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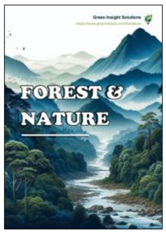

RESEARCH ARTICLE

Syngas Characteristics and Energy Performance of Betung Bamboo (*Dendrocalamus asper*) Pellets in a Downdraft Gasifier

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ABSTRACT

Indonesia currently faces a significant energy challenge, with 85% of national needs met by declining fossil fuel reserves. While biomass is a sustainable alternative, empirical data on the performance of betung bamboo (*Dendrocalamus asper*) pellets in downdraft gasifiers remains limited. This study aims to analyze the evolution of syngas composition, determine the lower heating value (LHV), and characterize the proximate properties of both the feedstock and the resulting residue. The research utilized a sample size of 20 kg of betung bamboo pellets in a 15-kWh downdraft gasifier operated for 60 minutes. Syngas components were monitored in real time using a portable infrared syngas analyzer, while proximate analysis determined moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon (FC). The results revealed an average syngas composition of 13.62% carbon monoxide (CO), 8.65% hydrogen (H_2), 2.55% methane (CH_4), 13.28% carbon dioxide (CO_2), and 1.64% oxygen (O_2), yielding a total combustible gas fraction of 24.82%. The average LHV was 887.57 kcal/m^3, with a peak value of 981.45 kcal/m^3 recorded as the reactor reached steady-state conditions. Proximate analysis indicated effective thermochemical conversion, as VM decreased from 74.11% in the pellets to 17.61% in the ash by-product, while AC increased from 12.02% to 73.09%. Furthermore, FC declined from 6.76% in the pellets to 4.63% in the residue. This study concludes that betung bamboo pellets are a highly suitable and promising renewable energy feedstock for small-scale applications in Indonesia, offering a scientific basis for decentralized biomass energy systems.

1. Introduction

The global energy landscape is increasingly shaped by the urgent need to reduce dependence on fossil fuels, which continue to dominate energy supply and contribute to greenhouse gas emissions and environmental degradation. In Indonesia, approximately 85% of national energy needs are still met by fossil fuels (MEMR, 2024), leaving the country vulnerable as domestic reserves continue to decline. Current estimates suggest that oil reserves may be exhausted within 9.5 years and natural gas within 22.3 years at current production rates (MEMR, 2024). At the same time, global CO_2 emissions from fossil fuel combustion reached 33.1 Gt in 2022 (IEA, 2022), accelerating climate change and underscoring the importance of transitioning to cleaner, more sustainable energy systems.

Biomass has emerged as one of the most promising renewable energy sources, primarily due to its abundance, renewability, and relatively carbon-neutral nature when sustainably managed. Globally, biomass accounts for approximately 55% of total renewable energy consumption and is projected to generate up to 1,250 TWh for electricity production by 2030 (Gronwald and Wang, 2024). In the context of Indonesian forests and plantations, a wide variety of biomass types are available, ranging from agricultural residues and timber industry waste to dedicated energy crops (Kan et al., 2016).

Betung bamboo is one of Indonesia's most economically and ecologically significant Non-Timber Forest Products (NTFPs), widely distributed across major islands including Java, Sumatra, Kalimantan, and Sulawesi (Syahbana et al., 2025). It can grow at a rate of 30–100 cm per day under optimal conditions and can be harvested within 3–5 years without replanting (Lobovikov et al., 2007). This remarkable regenerative capacity is attributed not only to its rapid vertical growth but also to its vegetative reproduction through an extensive underground rhizome network, from which new shoots continuously emerge (Liese and Köhl, 2015). Because culms arise from existing rhizomes rather than seeds, bamboo can be harvested repeatedly without replanting, making it one of the most sustainable lignocellulosic resources available (Su et al., 2026). Moreover, bamboo plantations act as CO_2 sequesters, with an estimated sequestration capacity of 5–12 tons per hectare per year, thereby contributing to the reduction of atmospheric greenhouse gas concentrations, a key component of climate change mitigation. Despite these advantages, the direct utilization of bamboo for thermochemical energy conversion remains challenging because freshly harvested bamboo has a high moisture content (50–60%) and low bulk density, necessitating densification into pellets before gasification (Maulana et al., 2019; Suri et al., 2024; Xiao et al., 2014).

Pelletization is a mechanical densification process that uses pressure and temperature control in a ring-die pellet mill to compress low-density fibrous biomass into homogeneous, high-density cylindrical fuel pellets. This technique is especially crucial for bamboo feedstocks to overcome their naturally high moisture content and low bulk density (100–150 kg/m^3), which otherwise render them unsuitable for steady gasifier operations (Xiao et al., 2014). By raising the bulk density to around 600–800 kg/m^3 and lowering the moisture content through frictional heat produced during compression, pelletization substantially enhances feedstock quality (Saputra et al., 2022; Sarker, 2023). To increase pellet durability and reduce the production of fine particles, a small amount of tapioca starch (3–5%) is sometimes used as a binder. In fixed-bed gasifier systems, the resultant 6–8 mm pellets allow for a more consistent gas flow and stable feeding (Hidayat et al., 2022; Saputra et al., 2022; Susastriawan, 2017).

Gasification is a process in which biomass is partially oxidized in the presence of a limited amount of oxygen to produce a fuel-useful gas mixture (Luo et al., 2018). The resulting syngas typically contains carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), and nitrogen (N_2). It can be utilized for power generation, thermal applications, or as a feedstock for chemical synthesis (Basu, 2018). Compared to direct combustion, gasification offers higher energy conversion efficiency and lower pollutant emissions (Luo et al., 2018). Gasifiers are generally classified into three main configurations based on the direction of gas and biomass flow: updraft (counter-current) gasifiers, in which the gasification agent flows upward against the descending biomass; downdraft (co-current) gasifiers, in which both the biomass and air flow downward; and fluidized bed gasifiers, which suspend biomass particles in an upward-flowing gas stream (Susastriawan et al., 2017). Among these, the downdraft (fixed-bed) type is particularly well-suited for small- to medium-scale applications due to its relatively simple design and capacity to produce syngas with low tar content, making it highly compatible with internal combustion engines and direct combustion systems (Amrullah and Oktaviananda, 2022).

Previous research has explored bamboo as a gasification feedstock across a range of reactor types and species. Kakati et al. (2022) conducted air–steam gasification of bamboo in a 10 kWe downdraft gasifier and reported a maximum H_2 yield of 37.12% at a steam-to-biomass ratio of 0.35, along with high cold gas efficiency—demonstrating that bamboo's high volatile matter content favors hydrogen-rich syngas production. Gopan et al. (2022) numerically investigated six bamboo species in a fluidized bed reactor and found that *Bambusa vulgaris* Wamin yielded the highest syngas quality at an equivalence ratio of 0.2–0.5 and a gasification temperature of 1073 K. Additionally, Gopan et al. (2024) comprehensively reviewed the bamboo gasification literature and concluded that air-based bamboo gasification typically achieves a lower heating value (LHV) of 4–6 MJ/Nm^3, with performance strongly dependent on moisture content and equivalence ratio. Collectively, these studies establish the thermochemical suitability of bamboo as a gasification feedstock; however, empirical data on *Dendrocalamus asper* pellets in downdraft systems under Indonesian conditions remain scarce.

As mentioned above, betung bamboo is a fast-growing species that can be cultivated on marginal land without competing with food crops (Gopan et al., 2024; Hidayat et al., 2024) and exhibits very high biomass productivity, reaching up to 78.3 tons/ha, far exceeding average wood productivity (Hidayat et al., 2024; Liang et al., 2023; Saputra et al., 2022). Furthermore, the pelletization process increases energy density, reduces moisture content, and improves the handling characteristics of the feedstock. Therefore, betung bamboo offers a strategic advantage as a gasification feedstock and has strong potential as a more reliable energy source in various regions. Despite the clear potential of betung bamboo as a gasification feedstock, empirical data on the syngas characteristics and energy performance of bamboo pellets in downdraft gasifiers remain limited. Therefore, this study aims to: (1) analyze the composition of syngas produced from the gasification of betung bamboo pellets using a downdraft gasifier; (2) determine the lower heating value (LHV) of the resulting syngas; and (3) characterize the proximate properties of both the pellet biomass and the ash by-product generated during gasification. The findings are expected to provide a scientific basis for the development of bamboo-based biomass energy systems in Indonesia.

2. Material and Methods

2.1. Time and Location of Research

This research was conducted from April 2025 to December 2025. The gasification process and syngas analysis were carried out at the Forest Product Technology Workshop, Integrated Laboratory, Faculty of Agriculture, University of Lampung. Proximate analysis and data analysis were carried out at the Forest Product Technology Laboratory, Department of Forestry, Faculty of Agriculture, University of Lampung.

2.2. Research Tools and Materials

A total of 20 kg of *Dendrocalamus asper* bamboo pellets used in this study was obtained from the National Research and Innovation Agency (BRIN), Cibinong, Bogor, West Java, Indonesia. The main equipment used in the study included a 15 kWh downdraft gasifier reactor (Sunbrand Industrial Co., Ltd., Jeollanam-do, South Korea) (**Fig. 1a**), a portable infrared syngas analyzer (Gasboard G3100-P, Wuhan Cubic Optoelectronics Co., Ltd., Wuhan, China) (**Fig. 1b, 1c**).

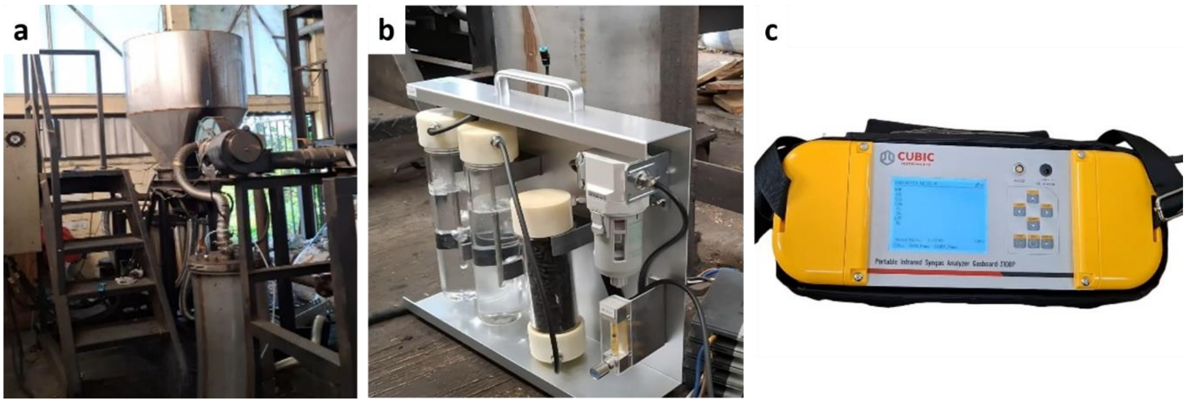

Fig. 1. The equipment used in the study included: (a) 15 kWh downdraft gasifier reactor, (b) gas analyzer conditioning unit, and (c) portable infrared syngas analyzer, Gasboard G3100-P.

2.3. Experiment

2.3.1. Sample preparation

To eliminate flawed, damaged, or irregularly sized bamboo pellets, the pellets were visually sorted. Crushed or cracked pellets may affect the stability of the gasification process. To preserve the stability of the gasification process, pellets that passed the selection process had a constant length of 10–30 mm and a standard diameter of 6–8 mm. The pre-sorted bamboo pellets were dried in an oven at 105°C until the moisture content reached 8-12%. To maintain moisture content throughout the study period, the pellets were thereafter stored at room temperature with a low relative humidity of 40–60%.

2.3.2. Gasification process

The gasification process of betung bamboo pellets began by feeding 20 kg of bamboo pellets into the downdraft gasifier hopper/reactor. The initial airflow pressures at two separate inlets—Pressure 1, corresponding to the primary air supply at the combustion zone, and Pressure 2, corresponding to the secondary air supply at the reduction zone—were each set to −1 kPa, as indicated on the reactor control panel. A blowtorch was used to ignite the surface layer of pellets at the combustion zone through the ignition port. Once a stable flame was established, the blowtorch was withdrawn, and the ignition port was immediately sealed to establish a controlled, oxygen-restricted environment necessary for gasification. Once the reactor temperature reached 200°C, the process was automated via the control panel. The bamboo pellets in the reactor will then flow downward toward the ignition zone at regular intervals, while the gasification by-product—biochar—flows and accumulates in the ash chamber. At the same time, the valve on the gas outlet connected to the gas analyzer conditioning hose was opened. The gasification process ran continuously for 60 minutes under air gasification conditions. The gasification process took place through four sequential stages in the reactor: drying (100–200°C), pyrolysis (200–700°C), combustion (700–1,200°C), and reduction (800–1,000°C), in accordance with standard downflow gasifier operation (Salem et al., 2022).

2.3.3. Syngas analysis

Syngas analysis was performed using the Gasboard G3100-P portable infrared syngas analyzer. This instrument identifies the composition of the gas produced from gasification, namely syngas. The Gasboard-3100P can simultaneously analyze major gas components in syngas, including CO, CO_2, H_2, CH_4, O_2, and other hydrocarbons. This analysis was performed in real time using specific gas analyzer software on a connected laptop. The instrument recorded the analyzed syngas data at defined time intervals (minimum 1 second), storing up to 2,560 data points. The steps for syngas analysis using the G3100-P PISAG were as follows: (1) the analyzer was turned on and allowed to stabilize for at least 15 minutes; (2) the gas conditioning unit was connected to the analyzer; (3) baseline calibration was performed using ambient air before each measurement session; (4) the conditioned syngas was introduced into the analyzer inlet, and real-time data logging began via the connected laptop software; and (5) syngas composition (CO, CO_2, H_2, CH_4, and O_2) and the calculated LHV were recorded at 1-minute intervals during the 60-minute gasification process.

2.3.4. Lower heating value (LHV) calculation

An analysis of the calorific value of syngas produced from bamboo pellet gasification was conducted to determine the energy potential of the gasification process using a downdraft gasifier. Calorific value is an important parameter that indicates the amount of energy released during syngas combustion and directly affects the thermal efficiency of the gasification process. The calorific value determined in this study was the Lower Heating Value (LHV). The Gasboard G3100-P is also equipped with an automatic calculation feature to determine the Lower Heating Value (LHV) of the syngas using Equation 1.

$$LHV\left(\frac{Kcal}{m^3}\right) = (30.18 \times CO\%) + (25.76 \times H_2\%) + (85.78 \times CH_4\%) \quad (1)$$

2.3.5. Proximate analysis

Proximate analysis was used to determine the basic composition of solid fuels, including bamboo pellets. This test assesses the effectiveness of energy conversion techniques, including gasification and the fuel's purity. The parameters measured included moisture content, volatile matter, ash content, and fixed carbon. Before analysis, the bamboo pellets and biochar pellets after gasification were ground into powder using a blender (HR 2116, Philips, Amsterdam, Netherlands) to ensure sample homogeneity. All proximate analysis experiments were conducted in triplicate.

a) Moisture Content

The moisture content was determined by oven-drying the samples until a constant mass was achieved, indicating that the remaining moisture had been removed. Approximately 1 gram (ASTM, 2021) of bamboo powder and biochar powder was placed in separate open dishes and oven-dried at 100°C for 24 hours (García et al., 2012). The moisture content was calculated using Equation 2.

$$MC = \frac{(W - B)}{W} \times 100\% \qquad (2)$$

where *MC* is moisture content (%), *W* is initial weight (g), and *B* is oven-dry weight (g).

b) Volatile Matter

Volatile matter (*VM*) refers to the fraction of a material that is released as gases when heated in the absence of air. A 1-g sample of bamboo powder and bamboo biochar powder was placed in a covered porcelain crucible and heated in a muffle furnace at 950°C for 7 minutes (García et al., 2012). The volatile matter content was calculated using Equation 3.

$$VM = \frac{Sample\ after\ heating\ (g)}{Dry\ sample\ (g)} \times 100\% \qquad (3)$$

c) Ash Content

Ash content (*AC*) refers to the percentage of non-volatile mineral residue remaining after combustion. Approximately 1 g of bamboo powder and bamboo biochar powder were placed in separate porcelain dishes and combusted in a muffle furnace at 750°C for 1 hour (García et al., 2012). The ash content was calculated using Equation 4.

$$AC = \frac{Ash\ weight\ (g)}{Dry\ sample\ weight\ (g)} \times 100\% \qquad (4)$$

d) Fixed Carbon

Fixed carbon (*FC*) is the solid fraction remaining in a sample after the reduction of moisture content, volatile matter content, and ash content. The fixed carbon was calculated using Equation 5:

$$Fixed\ carbon = 100\% - (MC + VM + AC) \qquad (5)$$

3. Result and Discussion

3.1. Syngas Composition during Gasification

Syngas composition analysis was conducted to identify and quantify the gas components formed during gasification. The syngas composition is a key parameter for evaluating the efficiency of thermochemical conversion processes and determining the techno-economic feasibility of utilizing syngas as an alternative energy source. Based on data from the gasification of betung bamboo pellets using a downdraft gasifier for 60 minutes, the resulting syngas composition comprised carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2), oxygen (O_2), and nitrogen (N_2), as shown in **Table 1**.

3.1.1. Carbon monoxide (CO)

CO is a colorless and odorless gas formed from the incomplete combustion of carbon in biomass during gasification. As one of the main combustible gases in syngas, it contributes significantly to the calorific value. Furthermore, CO plays a vital role in gasification chemical reactions, contributing to energy efficiency and hydrogen formation through the water-gas shift reaction (Putri et al., 2021). The CO content in the syngas produced from bamboo pellets fluctuated from 11.39% to 16.26% (**Fig. 2**), with an average value of 13.62% (**Table 1**). At the beginning of the gasification process, the CO concentration increased rapidly, reaching its highest value of 16.26% at the 3-minute mark (**Fig. 2**). The

CO level then gradually decreased to around 11.39% at the 43-minute mark, before increasing again in the final phase and reaching 13.65% at the 60-minute mark.

Table 1. Syngas composition from the gasification of betung bamboo (*D. asper*) pellets

Time (min)	CO (%)	CO_2 (%)	CH_4 (%)	H_2 (%)	O_2 (%)	N_2 (%)
0–10	15.25	12.94	2.81	7.46	1.73	59.67
10–20	14.16	14.06	3.17	6.63	1.65	60.55
20–30	13.71	13.28	2.83	7.91	1.72	60.93
30–40	12.48	12.93	2.48	9.08	1.91	60.75
40–50	12.37	13.30	2.18	10.39	1.65	61.38
50–60	13.76	13.14	1.85	10.42	1.20	59.47
Average	**13.62**	**13.28**	**2.55**	**8.65**	**1.64**	**60.46**

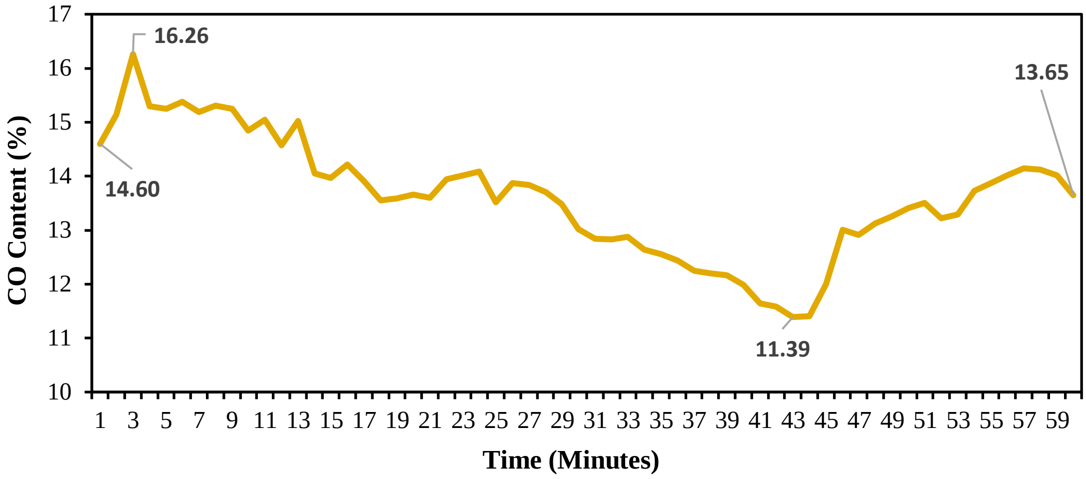

Fig. 2. CO content over time during the gasification of betung bamboo (*D. asper*) pellets.

The high CO content in the early phase was due to the dominance of reduction reactions involving solid carbon with CO_2 and water vapor, as shown in the Boudouard reaction ($CO_2 + C \rightarrow 2CO$) and the steam gasification reaction ($C + H_2O \rightarrow CO + H_2$) (Yazila et al., 2024). The decrease in CO levels midway through the process indicated a reduction in reactive carbon, thereby lowering CO production. However, in the final phase, relatively stable temperature conditions triggered a resurgence of reduction reactions, leading to a rise in CO concentrations again (Basu, 2018).

Setyawan et al. (2021) found that CO levels in biomass gasification with a downdraft configuration ranged from 12% to 15%, exhibiting a similar trend of increasing at the beginning of the process and then decreasing in the middle phase. Our results are in line with those of Setyawan et al. (2021), who observed CO concentrations of 12%–15% from wood chip gasification in a two-stage downdraft system. According to Roni et al. (2017), CO from palm trunk gasification in a downdraft setup, with biomass containing cellulose and lignin fractions comparable to betung bamboo, ranged from 11% to 16%. Furthermore, under similar conditions, Kasawapat et al. (2024) reported an average CO content of 17.98% from the downdraft gasification of rubber wood pellets. When combined, the 13.62% CO content of betung bamboo pellets is well within the 11–18% range typically reported for various lignocellulosic biomass types in downdraft gasifiers.

3.1.2. Carbon dioxide (CO_2)

Carbon dioxide (CO_2) is formed from the partial oxidation of carbon ($C + O_2 \rightarrow CO_2$). As a non-energy gas, CO_2 is classified as such in syngas because it has no calorific value. Excessively high CO_2 content reduces the calorific value of the syngas (Sikarwar et al., 2016). The CO_2 concentration in syngas ranged from 12.43% to 14.91% (**Fig. 3**), with an average of 13.28% (**Table 1**). The CO_2 concentration showed a relatively stable pattern at the beginning of the process, then gradually increased to a peak of 14.91% at the 17-minute mark (**Fig. 3**), and subsequently decreased towards the end of the gasification process. The relatively high CO_2 content in the early phase indicated the dominance of partial oxidation reactions ($C + O_2 \rightarrow CO_2$), which release heat and help maintain the reactor temperature. In the subsequent phase, some CO_2 is reduced to CO via the Boudouard reaction, thereby slightly decreasing its concentration. This phenomenon is common in gasification, where CO_2 acts as both an oxidant and a reactant in the formation of CO (Salem et al., 2022).

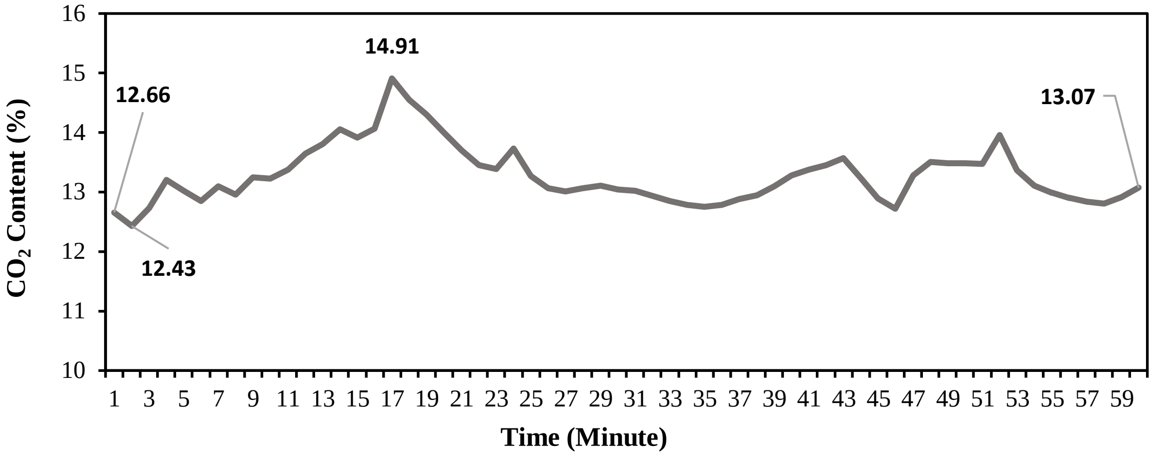

Fig. 3. CO_2 content over time during the gasification of betung bamboo (*D. asper*) pellets.

The average CO_2 concentration of 13.28% (**Table 1**) reported in this study falls within the normal range of 10%–15% for air-gasified lignocellulosic biomass (Tezer et al., 2022). Although it does not contribute to the calorific value of syngas, the presence of CO_2 is important as an indicator of gasification efficiency and reactor conditions (Luo et al., 2018). Setyawan et al. (2021) and Iriani et al. (2026) showed similar CO_2 values for wood chip gasification (about 12%–14%) and coconut shell gasification in a downdraft system. Since CO_2 generation in air gasification is mostly driven by the oxygen supply, which is shared by all air-based systems, rather than by feedstock-specific chemical composition, the similarities across various biomass types are mechanistically consistent.

3.1.3. Methane (CH_4)

CH_4 is a simple hydrocarbon and a key component of syngas. Methane has a very high calorific value of approximately 55.5 MJ/kg, making it a major contributor to the thermal energy content of the produced syngas (Waluyo et al., 2022). The CH_4 content in this study ranged from 1.69% to 4.08% (**Fig. 4**), with an average value of 2.55% (**Table 1**). The highest value was observed at the 17-minute mark (4.08%), while the lowest was measured at the 57-minute mark (1.69%; **Fig. 4**). This trend indicates that CH_4 was more dominant in the early- to mid-stage of the process but decreased in the final phase. CH_4 is formed from the pyrolysis of volatile biomass and the methanation reaction ($C + 2H_2 \rightarrow CH_4$). However, in downdraft reactors operating at high temperatures, CH_4 readily decomposes into CO and H_2 via hydrocarbon cracking reactions (Sikarwar et al., 2016). This results in a relatively low CH_4 concentration compared to other syngas components.

The average CH_4 content of 2.55% observed in this study (**Table 1**) is in close agreement with the 1%–5% range reported for the downdraft gasification of various lignocellulosic biomasses (Putri et al., 2021). Notably, Kasawapat et al. (2024) reported 1.57% CH_4 in rubber wood pellet gasification under similar downdraft conditions, and wood pellet air gasification in a fixed-bed system has consistently yielded CH_4 in the 1.5%–3.5% range (Havilah et al., 2022). The elevated CH_4 levels observed during the initial stage of the process (up to 4.08% at the 17-minute mark) indicate pronounced pyrolysis activity within the transient heating period, a phenomenon consistently reported across various biomass types in downdraft reactors (Basu, 2018).

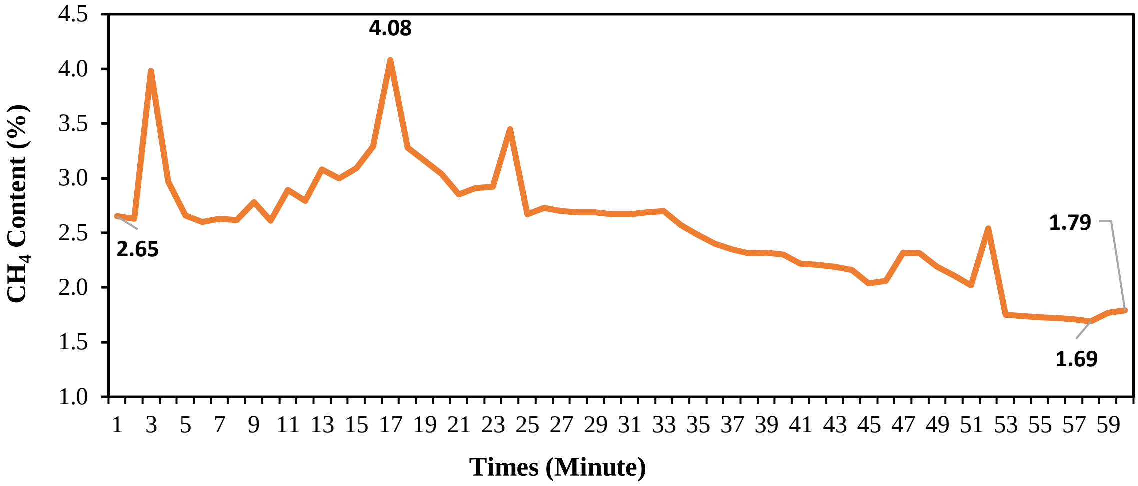

Fig. 4. CH_4 content over time during the gasification of betung bamboo (*D. asper*) pellets.

3.1.4. Hydrogen (H_2)

H_2 is a light, colorless, and highly reactive gas that is widely formed in gasification during reduction reactions. H_2 is produced from steam gasification reactions ($C + H_2O \rightarrow CO + H_2$) and water-gas shift reactions ($CO + H_2O \rightarrow CO_2 + H_2$). High H_2 levels indicate an efficient, optimal gasification process, thereby adding value to the syngas (Saputro et al., 2023). The H_2 concentration showed considerable variation, ranging from 6.10% to 11.92% (**Fig. 5**), with an average value of 8.65% (**Table 1**). The H_2 concentration exhibited an interesting pattern, with a relatively low value at the beginning of the process (7.84% at the 1-minute mark), before gradually increasing to a peak of 11.92% at the 52-minute mark (**Fig. 5**), and then stabilizing with a slight decrease towards the end. The increase in H_2 was associated with the water-gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$) and the steam gasification reaction ($C + H_2O \rightarrow CO + H_2$), which became increasingly dominant as oxygen levels declined. Thus, the H_2 content was inversely proportional to the decreasing O_2 in the final phase (Basu, 2018).

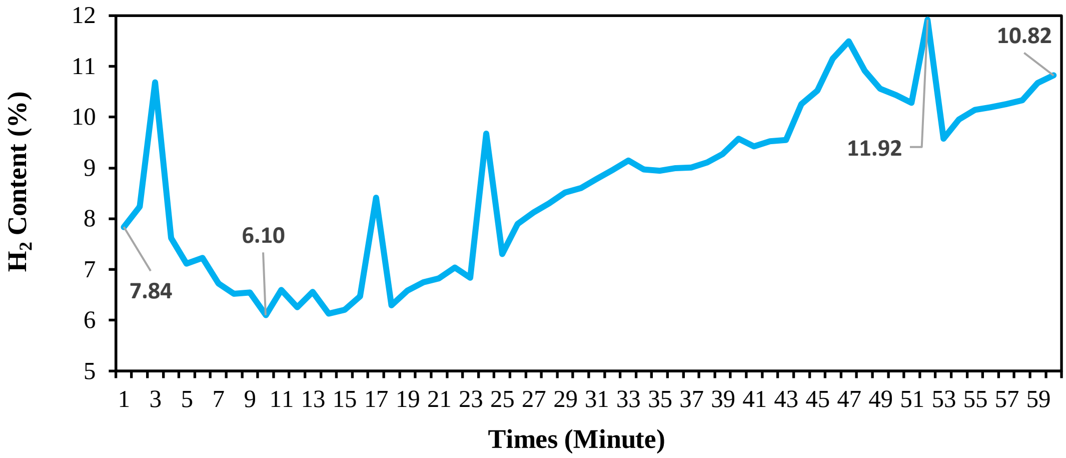

Fig. 5. H_2 content over time during the gasification of betung bamboo (*D. asper*) pellets.

The mean H_2 content of 8.65% reported here (**Table 1**) is notably higher than the 7.46% recorded during the initial 10-minute interval (**Table 1**), reflecting the progressive intensification of water-gas shift reactions as the reactor temperature stabilized. This upward trend aligns closely with the 10.04% average H_2 reported for rubber wood pellet gasification under the same downdraft configuration (Kasawapat et al., 2024) and with the 8.58% average reported by Havilah et al. (2022) for air-gasified wood pellets. The relatively higher ash content of betung bamboo pellets, reaching 12.02% in our study, may account for the considerably lower H_2 values compared to rubberwood, which typically has only 1%–3% ash. This increased ash level may somewhat hamper gas-solid interactions in the reduction zone.

3.2. *Lower Heating Value (LHV) of Syngas*

The LHV of the syngas showed a generally increasing trend over the 60-minute operation, ranging from 819.18 to 981.45 kcal/m³ (**Fig. 6**) with a mean value of 887.57 kcal/m³ (**Table 2**). The temporal LHV values at 10-minute intervals are presented in **Table 2**. The initial LHV of 870.66 kcal/m³ at the 10-minute mark reflects the transitional startup phase, during which the reactor had not yet reached thermal steady-state and H_2 concentrations were still relatively low (**Table 2**), coinciding with a lower H_2 level and a slight increase in CO_2. From the 40th minute onward, the LHV increased progressively as H_2 concentrations peaked and O_2 levels fell, reaching a maximum of 981.45 kcal/m³ at the 57-minute mark (**Fig. 6**). This upward trend in the final phase is consistent with the stabilization of thermochemical reactions and the intensification of endothermic reduction reactions, which favor the formation of CO and H_2 (Gopan et al., 2024).

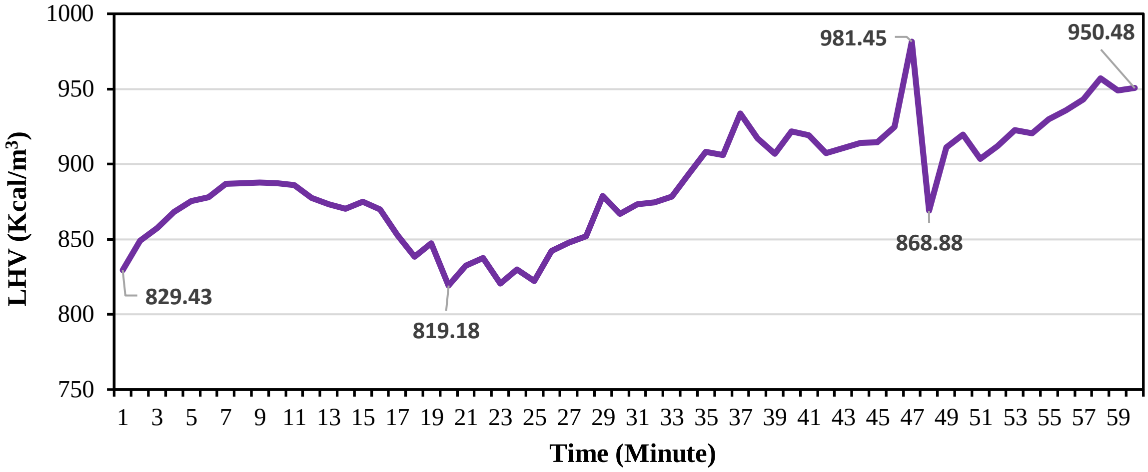

Fig. 6. LHV values in the gasification products of betung bamboo (*D. asper*) pellets.

The mean LHV of 887.57 kcal/m³ obtained in this study is within the range reported for the air gasification of lignocellulosic biomass. While steam-based gasification of bamboo can achieve an LHV of up to 6.22 MJ/Nm³ (~1,485 kcal/m³) (Gopan et al., 2024), air gasification inherently yields a lower heating value due to nitrogen dilution. Sakhiya et al. (2020) indicated that a minimum LHV of approximately 4–5 MJ/Nm³ (~955–1,195 kcal/m³) is required for internal combustion engine applications, suggesting that the syngas produced in this study, particularly in the latter stages of gasification, approaches the threshold for small-scale power generation. The total combustible gas fraction (CO + H_2 + CH_4 = 24.82%) confirms the adequate energy content of the syngas for thermal applications.

Table 2. Lower heating value (LHV) of syngas from betung bamboo (*D. asper*) pellet gasification

Time (Minute)	LHV (Kcal/m³)
10	870.66
20	860.95
30	843.02
40	901.35
50	917.14
60	932.30

3.3. *Proximate Analysis of Betung Bamboo Pellets and Gasification Ash (By-Product)*

The proximate analysis results for the betung bamboo pellets and the resulting gasification ash are summarized in **Table 3** and shown in **Fig. 7**. The comparison illustrates the magnitude of material transformation occurring during the thermochemical conversion process.

Table 3. Proximate analysis of betung bamboo (*D. asper*) pellets and their by-products

Repetition No.	Biomass				Repetition No.	Ash (by-product)			
	MC (%)	AC (%)	VM (%)	FC (%)		MC (%)	AC (%)	VM (%)	FC (%)
1	7.19	11.72	75.88	5.21	1	5.01	73.12	17.80	4.07
2	7.43	13.14	72.78	6.64	2	4.57	74.49	17.49	3.45
3	6.69	11.21	73.66	8.44	3	4.42	71.67	17.54	6.37
Average	7.10	12.02	74.11	6.76	Average	4.67	73.09	17.61	4.63

Notes: MC = moisture content, AC = ash content, VM = volatile matter, FC = fixed carbon.

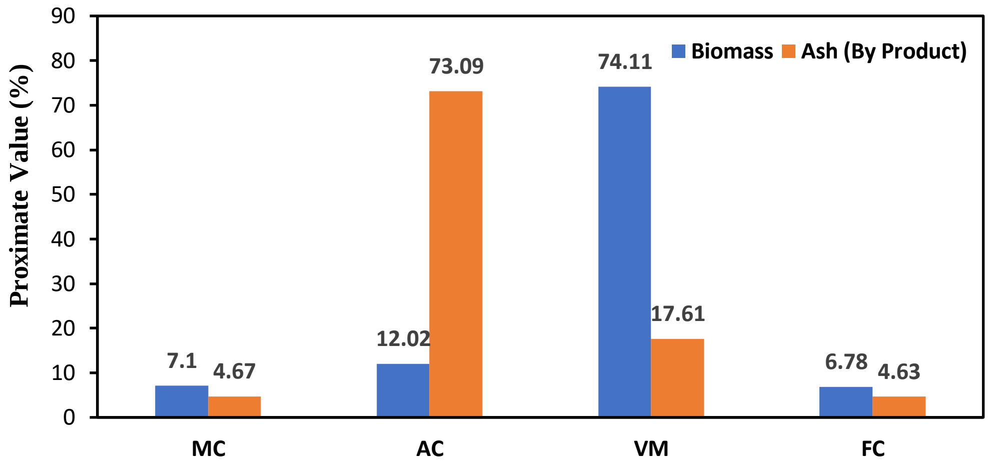

Fig. 7. Proximate analysis comparing the betung bamboo (*D. asper*) biomass and its ash by-product after gasification.

The mean moisture content of the betung bamboo pellets was 7.10% (**Table 3**), well below the 20% threshold recommended for stable downdraft gasification (Susastriawan et al., 2017) and compliant with SNI 8675-2018 specifications for industrial biomass pellets (<12%). This low moisture content is partly attributable to the pelletization process, which involves compression and heat treatment, effectively reducing biomass moisture content (Saputra et al., 2022). After gasification, the ash moisture content decreased further to 4.67% (**Table 3**), consistent with the complete evaporation of residual moisture in the reactor drying zone, a pattern also documented in char residues from bamboo carbonization (Rani et al., 2023).

The volatile matter content of the betung bamboo pellets averaged 74.11% (**Table 3**), characteristic of lignocellulosic biomass and within the general range of 75%–85% reported by Sakhiya et al. (2020) for bamboo species, including *Dendrocalamus asper*. High volatile matter content is favorable for gasification, as it indicates a large fraction of the biomass that can be converted to combustible gases during pyrolysis (Saputra et al., 2022; Tambunan et al., 2023). Kakati et al. (2022) demonstrated that bamboo with high volatile content tends to produce higher CO and H_2 concentrations in the syngas. After gasification, the volatile matter of the ash by-product declined sharply to 17.61% (**Table 3**), confirming that the majority of the volatile fraction had been successfully converted to gas-phase products during the thermochemical process. The remaining volatile content in the ash suggests incomplete conversion, which may be attributed to non-uniform heat distribution within the reactor or insufficient residence time in the reduction zone (Gao et al., 2023; Iryani et al., 2023).

The ash content of the betung bamboo pellets was 12.02% (**Table 3**). Although this value exceeds the SNI 8675-2018 guideline of < 5% for industrial pellets, it remains manageable in a downdraft gasifier, provided ash removal protocols and reactor cleaning are consistently maintained. Moreover, the ash content of the by-product after gasification was 73.09%, reflecting the progressive concentration of the inorganic fraction as organic carbon is converted into synthesis gas during the thermochemical conversion. This pattern aligns with the findings of Hutasoit et al. (2025), who documented a similar increase in the inorganic residue fraction during the gasification of high-ash biomass. The resulting ash by-product contains minerals such as potassium, calcium, and phosphorus, which have the potential to provide agronomic value as soil amendments (Gu et al., 2019; Maulani et al., 2024).

The fixed carbon content of the betung bamboo pellets was 6.76% (**Table 3**), while the gasification ash retained 4.63%. The reduction in fixed carbon from feedstock to ash indicates that a portion of the solid-phase carbon was consumed through the Boudouard reaction ($C + CO_2 \rightarrow 2CO$) and the water-gas reaction ($C + H_2O \rightarrow CO + H_2$) in the reduction zone of the gasifier (Gao et al., 2023). The residual fixed carbon in the ash (4.63%) suggests incomplete carbon conversion, a phenomenon commonly observed in small-scale downdraft gasifiers and potentially improvable by optimizing the air-to-fuel ratio and residence time (Iryani et al., 2023; Nabila et al., 2023; Susastriawan et al., 2017). The VM/FC ratio of the betung bamboo pellets (74.11/6.76 ≈ 10.96) indicates a biomass dominated by volatile fractions rather than solid carbon. This characteristic is generally advantageous for gasification as it promotes rapid devolatilization and syngas formation (Kasawapat et al., 2024).

3.4. Potential of Betung Bamboo Pellet Syngas as a Renewable Energy Source

Taken together, the results of this study demonstrate that betung bamboo pellets possess multiple characteristics that support their use as a feedstock for downdraft gasification. The low moisture content (7.10%), high volatile matter (74.11%), and low fixed carbon content (6.76%) are consistent with a highly volatile biomass, where the dominant energy-bearing fraction is the gaseous products of pyrolysis rather than solid-phase carbon combustion. The resulting syngas, with a combustible gas fraction averaging 24.82% and an LHV of up to 981.45 kcal/m^3, indicates meaningful energy conversion potential for small-scale applications such as household thermal energy, drying systems, and electricity generation. Based on the LHV data from this study (mean: 887.57 kcal/m^3; peak: 981.45 kcal/m^3) (**Table 2**) and assuming an average syngas yield of approximately 2.0–2.5 Nm^3/kg for the air gasification of pelletized lignocellulosic biomass at an equivalence ratio of ~0.3 (Susastriawan et al., 2017), the estimated thermal energy potential of betung bamboo pellets in this study is approximately 1.78–2.22 MJ/kg of feedstock. For the 20 kg batch used in this experiment, the total estimated thermal energy yield is approximately 35.5–44.4 MJ, equivalent to roughly 9.9–12.3 kWh. This output is sufficient to power a 1 kW household thermal appliance for approximately 10–12 hours on a single batch charge, supporting the practical feasibility of small-scale betung bamboo pellet gasification for rural energy applications in Indonesia.

Furthermore, the broader sustainability advantages of betung bamboo, including its 3–5-year harvest cycle, regeneration capacity without replanting, and CO_2 sequestration of 5–12 tons ha^{-1} yr^{-1} (Song et al., 2011), position it as a particularly compelling feedstock within Indonesia's renewable energy development agenda (Nabila et al., 2023). Similarly, bamboo was identified as one of the most promising biomass crops for tropical energy systems owing to its high growth rate and carbon storage capacity.

4. Conclusion

This study demonstrates that betung bamboo (*Dendrocalamus asper*) pellets are a suitable and promising feedstock for downdraft gasification. The syngas produced over 60 minutes of operation had an average composition of 13.62% CO, 8.65% H_2, 2.55% CH_4, 13.28% CO_2, and 1.64% O_2, yielding a total combustible gas fraction of 24.82%. The average LHV of the syngas was 887.57 kcal/m^3, with a peak of 981.45 kcal/m^3 at the 57th minute, indicating improved gasification efficiency as the reactor approached steady-state conditions. Proximate analysis confirmed the suitability of betung bamboo pellets as a gasification feedstock: the moisture content (7.10%) was well within the operational threshold for downdraft gasifiers, and the high volatile matter (74.11%) supports effective pyrolysis and gas yield. The ash by-product exhibited substantial transformation, with volatile matter decreasing from 74.11% to 17.61%, ash content increasing from 12.02% to 73.09%, and fixed carbon declining from 6.76% to 4.63%—confirming successful thermochemical conversion of the organic fraction. These findings provide an empirical basis for developing betung bamboo pellet-based energy systems and underscore the species' significant potential as a renewable energy resource in Indonesia.

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