1 Bibliometric Analysis

Figure 3 presents the bibliometric analysis derived from 48 Scopus-indexed articles using the keywords higher heating value (HHV) and briquettes. Bibliometric analysis, as supported by recent methodological studies, offers a comprehensive way to map current research trends, identify dominant themes, and uncover relationships between variables. This has been confirmed in previous studies. In this case, the VosViewer analysis confirms that the primary emphasis across studies lies in evaluating the energy quality of solid fuels, particularly biomass-based briquettes.

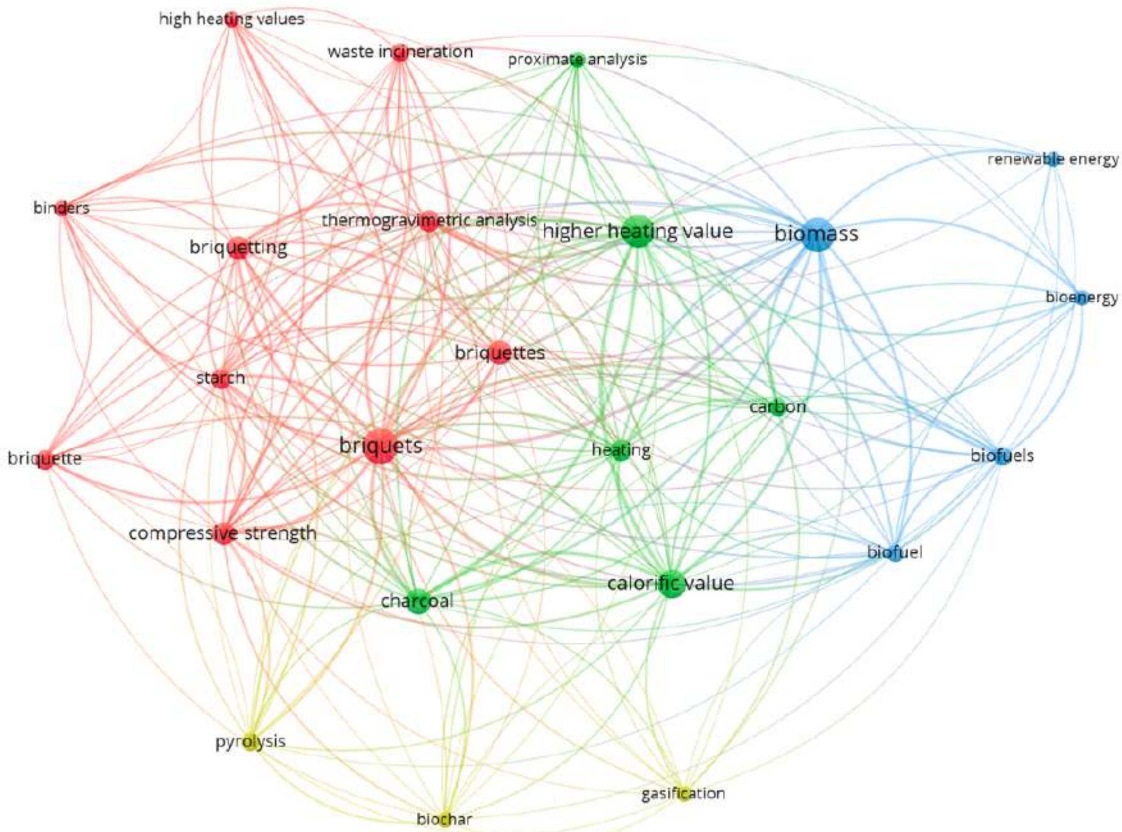


Fig. 3. Bibliometric analysis with keywords HHV and briquettes (items=24, clusters=4, links=218, and TLS=668)

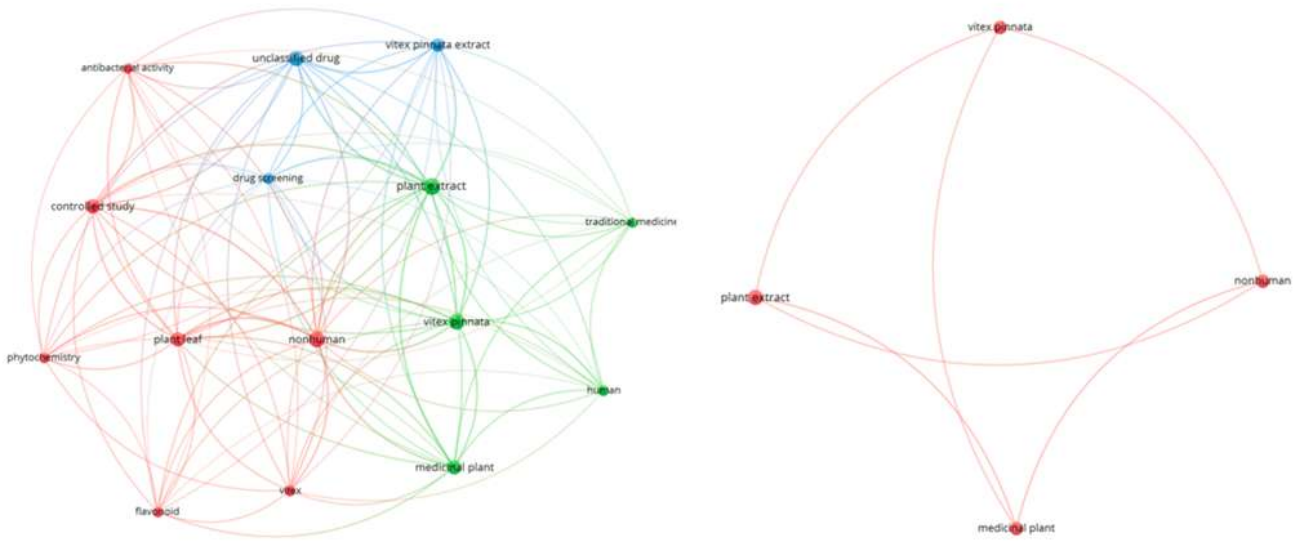
The network visualization in Fig. 3 places higher heating value and calorific value at the center of a dense cluster. These terms are directly linked with proximate analysis variables such as carbon content and charcoal, forming a thematic focus on thermal performance. Simultaneously, terms like briquetting, starch binder, and compressive strength form a parallel cluster concerned with the mechanical aspects of briquette production.

This dual clustering pattern implies that the energy quality of briquettes depends not only on the chemical nature of the raw materials but also on how those materials are processed—particularly in terms of compaction pressure and binder selection.

The relationship between raw material characteristics and calorific output is further supported by the data in Table 1, which shows significant variability in HHV values across different biomass types. Among these, charcoal-based materials—especially hardwood varieties—demonstrate relatively high energy performance, underscoring their potential as effective feedstock for briquette production. As one such material, Vitex pinnata (halaban wood) holds strong promise due to its carbon-rich structure, which favors high fixed carbon and low moisture properties desirable for combustion.

Figure 4 (a) illustrates the bibliometric analysis conducted using VosViewer on the keyword Vitex pinnata, based on 19 articles indexed in the Scopus database. The visualization shows that current research on Vitex pinnata is predominantly concentrated in the biopharmaceutical domain. Specifically, keywords such as phytochemical, antioxidant, and ethnomedicine dominate the thematic clusters, highlighting a strong focus on the medicinal properties of this species.

Further refinement in Fig. 4(b) narrows the scope to publications originating from Indonesia, revealing only eight relevant articles. Notably, all of these also remain within the health and phytochemical sectors, with no significant representation of keywords related to renewable energy—such as charcoal, biomass, briquettes, or calorific value. This gap suggests a lack of research on the thermal energy potential of Vitex pinnata, particularly in the context of its use as a briquetting material.



(a) (b)

Fig. 4. Bibliometric analysis with the keyword Vitex pinnata (items=15, cluster=3, links=102, TLS=404). (b). Further bibliometric analysis for Indonesia (item=4, cluster=1, links=6, TLS=20)

The integration of insights from Figs. 3 and 4 provide a clear rationale for the focus of this study. The HHV-focused bibliometric network (Fig. 3) emphasizes how calorific value is closely tied to proximate properties such as moisture, volatile matter, and fixed carbon, as well as to processing variables like compression and binder content. In contrast, the Vitex pinnata bibliometric map (Fig.

4) reveals an absence of energy-related research on this species, particularly in Indonesia. This disparity confirms the novelty of exploring Vitex pinnata as a renewable energy source.

Accordingly, this study adopts Vitex pinnata charcoal residue as the primary raw material, applies a fixed binder ratio of seven percent using tapioca starch, and introduces variation in compression pressure to modulate porosity and moisture retention. This approach is designed to optimize fixed carbon levels and enhance HHV, offering a new scientific contribution that extends the use of Vitex pinnata from phytochemical applications to sustainable energy production.

3.2 Briquette Making Process

The briquette production process began by crushing Vitex pinnata (halaban) charcoal into a fine powder using a 70-mesh sieve. This grinding step was essential to reduce particle size, thereby enhancing the density, compactness, and uniformity of the resulting briquette mixture. After grinding, the charcoal was sieved again to ensure a consistent particle size distribution, which directly influences combustion quality and mechanical integrity. Fine particles are easier to bind and tend to produce smoother briquette surfaces. The second stage involved drying the 70-mesh charcoal powder in an oven at 100°C for 60 minutes until the weight stabilized. This pre-drying step was crucial to remove residual moisture, which otherwise could impair adhesion, affect compression outcomes, and reduce combustion efficiency. The third stage was the preparation of the adhesive binder. A natural adhesive—cassava starch—was used, mixed at a fixed ratio of seven percent of the total mixture weight. This proportion was selected to balance mechanical strength and thermal performance. While higher adhesive content can enhance compressive strength, it may reduce calorific value due to the introduction of non-carbon material. The adhesive was gradually added and mixed thoroughly to ensure even distribution throughout the charcoal powder. The final mixture was adjusted to achieve a consistency that was moist enough for molding yet not overly wet. In the fourth stage, the mixture was molded into cylindrical briquettes with a diameter of 20 millimeters using a hydraulic pressing machine. The prepared mixture was pressed using three pressing loads, namely 1.0, 2.5, and 3.0 tons, to evaluate the effect of compaction level on briquette quality. Compression pressure is a critical parameter in determining both the mechanical stability and combustion behavior of the briquettes. The molded briquettes followed standardized dimensions to facilitate handling, packaging, and use.

Subsequently, an activation or secondary drying process was performed by heating the briquettes in an oven at 500°C to 700°C for 60 minutes. This stage aimed to reduce the moisture content to an optimal range of 5% to 8%, as excess moisture diminishes energy content and leads to uneven combustion. Proper drying at this stage enhances both strength and burn efficiency. The final step was quality evaluation.The briquettes were evaluated based on proximate properties and calorific value, including moisture content, ash content, volatile matter, fixed carbon, and HHV. Calorific value was measured using bomb calorimetry to assess energy content per unit mass, while compressive strength testing ensured the briquettes could withstand physical stress during transport and storage. Since the starch binder content was fixed at 7 wt.% in all treatments, the observed differences in HHV were interpreted mainly as the effect of pressing load and the resulting changes in moisture retention and fixed carbon content. The results of this testing were used to determine the optimal combination of binder ratio and compression pressure that delivers both thermal efficiency and structural reliability.

3.3 Laboratory Test Results

Table 2 presents the laboratory test results for briquettes produced under a pressing pressure of 1 ton. The sample exhibited a moisture content of 8.51% and an ash content of 1.53%, both of which are considered suitably low for efficient combustion. Low moisture reduces energy loss from evaporation, while minimal ash indicates reduced inert residue that could hinder thermal efficiency. The volatile matter (VM) content was 38.60%, a moderate level that supports ease of ignition without excessively reducing the fixed carbon fraction.

Most notably, the fixed carbon (FC) content reached 51.36%, signifying a substantial proportion of solid carbon that prolongs burning and sustains thermal output. These characteristics contributed to a high calorific value, measured at 6,113.76 cal/g or approximately 25.58 MJ/kg, placing the briquettes within the upper performance range for hardwood-derived biomass fuels. Overall, the 1-ton pressing condition offered the most balanced profile, with low moisture and ash, moderate VM, and high FC, translating into clean, stable combustion and strong energy output.

Table 2
Laboratory Test Results at a Pressure Variation of 1 ton

Test Parameters	Unit	Result	Method
Water content	%	8.51	Gravimetric
Ash content	%	1.53	Gravimetric
Volatile matter (VM)	%	38.60	Gravimetric
Fixed carbon (FC)	%	51.36	Gravimetric
Calorific value (HHV)	Cal/g	6,113.76	Bomb Calorimeter

Table 3 shows the laboratory results for briquettes pressed at 2.5 tons. The moisture content increased to 10.76%, and the ash content rose slightly to 2.10%. The VM content reached 41.12%, while the FC decreased to 46.02%. These changes resulted in a reduced calorific value of 5,842.73 cal/g or approximately 24.45 MJ/kg, which is lower than the value observed at 1 ton. The elevated moisture content at this pressure level likely contributed to a reduction in net energy output, as more energy is consumed during evaporation, and fixed carbon is less concentrated due to compaction-induced moisture retention.

Table 3
Laboratory Test Results at a Pressure Variation of 2.5 tons

Test Parameters	Unit	Result	Method
Water content	%	10.76	Gravimetric
Ash content	%	2.10	Gravimetric
Volatile matter (VM)	%	41.12	Gravimetric
Fixed carbon (FC)	%	46.02	Gravimetric
Calorific value (HHV)	Cal/g	5,842.73	Bomb Calorimeter

Table 4 presents the test results at the highest compression level of 3 tons. While the ash content decreased to 1.26%, the moisture content increased further to 12.19%, and VM remained high at 40.76%. The FC content was slightly reduced to 45.79%. The resulting calorific value was 5,931.72 cal/g, equivalent to 24.82 MJ/kg. Although this value was higher than that of the 2.5-ton treatment, it remained below the HHV obtained under the 1-ton condition. The increased moisture and marginally lower FC likely offset gains in structural integrity from higher compression.

Table 4
Laboratory test results at a pressure variation of 3 tons.

Test Parameters	Unit	Result	Method
Water content	%	12.19	Gravimetric
Ash content	%	1.26	Gravimetric
Volatile matter (VM)	%	40.76	Gravimetric
Fixed carbon (FC)	%	45.79	Gravimetric
Calorific value (HHV)	Cal/g	5,931.72	Bomb Calorimeter

3.4 Discussion

This study is categorized as successful for improving and creating ideas for making briquettes. This is in line with current studies regarding briquette production [26-32]. The results across the three pressure treatments revealed a consistent trend: increasing compression pressure led to a rise in moisture content, a decline in fixed carbon (FC), and a corresponding reduction in higher heating value (HHV). At the 1-ton pressure level, briquettes demonstrated a moisture content of 8.51% and FC of 51.36%, resulting in an HHV of 6,113.76 cal/g (≈25.58 MJ/kg). By contrast, briquettes pressed at 2.5 tons exhibited a moisture content of 10.76%, FC of 46.02%, and a lower HHV of 5,842.73 cal/g (≈24.45 MJ/kg). Similarly, at 3 tons, moisture content rose to 12.19%, FC slightly declined to 45.79%, and HHV reached only 5,931.72 cal/g (≈24.82 MJ/kg). These findings align with the established understanding that HHV increases when moisture and volatile matter (VM) are reduced, while high FC enhances net energy release [7-10].

The low ash content across all samples (ranging from 1.26 to 2.10%) further supports efficient combustion, as ash does not contribute to energy and can cause slagging when present in excess [5, 6]. However, the decline in HHV at higher pressures suggests a case of over-compaction. Excessive pressure likely compressed internal pore structures, impeding moisture release during drying and resulting in greater residual water retention. This reduces combustion efficiency even as mechanical strength increases, an outcome frequently cited in densification literature [3, 4].

Moreover, at higher pressures, the fixed 7% starch binder may occupy more relative volume due to the closure of pore networks. This condition not only limits the increase in FC but may also increase the proportion of volatile non-carbon components, thereby reducing the net HHV. Conversely, the 1-ton setting preserves pore pathways for moisture diffusion and results in a more favorable combination of low moisture and high FC, which explains its superior energy output.

The HHV of 25.58 MJ/kg achieved under the 1-ton condition places the halaban briquettes within the upper tier of biomass fuel quality (typically 18–26 MJ/kg), affirming its viability for household and MSME energy applications [5, 22]. Though the 2.5-ton and 3-ton treatments still produced acceptable HHV values (24.45–24.82 MJ/kg), the energy yield difference of up to 1.13 MJ/kg is nontrivial. For end-users, this difference affects combustion duration, cooking time, and fuel efficiency, especially in resource-constrained contexts [22].

The approximately 3.7% increase in moisture content between the 1-ton and 3-ton treatments translates to an extra 37 grams of water per kilogram of briquettes. This water must be evaporated during combustion, absorbing heat and producing a cooler, less efficient flame [7]. Thus, reducing moisture is critical to maintaining thermal quality.

While VM contents of 41.12% and 40.76% in the 2.5-ton and 3-ton briquettes, respectively, may aid ignition, they often correspond to lower FC and reduced total energy [9, 10]. This correlation is reflected in the decreasing FC values across higher pressure treatments. For a fixed binder composition of 7%, these findings suggest that a pressing pressure of around 1 ton offers the best balance between thermal and physical properties. However, if logistical constraints necessitate higher compression (e.g., to improve stacking or shipping), extended or enhanced drying (such as longer oven time or improved air circulation) must be employed to reduce moisture to optimal levels (≤8–10%). This aligns with general densification principles that recommend simultaneous optimization of pressure, particle size, and moisture to achieve desirable combustion behavior [3, 4, 6].

When briquettes are properly produced with low moisture, moderate VM, and high FC, their combustion tends to be cleaner and more stable than raw biomass. This results in more even burning, longer burn times, and reduced smoke emissions, benefits that are especially important for indoor household environments [33]. These health benefits are supported by findings linking indoor biomass smoke exposure to increased respiratory illness risk [34]. Nevertheless, such benefits depend heavily on the compatibility between briquette quality and stove design. Inappropriate stove use can counterintuitively increase CO_2 and particulate emissions, highlighting the need for stove adaptation and user training [35].

From a sustainability perspective, the utilization of halaban charcoal residues to produce standardized briquettes exemplifies Circular Economy principles. It transforms waste into high-value products, reduces emissions, and enhances resource efficiency [36]. Moreover, the development of briquette industries at the village level aligns with SDG 7 for ensuring access to affordable, reliable, and modern energy. To realize this potential, several enabling conditions must be met:

(i) Policy support in the form of incentives, microfinance access, and quality standardization;
(ii) Technological support from universities and research institutions for process optimization, testing, and stove compatibility;
(iii) Transparent village-level business models to manage supply chains, production, and profit-sharing; and
(iv) Branding and certification strategies to increase competitiveness with imported products.

When these components are integrated, Tapuk Village has the potential to emerge as a model for community-based renewable energy development, rooted in empirical laboratory testing, economic feasibility, and sustainable rural empowerment. Finally, this study adds new information regarding SDGs as reported elsewhere [37, 38].

4. Conclusion

This study confirmed that a pressing pressure of one ton with 7% starch binder produces briquettes with optimal thermal and physical properties. The open pore structure at this setting supports efficient drying, minimizes latent heat loss, and maximizes fixed carbon, resulting in superior calorific value. In contrast, higher pressures retain moisture and suppress energy output despite improving mechanical strength. Therefore, one-ton compaction is recommended unless accompanied by enhanced drying strategies. These findings offer actionable process guidelines for rural charcoal producers, contributing to improved combustion efficiency, economic value, and alignment with renewable energy goals.

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Conflict of Interest Statement
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