

COMPARATIVE ASSESSMENT OF PHYSICAL, CHEMICAL, AND ENERGY PROPERTIES OF PELLETS FROM INDIGENOUS SARAWAK BAMBOO SPECIES FOR COMMERCIAL UTILISATION

Rafidah J^{1,*}, Hashim B², Mahanim S¹, Tumirah K¹, Shaharuddin H¹, Puad E¹, Nicholas AL², Johari Z², Wan CC² & Rickey AD²

¹Wood Chemistry and Non Wood Utilisation Programme, Forest Products Division, Forest Research Institute Malaysia (FRIM), 52109 Kepong, Selangor Darul Ehsan

²Sarawak Timber Industry Development Corporation (STIDC), Jalan Stadium, Petra Jaya, 93050 Kuching, Sarawak

*rafidahjalil@frim.gov.my

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This study investigates bamboo pellet production through a comparative analysis of the physical, chemical, and energy properties of various bamboo species from Sarawak, Malaysia, for commercial applications. Recognised for their rapid growth and high energy potential, five species of bamboo were analysed: Aur, Aur kuning, Betung, Beting, and Pring. The study evaluates the impact of species variation and parts on pellet quality, focusing on parameters such as bulk density, calorific value (CV), fixed carbon (FC), ash, and volatile matter (VM) content. Findings revealed that converting bamboo into pellets resulted in decreased VM content while increasing ash and FC content, as well as its CV. Among the species, Betung bamboo has been rated as the highest quality for bamboo pellets, with an average density of 1190 kg/m³, VM content of 78.73%, ash content of 2.38%, FC content of 18.89% and CV of 19.31 MJ/kg. Statistical analysis indicated significant effects of bamboo species and no significant effects of bamboo parts on bamboo pellets quality. In conclusion, Betung bamboo demonstrated considerable potential as a renewable energy resource for pellet production, with applications in energy generation, animal feed, soil enrichment, and construction materials. This research enhances the understanding of bamboo as a viable feedstock for renewable energy and supports the development of the bamboo industry in Sarawak.

Keyword: Bamboo, pellets, physical properties, energy properties, renewable energy

INTRODUCTION

Biomass is a sustainable resource with a high demand for energy production and reducing dependency on fossil fuel resources. It is regarded as one of the primary options for diversifying the sources of energy. It is the only carbon-based sustainable energy with a wide variety that can be utilised by most people around the world (Liu et al. 2013). According to Acda & Devera (2014), the utilisation of biomass for energy generation is also considered carbon neutral if harvested from sustainably managed sources. The energy and use of biomass tend to promote the development of economically disadvantaged regions through job creation and income generation, reducing the problem of rural exodus and dependence on foreign

energy. In terms of global warming issues, utilisation of this biomass could reduce reliance on global energy, the usage of fossil fuels, and the emission of greenhouse effect gases (GHG) (Sette et al. 2016). According to Kamga et al. (2024), pollutants such as carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄), nitrogen oxides (NO_x) and sulphur oxides (SO_x) emitted from fossil fuels contribute to the increase of GHG emission and automatically increase the impact on global warming issues. As an alternative to overcome these issues, plant-based materials such as wood, agricultural wastes, forestry residuals, and grasses have been used to provide renewable energy in place of fossil fuels and natural gas (Liu et al. 2014). Due

to their high growth rate and increased biomass output for energy usage, certain bamboo species have been recognised as a potential substitute for energy for fossil fuels. The projected global area planted with bamboo species is 40 million hectares (Sette et al. 2016).

Bamboo is a fast-growing and ingenious plant, particularly for household applications, the pulp and paper industry, furniture, construction materials, and many more. Dwivedi et al. (2014) reported that more than 1200 species of bamboo can be found all over the world, and around 400 species are mainly from China. Among these species, *Dendrocalamus asper*, *Bambusa vulgaris* and *B. tulldoides* are identified as the most common and widespread exotic tropical species with great potential due to rapid growth and significant biomass. However, the lack of scientific knowledge on bamboo species and the possibility of using them as an energy source has delayed the full development of the culture (Sette et al. 2016). Like wood, bamboo is composed of cellulose, hemicellulose and lignin (Liu et al. 2013). According to Bai et al. (2013), the chemical composition of raw bamboo comprised 47.2% cellulose, 23.9% hemicellulose, 23.8% lignin, and 1.4% ash. Generally, bamboo matures in three (3) years and can be harvested four (4) times a year. Then, it becomes an ideal feedstock to produce high-value-added products such as charcoal, pellets, and activated carbon. However, pellets are among the promising renewable energy sources most widely used in the world to substitute fossil fuels that have been used for heating and combustion (Sette et al. 2016). Pellets have characteristics superior to other biomass products, such as woodchips and briquettes, especially in regard to mass and energy densities. Such higher density results in lower transportation costs and greater efficiency in regard to energy conversion; having suitable properties is essential for use on residential and industrial scales. In China, bamboo has been identified as a new biomass for solid fuel production with a high potential to be used as feedstock for commercial pellets. The bamboo pellets produced should meet the minimum requirement for making commercial pellets of DIN 51731 (DIN 1996), which has an energy value of more than 17.5 MJ/kg (Liu et al. 2013). Generally, commercial pellets, particularly those derived from biomass sources, have a wide

range of applications across various sectors, such as for energy production, animal feed, soil amendments, industrial applications for energy generation, and as raw materials for further processing in catalytic processes such as the conversion of ethanol into butanol and utilised in environmental applications, such as for carbon sequestration and waste management (Nunes et al. 2016, Garcia et al. 2019, Gilvari et al. 2020). In terms of economy and world demand, from 2006 to 2012, there was an increase in global pellets output of 7 to 19 million tonnes (Sette et al. 2016). Moreover, for the pellet global market demand, the market size is expected to grow from \$5882.8 million in 2018 at a CAGR of 1.9% from 2021 to 2024 (Anon 2023).

Conversion of bamboo into pellets could enhance its properties and storability, allowing it to produce cheaper products and substitute charcoal. Pelletising bamboo is one of the possibilities for enhancing energy storage by increasing its energy value, thereby improving storability. The production process involves multiple stages such as pre-treatment (raw material preparation), pelletising process (compressing and densifying biomass materials into small pellet forms), and post-treatment (cooling process, screening, and packaging of pellets) (Stelte et al. 2012). Typically, biomass pellets have a diameter of 6 to 8 mm, and their length can range from 10 to 30 mm. These sizes are considered standard for residential heating applications and are widely used in pellet stoves and boilers. Some advantages of pellets produced from biomass include higher bulk and energy density, better flow and storage properties, and lower material wastage (Adapa et al. 2006, Liu et al. 2016). Thus, the aim of this paper is to utilise bamboo as a solid fuel in the form of pellets and to evaluate the potential of pellets produced from five different species of bamboo obtained from Sarawak for commercial applications.

MATERIALS AND METHODS

Raw bamboo preparation

Five bamboo species, each four years old, were received in the form of strips (1 meter in length) from Sarawak Timber Industry Development Corporation (STIDC). The species included

Aur bamboo (*Bambusa vulgaris*), Aur kuning bamboo (*B. vulgaris* var. *striata*), Betung bamboo (*Dendrocalamus asper*), Beting bamboo (*Gigantochloa levis*), and Pring bamboo (*G. atter*). All of these bamboos were collected from the Sarawak wild forest, in the areas of Bau, Kota Samarahan, and Padawan. The strips, consisting only of internode sections, were divided into top, middle, and basal portions. These strips were cut into smaller pieces to form bamboo chips, which were then crushed into fibres with particle size between 2 to 5 mm. Initially, the average moisture content (MC) of bamboo fibres is 25%. Then, these fibres were oven-dried to reduce the MC to below 10%, preparing them for pellet production (Figure 1).

Bamboo pelletisation process

Biomass pellets were produced using a laboratory-scale pelletiser machine (Model: SE/SP300B) equipped with an electric motor

that has a power supply of 22 kW and a capacity of 80 to 100 kg/hr (Figure 2). Bamboo pellets were produced by compressing bamboo fibres into a mould according to the required diameter. The pelletiser machine was a fixed-die type consisting of multiple components, including a gearbox, hopper, roller, cutting knife, electrical motor, and fixed dies. The bamboo materials with MC below 10% were fed into the hopper, where they were pressed and extruded using a roller. Then, the dies were activated when the roller generated frictional force through centrifugal rotation (Mahanim et al. 2025).

The pelletising process was carried out at a temperature between 50 to 60 °C, with a compression pressure of 4 tons for a duration of one hour. This process yielded one kilogram of bamboo pellets from three kilograms of raw bamboo (Figure 3). The high pressure applied during the process caused the temperature of the sample to rise, and the lignin content present

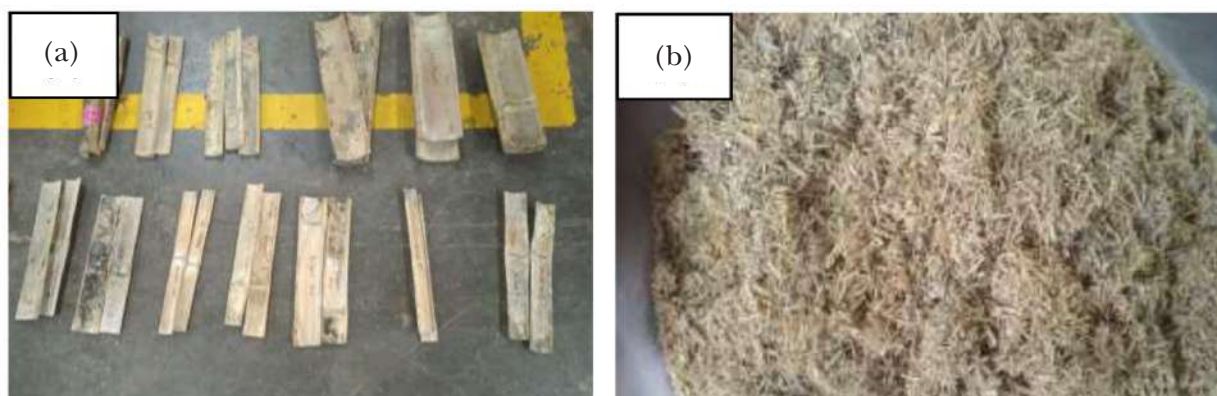


Figure 1 Bamboo strips (a) and bamboo fibres (b)



Figure 2 Laboratory-scale pelletising machine



Figure 3 Production of bamboo pellets using pelletising machine

in the bamboo acted as a natural binder upon cooling. This pelletising process was repeated for all the selected bamboo species in this study.

Characterisation of bamboo pellets

The characteristics of the produced bamboo pellets, in terms of physical, chemical, and energy properties, were compared with the International standard method, specifically referencing the European (EN) Standard for commercial pellets. Figure 4 illustrates the physical, chemical, energy, and ultimate analyses conducted on the bamboo pellets sample. The following procedures were carried out extensively in triplicate to obtain more accurate results.

Physical properties

The physical properties of the bamboo pellets, which include density, bulk density, durability, fines, length, and diameter, were comprehensively characterised. Bulk density and density are essential parameters influencing handling, storage, and combustion efficiency. Bulk density, the mass of the pellets per unit volume, was determined by filling bamboo pellets into a 500 mL measuring cylinder on

an analytical balance with an accuracy of 0.01 g (Figure 4a). Their weight was recorded and then calculated using Equation 1 (Mahanim et al. 2025). The density was measured with a densitometer in triplicate (Figure 4c). For pellet diameter and length, a veneer calliper with an accuracy of 0.01 mm was used to measure the diameter and length of 100 g of bamboo pellets. It was measured three times to get more accurate results. This method provides precise measurements and is suitable for both small and large batches of pellets (Figure 4b).

$$\text{Bulk density} = \frac{\text{weight (kg)}}{\text{volume (m}^3\text{)}} \quad (1)$$

Durability and fines are key for assessing bamboo pellets' ability to withstand mechanical stress during transport and storage (Mahanim et al. 2025). Durability indicates resistance to crumbling and breaking, which is crucial for maintaining pellet integrity. Fines are small particles formed during production and handling. The durability of the produced bamboo pellets was evaluated in accordance with the European Standard (BS EN 15210: 2009 by placing 500 g of pellets in a rotating cylindrical vessel at 35 rpm for 10 minutes (Figure 4d) and calculated using Equation 2 (Brunerova

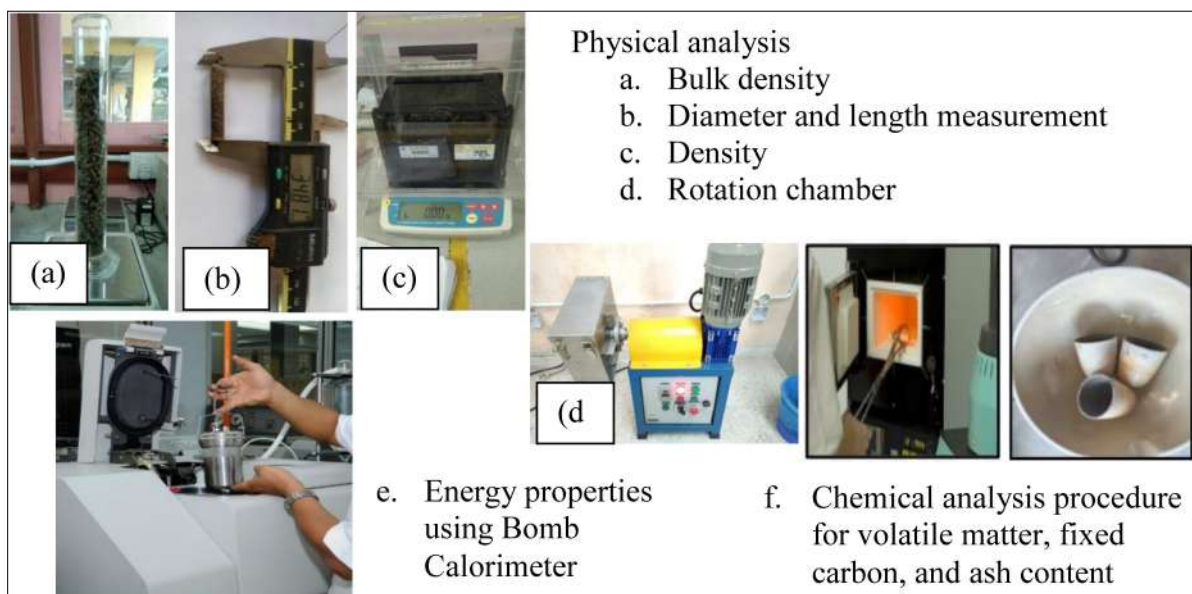


Figure 4 Apparatus and methods used for the characterisation of bamboo pellets, including (a) bulk density measurement, (b) diameter and length analysis, (c) density determination, (d) durability testing using a rotation chamber, (e) energy properties evaluation with a bomb calorimeter, and (f) chemical analysis for volatile matter, fixed carbon, and ash content

et al. 2018). For the fines measurement, the fines after the durability measurement process were separated and weighed using an analytical balance (Model: A&D GR-200) with an accuracy of 0.01 g. Equation 3 determined the fines percentage in the bamboo pellet samples (Mahanim et al. 2025).

$$\text{Durability (\%)} = \frac{\text{Weight of pellet after rotation (g)}}{\text{Weight of pellet before rotation (g)}} \times 100\% \quad (2)$$

$$\text{Fines content (\%)} = \frac{\text{Weight of fines (g)}}{\text{Weight of sample (g)}} \times 100\% \quad (3)$$

Chemical properties

The chemical properties of bamboo pellets: moisture content (MC), volatile matter (VM), ash, and fixed carbon (FC) were analysed according to British Standards (BS EN 14774-2, BS EN 15148, BS EN 14775). MC was measured using the oven drying method, where pellets were dried at 105 °C for 24 hours in the oven (Model: Ecocell-111), with weights recorded before and after drying using a 0.01 g accuracy analytical balance (Model: A&D GR-200) and calculated using Equation 4. Ash content, indicating non-combustible minerals, was measured by burning pellets at 700 °C for 4 hours in a furnace (Model: Vulcan D-550) and calculated using Equation 5.

$$\text{Moisture content (\%)} = \frac{\text{Wet weight (g)} - \text{Dry weight (g)}}{\text{Wet weight (g)}} \times 100\% \quad (4)$$

$$\text{Ash content (\%)} = \frac{\text{Weight of ash (g)}}{\text{Weight of initial sample (g)}} \times 100\% \quad (5)$$

VM refers to the gases, such as methane, hydrogen, and carbon monoxide, released when bamboo pellets are heated. This measurement indicates the amount of combustible gases that evaporate during the initial combustion stages, impacting the pellet's ease of ignition and burning (Racero-Galaraga et al. 2024). VM content was measured by burning the pellets in a furnace at 900 °C for 7 minutes and calculated using Equation 6, where it was not calculated on a dry basis. Meanwhile, FC content was calculated using Equation 7.

$$\text{VM content (\%)} = \frac{\text{Final weight (g)} - \text{Initial weight (g)}}{\text{Initial weight (g)}} \times 100\% \quad (6)$$

$$\text{FC content (\%)} = 100 - [\text{ash (\%)} + \text{VM (\%)}] \quad (7)$$

Energy properties

The calorific value (CV) of bamboo pellets was measured using a bomb calorimeter (Model: LECO Instrument), according to British

Table 1 Properties of raw bamboo

Properties	Aur	Aur kuning	Betung	Beting	Pring
Density (kg/m ³)	752 (40.41)	800 (50.00)	898 (25.17)	846 (21.00)	948 (54.37)
VM (%)	81.49 (0.42)	89.59 (0.53)	82.22 (0.85)	83.42 (0.64)	87.36 (0.36)
FC (%)	11.52 (0.87)	9.41 (0.56)	16.38 (0.82)	15.08 (1.79)	10.47 (2.01)
Ash (%)	2.04 (0.14)	1.01 (0.03)	1.40 (0.06)	1.50 (0.14)	2.17 (0.14)
CV (MJ/kg)	16.53 (0.38)	15.88 (0.02)	16.78 (0.01)	15.99 (0.03)	16.48 (0.16)

() = Standard deviation

Standard (BS EN 14918:2009). About 1.0 g of bamboo pellets were weighed, attached to a thread, and burned in the calorimeter with constant oxygen. The instrument automatically calculated the gross calorific value (GCV) based on the temperature difference.

Ultimate properties

The ultimate analysis of bamboo pellets was carried out to determine the carbon, hydrogen, oxygen, nitrogen, and sulphur (CHONS) content using a CHNS analyser (Model: LECO Instrument 628). The C, H, N and S contents were directly measured, while the O content was calculated. These elements are essential for assessing the quality of the bamboo pellets.

Statistical analysis

Analysis of variance (ANOVA) of single factor analysis using Microsoft Excel Data Analysis was used for the statistical analysis of physical, chemical and energy properties of pellets according to the species and parts of bamboo, with a significance value of $p < 0.05$.

RESULTS AND DISCUSSION

Physical, chemical and energy properties of raw bamboo

The physical, chemical, and energy properties of five bamboo species were assessed to establish a baseline for comparison with bamboo pellets. Measurements were done in triplicate, with average values and standard deviations shown in Table 1. The properties ranged from 752 to 948 kg/m³ (density), 81.49 to 89.59% (VM), 9.41 to 16.38% (FC), 1.01 to 2.17% (ash), and 15.88

to 16.78% (CV). Hartono et al. (2022) studied the density of six species of bamboo and the average value ranging from 623 to 829 kg/m³. Density variations are influenced by anatomical structure, fibre composition, and environmental conditions (Wahab et al. 2012; Burn et al. 2018; Barnabas et al. 2020; Maulana et al. 2021).

Physical properties of bamboo pellets

The comparison of bamboo pellet lengths and diameters from different species and parts is presented in Table 2. The longest pellets (38.66 mm) were produced from the top part of Pring bamboo, while the shortest (19.68 mm) were from the middle part of Aur kuning bamboo. The largest diameter (6.60 mm) came from the basal part of Aur kuning bamboo, and the smallest (6.04 mm) was from the top part of Beting bamboo. According to British Standards (BS EN 14961-2), Grade 1 commercial pellets require diameters of 6 to 8 mm and lengths under 32 mm (Kamga et al. 2024). All samples met diameter standards, but only Pring bamboo exceeded the length limit. This compliance is essential for market acceptance and optimal performance in applications such as combustion and gasification. The variations in pellet dimensions resulted from the inherent characteristics of bamboo species, bamboo parts used, and factors such as raw material properties, processing conditions, and equipment utilised. The biomass particle interaction during compression led to variations in pellet shape and size, as the particles might not flow uniformly through the die (Jackson et al. 2016). Pellet length and diameter are crucial for fuel-feeding properties and combustion efficiency, as shorter pellets typically have better feeding rates and flow more easily, while thinner pellets promote uniform combustion

Table 2 Comparison of length and diameter of bamboo pellets

Bamboo species	Length (mm)			Diameter (mm)		
	Top	Middle	Basal	Top	Middle	Basal
Aur	31.01	32.60	28.60	6.39	6.49	6.56
Aur kuning	21.59	19.68	20.66	6.40	6.55	6.60
Betung	21.90	24.15	25.03	6.39	6.40	6.31
Beting	34.49	27.36	36.10	6.04	6.18	6.36
Pring	38.06	36.66	36.24	6.34	6.18	6.23

rates, particularly in small furnaces (Paivi 2001). Numerous studies have investigated pellet production from various types of biomass using different pelletising machine under different processing conditions. For example, Gilvari et al. (2020) produced sawdust pellets ranging from 10.0 to 46.3 mm in length, and Sudhagar et al. (2006) reported pellet lengths between 5.0 and 40.0 mm, with diameters of 6 to 8 mm. Liu et al. (2012) found bamboo pellet lengths between 11.7 and 12.7 mm and diameters between 6.0 to 6.1 mm. Meanwhile, Sette et al. (2016) produced bamboo pellets with diameter of 6.0 to 6.2 mm and 28.0 to 29.8 mm in length.

Density and bulk density are key quality indicators for evaluating storage facilities and handling systems. The density and bulk density of bamboo pellets after processing are shown in Table 3. The highest density was found in the top part of Betung bamboo (1275 kg/m³), followed by the middle part of Beting bamboo (1226 kg/m³), and the basal part of Betung bamboo (1181 kg/m³), with standard deviations ranging from 10.41 to 68.07%. The increase in density resulted from the compaction process of raw bamboo during the pelletising process. For bulk density, bamboo pellets made from the top

part of Betung bamboo had the highest value at 624 kg/m³, followed by the middle and top part of Aur kuning bamboo (621 kg/m³ and 620 kg/m³), with standard deviations ranging from 0.38 to 4.62%. These results indicated that all bamboo pellets produced met the commercial standard of a bulk density exceeding 600 kg/m³. According to Liu et al. (2013), higher bulk density enhances transportation efficiency and reduces storage needs. Liu et al. (2016) noted that increased bulk density improves efficiencies in transport, handling, and storage while also lowering costs and boosting energy conversion efficiency, making the pellets suitable for both domestic and industrial uses (Sette et al. 2016, Artemio et al. 2018).

The durability of bamboo pellets is crucial for efficient handling and transportation, as defined by ISO 16559. This standard considers durability as the ability of pellets to maintain their integrity throughout supply chain processes, including loading, unloading, and transportation. Commercial bamboo pellets typically exhibit a durability exceeding 97.5%. A comparative study revealed that all produced bamboo pellets had a durability above 97% (Table 4), with the highest durability recorded

Table 3 Comparison of density and bulk density of bamboo pellets

Bamboo species	Density (kg/m ³)			Bulk Density (kg/m ³)		
	Top	Middle	Basal	Top	Middle	Basal
Aur	1124	1095	1063	608	611	611
Aur kuning	1109	1171	1011	620	621	610
Betung	1275	1114	1181	624	607	604
Beting	1118	1226	1176	606	609	606
Pring	1118	1064	1157	617	610	606

Table 4 Comparison of durability and fines content of bamboo pellet

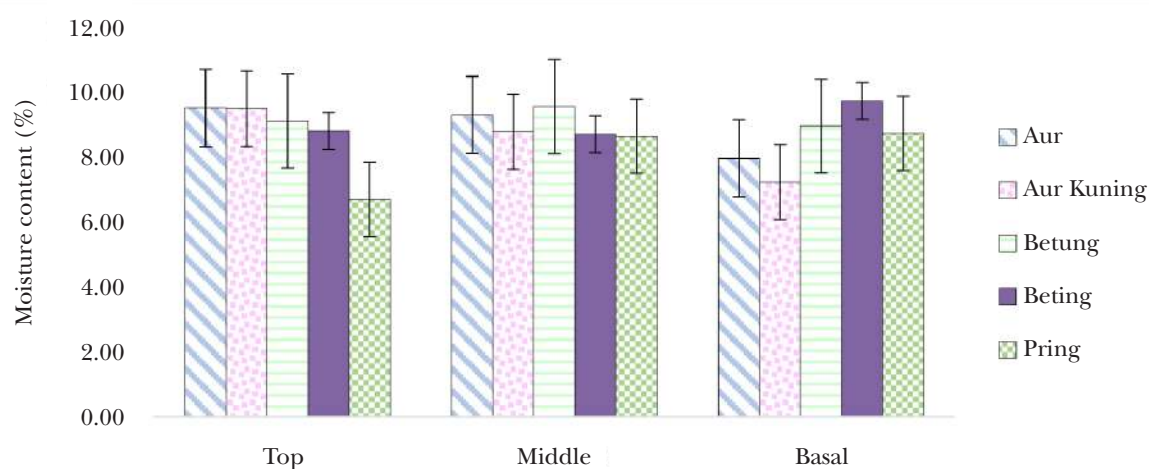
Bamboo species	Durability (%)			Fines (%)		
	Top	Middle	Basal	Top	Middle	Basal
Aur	97.67	97.63	97.80	0.95	1.08	1.23
Aur kuning	97.50	98.07	97.67	1.27	1.22	1.11
Betung	97.63	97.51	97.82	1.17	0.90	1.60
Beting	97.70	97.60	97.67	1.15	1.17	1.02
Pring	97.53	97.77	97.70	1.27	1.30	1.49

for the middle part of Aur kuning bamboo (98.07%), followed by the basal part of Betung bamboo (97.82%) and the basal part of Aur bamboo at (97.80%) with standard deviation ranging from 0.12 to 0.31%. According to Sette et al. (2016) and Liu et al. (2014), bamboo pellet durability typically ranges between 95 and 98%, indicating their robustness during transportation. Moreover, low durability values can hinder effective transport and processing. This challenge can be mitigated by using longer pellets of over 15 mm (Williams et al. 2018). Additionally, fines content affects pellet quality, with all bamboo pellets exhibiting fines below 2.00% (Table 4). The middle part of Betung bamboo has the lowest fines content at 0.90%, followed by the top basal part of Aur bamboo (0.95%) and the basal part of Beting bamboo (1.02%) with a standard deviation ranging from 0.06 to 0.11%. Gilvari et al. (2020) highlighted a strong correlation between durability and fines content, where improved durability contributes to diminished fines and dust during handling.

Chemical properties of bamboo pellets

Initially, the average moisture content (MC) of raw bamboo during delivery and before oven dried is about 25%, and the MC of bamboo pellets produced is below 10% after the conversion process (Figure 5). According to EN standard requirements, the commercial pellet should have an MC of less than 10%. The decrease in MC is attributed to the removal of water during the pelletising process, which is driven by frictional heat generated in the pellet die (Tumuluru 2019).

The conversion of raw bamboo into bamboo pellets resulted in a significant increase in fixed carbon (FC) content (Figure 6). Among the species studied, the top and middle parts of Aur Kuning bamboo had the highest FC content at 22.09%, followed by the top part of Aur bamboo (21.47%), and the top part of Beting bamboo (20.56%). Initially, raw Aur Kuning bamboo has an FC content of 9.41%, indicating a conversion percentage of 134.75%

**Figure 5** Moisture content of bamboo pellets

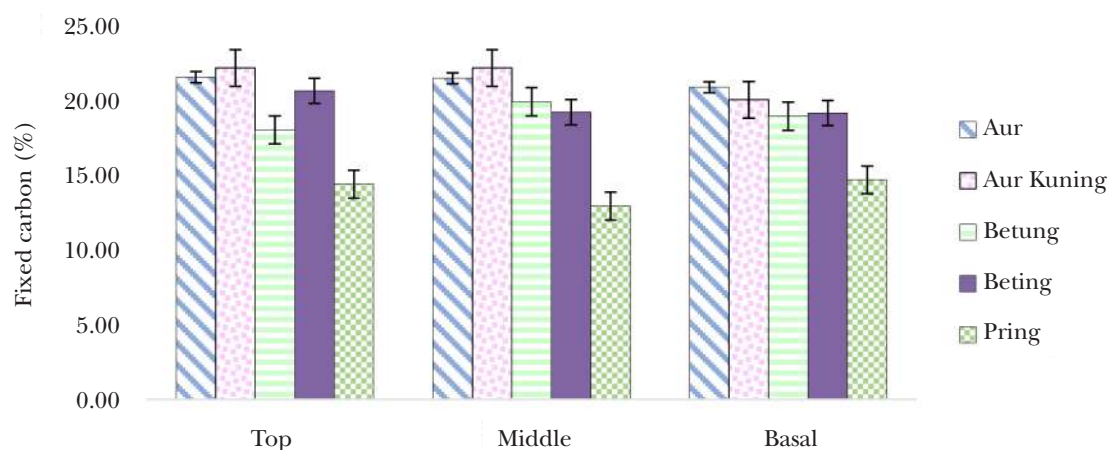


Figure 6 Fixed carbon content of bamboo pellets

into pellets. The increase in FC content was attributed to the decomposition of biomass components, particularly hemicellulose and cellulose, during the pelletising process when heat was applied. This process released volatile matter (VM) while enriching the remaining material with fixed carbon (Peng et al. 2013). Dewi et al. (2023) and Lin et al. (2016) noted that the removal of VM also reduces oxygen content, thereby increasing the ratio of FC, which is primarily carbon (C). This effect enhances the energy density of the pellets. Furthermore, the breakdown of lower carbon-dense components results in a higher lignin proportion, contributing to increased FC content (Sermyagina et al. 2022, Oyeboode & Ogunsuyi et al. 2021). High FC content pellets burn more slowly, extending their residence time in combustion systems, suggesting a

relationship between FC and VM content that influences the reactivity of biomass (Mat Rasat et al. 2016).

The VM content of bamboo pellets is crucial for evaluating their combustion properties (Figure 7). After combustion, volatile fractions include light hydrocarbons, carbon monoxide, carbon dioxide, hydrogen, moisture, and tars (Mat Rasat et al. 2016). Unlike FC, converting raw bamboo into pellets reduces the VM content. The highest quality bamboo pellets, derived from the middle part of Aur kuning bamboo, achieved a VM content of 74.37%, with a percentage reduction of 16.99% from the raw bamboo (89.59%). Among the bamboo species studied, Aur kuning exhibited the lowest VM content (74.37%), followed closely by Aur bamboo (75.93%) and Beting bamboo (75.98%). This trend illustrates a direct

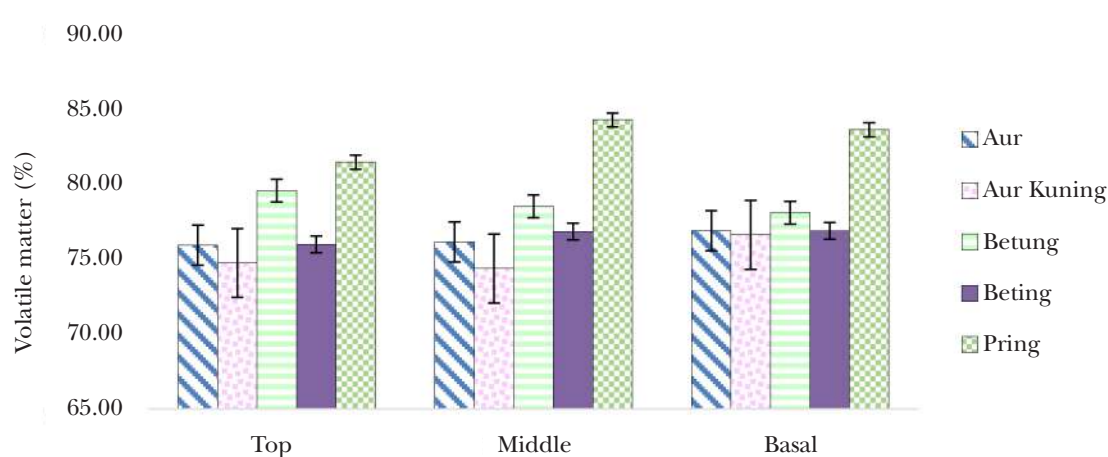


Figure 7 Volatile matter content of bamboo pellets

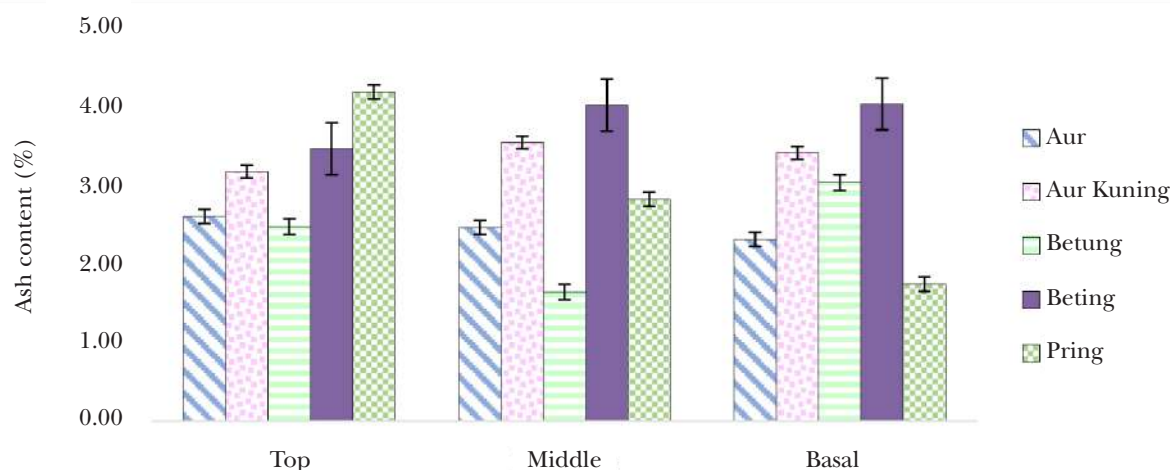


Figure 8 Ash content of bamboo pellets.

correlation between FC and VM content, where the conversion enhanced FC while diminishing VM, attributed to moisture and volatile loss during the pelleting process. The VM content in biomass typically ranges from 65 to 85%, influencing combustion rates and thermal decomposition (Werther et al. 2000, Sette et al. 2016, Kamga et al. 2024). The reduction in VM during pelleting arises from both thermal and mechanical processes. Heat breaks down biomass components, especially hemicellulose and cellulose, releasing volatile compounds, as higher temperatures lead to greater moisture evaporation (Frodeson et al. 2019, Barmina et al. 2020). Additionally, grinding biomass into finer particles before pelleting promotes volatile release, resulting in lower VM content (Luo et al. 2011). Effective biomass processing is crucial for optimising the properties of bamboo pellets as a renewable energy resource.

The comparison of ash content in bamboo pellets produced from different species indicates an increasing trend over time. High-quality pellets had low ash content. Figure 8 shows the middle part of Betung bamboo had the lowest ash content (1.64%), followed by the basal part of Pring bamboo (1.74%), and Aur bamboo (2.31%); with percentage increase of 17.14% from raw Betung bamboo (1.40%). According to EN standards, commercial pellets should contain less than 0.7% ash, as high ash levels, primarily due to high silica content, can damage burner structures (Sette et al. 2016, Amirta et al. 2018). Kamga et al. (2024) and Mahanim et al. (2025) reported that ash content for wood pellets

is less than 3%. High ash content can complicate combustion processes, leading to operational challenges like ash removal and equipment corrosion (Oberberger et al. 2006, Acda & Devera 2014, Amirta et al. 2018). Ash content after pelletising is influenced by mineral content of feedstock and pelletising conditions, with potential contamination from external sources during processing (Nasrin et al. 2021; Do et al. 2025).

Energy density of bamboo pellets

The energy density comparison among bamboo pellets, as shown in Figure 9, indicates that the CV increment after conversion across all studied bamboo species. The middle part of Aur Kuning bamboo exhibited the highest CV at 20.64 MJ/kg, followed by the basal part of Betung bamboo at 19.56 MJ/kg and the basal part of Aur bamboo at 19.51 MJ/kg; with percentage increase of 29.97% from raw Aur kuning bamboo (15.88 MJ/kg). According to EN standards, the CV range for commercial pellets is between 16.50 and 19.00 MJ/kg, with all bamboo pellet CVs falling within this range. A higher CV indicates suitability for bioenergy production (Acda & Devera 2014). The pelletising process compresses biomass, leading to increased density and greater energy concentration per unit volume. Moisture is expelled during this process, further elevating CV, as reduced moisture content allows for more available energy during combustion (Ifukhar et al. 2019). Esteves et al. (2023) highlighted that the CV of pellets is significantly

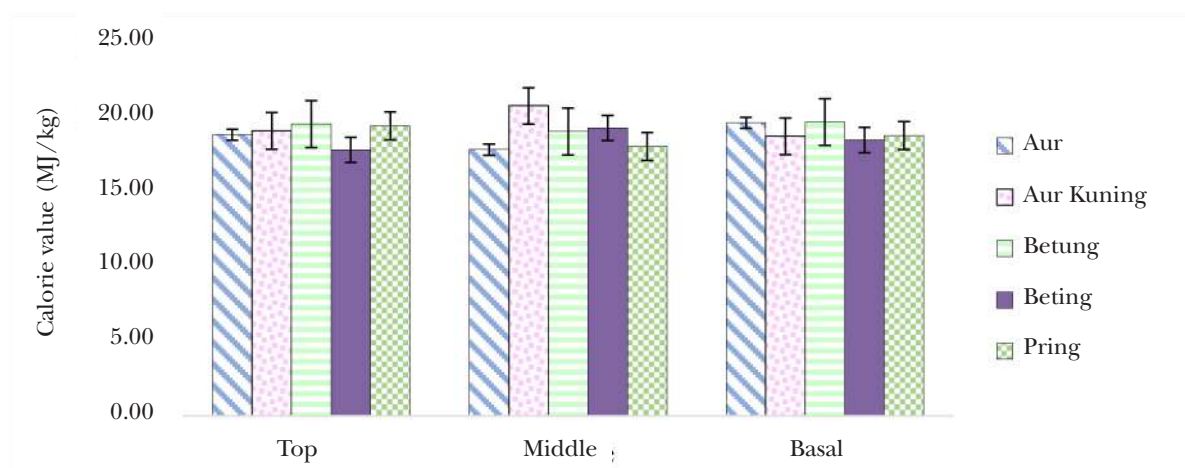


Figure 9 Calorific value of bamboo pellets.

influenced by the raw materials used, especially the proportions of cellulose, hemicellulose, and lignin. Lignin has a higher heating value (23.26–25.58 MJ/kg) compared to polysaccharides like cellulose and hemicellulose (18.6 MJ/kg). Therefore, biomass with higher lignin content typically exhibits increased CV, enhancing its energy potential during combustion.

Ultimate content of bamboo pellets

The bamboo pellets' ultimate analysis focusing on their CHONS content: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulphur (S), is essential for evaluating their energy properties. A comparative study of five bamboo species revealed that Betung bamboo possessed the highest carbon content at 47.20%, followed by Aur bamboo (42.85%), and Beting bamboo (40.39%). According to DIN51731 standards, the ideal C content should be between 48 and 50%, with Betung bamboo nearly reaching

this range, indicating its suitability for energy applications. In terms of H content, only Betung bamboo (6.58%) and Pring bamboo (6.42%) met the minimum requirement of 6.20%. All tested species exhibited O content exceeding 42%, which is crucial for their combustion characteristics and energy yield. These findings have underscored the importance of species selection in enhancing bamboo pellets for bioenergy production. Meanwhile, the N content in all bamboo pellets was below 0.30%, which met standard requirements except for Betung bamboo at 0.34%. High N content indicates excessive chemical fertiliser use, increasing nitrate gas emissions (Souza et al. 2020). In contrast, S content was generally high and did not meet standards, with only Aur bamboo and Aur kuning bamboo nearing the DIN51731 guideline at 0.08%. Elevated sulphur poses risks during combustion, releasing sulphur gases linked to erosion. This increase in sulphur is often due to contamination from insecticides and preservatives in raw materials, emphasising

Table 5 Comparison of CHONS content in bamboo pellets

Element	C (%)	H (%)	O (%)	N (%)	S (%)
Aur	42.85	2.14	54.77	0.24	0.08
Aur Kuning	39.61	3.51	56.56	0.24	0.08
Betung	47.20	6.58	45.77	0.34	0.10
Beting	40.39	3.14	56.13	0.25	0.09
Pring	33.53	6.42	59.90	0.06	0.11
EN Standard				< 0.30	< 0.03
DIN51731(1996)	48 - 50	6.20	42.00	< 0.30	< 0.08

Table 6 Summary of ANOVA single factor analysis of bamboo pellets.

Properties	Different species			Different part		
	F	F _{crit}	P	F	F _{crit}	P
Length	44.351	3.056	0.000	0.038	3.239	0.990
Diameter	11.159	3.056	0.000	0.337	3.239	0.799
Density	3.180	3.056	0.044	0.191	3.239	0.901
Bulk density	2.084	3.056	0.134	1.728	3.239	0.201
Durability	0.341	3.056	0.846	1.007	3.239	0.415
Fines	1.934	3.056	0.157	0.817	3.239	0.503
Volatile matter	60.018	3.056	0.000	0.202	3.239	0.893
Ash content	5.332	3.056	0.007	0.134	3.239	0.939
Fixed carbon	54.893	3.056	0.000	0.156	3.239	0.924
Calorific value	1.932	3.056	0.157	0.019	3.239	0.996

the need for careful management of bamboo feedstock.

Statistical analysis of pellets produced from different species and different parts of bamboo

ANOVA with a single factor was used to analyse the pellets produced from various bamboo types and parts, as summarised in Table 6. The study focused on two independent variables: bamboo species and part. Results indicated that the F value exceeded the critical F value with a P value less than 0.05 for species, indicating significant effects on pellet properties such as length, diameter, density, volatile matter, ash, and fixed carbon. However, parameters like bulk density, durability, fines content, and calorific value showed no significant differences, while bamboo parts exhibited no impact on pellet quality.

Selection of suitable bamboo for commercial production

Statistical analysis showed that different bamboo parts did not significantly impact pellet production, so selection was based on average values. Density and ash content are the most critical factors influencing pellet quality, where dense pellets and low ash facilitate efficient handling, transport, storage, and combustion efficiency (Whittaker & Shield 2017 Rafidah et al. 2021). A rating system of 1 to 5 was established based on the highest density and lowest ash, with Betung bamboo receiving the top quality rating. All selected species are suitable for pellet production based on proximate analysis and density, supporting findings by Osman et al. (2022) that bamboo species significantly affect chemical and physical properties, highlighting the importance of species selection.

Table 7 Comparison of total rating for different species of bamboo

Bamboo species	Density (kg/m ³)	Ash (%)	Total rating
Aur	1094 (5)	2.46 (2)	7
Aur kuning	1097 (4)	3.37 (4)	8
Betung	1190 (1)	2.38 (1)	2
Beting	1173 (2)	3.84 (5)	7
Pring	1113 (3)	2.91 (3)	6

CONCLUSIONS

The quality of pellets produced from five different bamboo species showed that they meet commercial standards in terms of physical, chemical, and energy properties. Statistical analysis demonstrated that the species of bamboo significantly affected pellet production, particularly concerning density, volatile matter (VM), ash, and fixed carbon (FC) content. This highlights the importance of selecting appropriate bamboo species, as their unique characteristics influence pellet quality. Conversely, the study found that the specific parts of the bamboo plant did not considerably impact quality, allowing for blending across parts. Among the tested species, Betung bamboo emerged as the superior choice, boasting impressive pellet characteristics with a density of 1190 kg/m³ and 2.38% ash content. Overall, the findings suggested that Betung bamboo not only holds promise for bioenergy projects but also serves as a great alternative biomass fuel, benefiting both residential and industrial users looking for sustainable energy sources.

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