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Valorization of coffee parchment waste from agroforestry systems via downdraft gasification for renewable syngas production

Gusti Wijaya[1], Bugae Park[2], Bainah Sari Dewi[1], Wahyu Hidayat*[1]

[1]*Department of Forestry, Faculty of Agriculture, University of Lampung, Bandar Lampung, Indonesia*

[2]*Research and Development Department, Sunbrand Industrial, Jeollanam Province, South Korea*

*Corresponding Author: wahyu.hidayat@fp.unila.ac.id

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ABSTRACT

Coffee-based agroforestry systems generate large quantities of coffee parchment, which is commonly underutilized and becomes waste after processing. To date, there is no information regarding its effective utilization. Therefore, to improve its quality and increase its economic value, the production of renewable syngas through gasification is a promising approach. Gasification experiments were conducted using a downdraft gasifier reactor. Syngas composition was measured using a Portable Infrared Syngas Analyzer. Moisture content (MC) and proximate analysis (including volatile matter (VM), ash content (AC), and fixed carbon (FC), of both biomass and gasification solid by-products in the form of biochar were performed. The syngas composition of coffee parchment consisted of 4.95% CO, 5.81% CO_2, 0.56% CH_4, 4.24% H_2, and 13.19% O_2. The LHV of the produced syngas ranged from 256.15 to 417.19 kcal/m³ during the gasification process. The MC, VM, AC, and FC of coffee parchment were 14.85%, 11.94%, 4.85%, and 83.21%, whereas those of the solid by-product were 26.85%, 8.63%, 6.81%, and 84.56%, respectively. The relatively high fixed carbon content indicates that coffee parchment has promising characteristics as a solid bioenergy feedstock. However, the dominance of oxygen in the syngas composition suggests that airflow conditions in the gasifier were unstable, affecting the quality of the produced gas. In conclusion, coffee parchment waste from agroforestry systems has potential as a renewable energy resource, although optimization of gasification operating conditions is required to improve syngas quality and energy efficiency.

Keyword: Coffee Parchment, Downdraft Gasifier, Gasification, Renewable Energy, Syngas

1. Introduction

Biomass suppliers in Indonesia's forestry sector generally come from areas with agroforestry systems. Agroforestry is a land-use system managed by communities that integrates the cultivation of various plant species, enabling the production of multiple types of harvests within a single plot [1], which is used to meet energy and industrial raw material needs. Agroforestry integrates forestry crops with agricultural or livestock commodities, creating a diverse, productive, and sustainable ecosystem [2]. One conceptually developed model is coffee-based agroforestry. This model has the potential to provide ecosystem services equivalent to those produced by forest ecosystems while meeting the social, economic, and ecological needs of surrounding communities [3]. Lampung Province is the largest coffee producer in Indonesia, accounting for 61% of total national coffee exports [4]. Based on data from the Central Statistics Agency, robusta coffee production in this province reached 141,918 tons, an increase of 36,111 tons over 2023, with Tanggamus Regency the second-largest producer after West Lampung [5].

In coffee production, the bean is the primary product. In contrast, the remaining parts of the coffee fruit are generated as by-products in large quantities, with compositions and proportions that vary depending on species and processing methods [6]. In wet processing, the main residues include pulp, mucilage, and coffee parchment, with pulp accounting for approximately 37-43%, mucilage 11.8%, and parchment around 5.8-6.1% of the total coffee fruit weight. Although parchment represents a smaller fraction, it is a distinct and consistently produced component during the post-harvest stage [7,8]. Parchment is the protective endocarp layer of the bean, typically separated through wet or semi-dry processing, whereas in dry processing, it generally remains integrated within the coffee husk [7,8]. Despite its lower proportion compared to pulp, parchment is of particular interest for further study, as it is a lignocellulosic biomass with high fiber content and significant potential for valorization [9,10]. Lignocellulosic components originate from plant cell walls and are widely distributed across various types of biomass, including wood and agricultural residues [11], with coffee parchment being one such example.

Coffee parchment waste contains 63% cellulose, 2.3% hemicellulose, 17% lignin, and 45.3% total carbon [12]. Biomass can be converted into a valuable energy carrier through gasification, a thermochemical process involving partial oxidation under oxygen-deficient conditions that produces synthetic gas (syngas) as its primary gaseous product [13]. This syngas is mainly composed of carbon monoxide (CO) and hydrogen (H_2), along with methane (CH_4), carbon dioxide (CO_2), and small amounts of other gases or impurities, depending on the feedstock and operating conditions [14]. Owing to this composition, syngas can serve as a cleaner and more versatile fuel for heating, power generation, engines, turbines, vehicles, and fuel cells, and it can also function as an intermediate feedstock for downstream energy systems such as methanation [15]. Furthermore, syngas is an important chemical feedstock for producing methanol, ammonia, urea, hydrogen, alcohols, hydrocarbons, and other value-added fuels and chemicals, highlighting biomass gasification as a promising pathway toward more sustainable energy and industrial production [16]. Developing an efficient, low-emission biomass gasification system is a strategic step toward supporting the transition to clean energy [17]. To reduce existing emissions, regulations and resource allocations are needed to convert these resources into renewable energy, enabling their efficient and effective utilization [18]. The gasification process can also produce a by-product in the form of biochar, which is beneficial for improving degraded land quality, reducing soil acidity, and minimizing nutrient loss and pesticide leaching [19].

To date, several studies on syngas production through gasification have focused on rice husk [20], bagasse [21], palm kernel shell [22], and corn cob [23] as feedstocks. The syngas produced from raw rice husk using a bubbling fluidized bed gasifier consists of 17% CO, 32% H_2, and 39% CO_2 [24]. In another study, Adnan et al. [25] reported that syngas from the gasification of raw palm kernel shell using a downdraft gasifier contained 94.9% CO, 0% H_2, 1.8% CO_2, and 2% CH_4. However, no studies have investigated syngas production from the gasification of coffee parchment.

As mentioned above, large quantities of coffee parchment waste are available and commonly underutilized. However, information regarding its effective utilization remains limited. To improve its quality and increase its economic value, producing syngas through gasification is a promising approach. Therefore, this study was conducted to characterize the syngas produced from the gasification of coffee parchment waste to evaluate its potential and quality as a sustainable alternative energy source, as well as to analyze the composition of the synthesis gas (syngas), lower heating value (LHV), and energy characteristics of coffee parchment produced through the gasification process using a downdraft gasifier.

2. Methods

2.1. Research time and location

The research was conducted from April to December 2025. Tools and material preparation, sampling, and syngas composition analysis were carried out at the Workshop, the Forest Product Technology Laboratory, and the Integrated Laboratory in the Faculty of Agriculture, University of Lampung. Proximate analysis was carried out at the Forest Product Technology Laboratory, Department of Forestry, Faculty of Agriculture, University of Lampung.

2.2. Research tools and materials

The research material used was 30 kg of robusta coffee parchment. The main equipment and tools used in the research included a 15 kWh downdraft gasifier reactor, Portable Gas Pre-Treatment and Portable Infrared Syngas Analyzer Gasboard (PISAG) G3100-P, and Gas Analyzer V2.0.12. software.

2.3. Data collection methods

2.3.1. Preparation of raw materials

The main sample used in this study was coffee parchment (Figure 1). The material was chopped into small particles and then sun-dried. Coffee parchment consisted of irregular flakes with particle sizes ranging from approximately 1 to 5 mm. Drying was carried out to reduce the raw material's moisture content to equilibrium levels below 15% to support an efficient gasification process.

2.3.2. Gasification process

One type of gasifier used in the study was a downdraft gasifier. The gasifier reactor has components that serve specific functions during the process (Figure 2). The gasification process occurs in the gasification zone, which consists of several stages. Irrespective of reactor configuration, gasification proceeds through a series of thermochemical stages, namely drying, pyrolysis (devolatilization), partial oxidation (combustion), and reduction (gasification) [26]. The directions of gas and solid flow from the downdraft gasifier reactor are both downward. The first stage of the gasification process is drying, which reduces the feedstock's moisture content without causing chemical decomposition [27].

Figure 1. Coffee parchment raw material.

The next stage is Pyrolysis, which is the thermal decomposition of dry feedstock at 150-700°C in the absence of oxygen, producing volatile compounds and solid residues such as char and ash. The resulting volatiles typically include hydrogen, CO_2, CO, tar, water vapor, and light hydrocarbons [28]. The third stage is oxidation, which occurs at temperatures between 600°C and 1,400°C. Oxygen reacts with combustible substances to produce H2O and CO_2 and provides heat for the endothermic reactions in the next stage [29]. The final stage is reduction, which involves a series of endothermic reactions at temperatures between 600°C and 900°C, producing combustible gases such as H_2, CO, and CH_4 [30]. When the gasification process is complete, it produces two products: synthetic gas (syngas) and a solid by-product of gasification (biochar).

Figure 2. Parts of a downdraft gasifier reactor and the gasification process.

2.4. Data analysis

2.4.1. Syngas analysis

Syngas analysis was conducted to determine the content of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and methane (CH_4) in the raw material. The test was conducted using a Portable Infrared Syngas Analyzer (Gasboard 3100-P, Wuhan Cubic Optoelectronics Co, Ltd), which simultaneously measured the concentrations of CO, CO_2, CH_4, H_2, and O_2 in syngas (synthetic gas). The converted syngas was then analyzed directly using the Gas Analyzer V2.0.12 software and exported to Excel format (Figure 3).

2.4.2. Lower heating value (LHV) analysis

The calorific value is obtained through PISAG G3100-P. The calorific value obtained through PISAG G3100-P is the lower heating value (LHV). LHV is the net energy value available after deducting the energy required to evaporate the water content in the fuel and combustion products [31]. The lower heating value (LHV) can be calculated using Equation 1.

$$\text{LHV (kcal/m}^3) = (30.18\% \times \%\text{CO}) + (25.67 \times \%\text{H}_2) + (85.78 \times \%\text{CH}_4) \quad (1)$$

Figure 3. Syngas measurement using PISAG 3100-P.

2.4.3. Analysis of gasification by-product (biochar)

Biochar is the residue from the combustion of raw materials after gasification. As a gasification by-product, biochar was collected after it cooled. The analyses conducted included moisture content analysis and proximate analysis. These analyses are useful for assessing the combustion potential of the material.

Moisture content

Moisture content was determined by heating the material until equilibrium was reached between its moisture content and the surrounding air's humidity. In the oven-drying test, 1 g of material was placed in a porcelain crucible and replicated three times. The temperature used was 100°C for 24 hours. The moisture content was then measured using Equation 2.

$$MC\ (\%) = \frac{(W_1+W_2)}{W_1} x100\% \quad (2)$$

Description:
MC = Moisture content (%)
W1 = Weight before oven-drying (g)

W2 = Weight after oven-drying (g)

Proximate Analysis

Proximate analysis of both untreated and biochar coffee parchment was conducted for comparison to determine volatile matter content, ash content, and fixed carbon, following the methodologies of Chrisyan et al. [32] and SNI 8675:2018. Each analysis of both samples was replicated three times. Volatile matter content is the portion of material that loses mass due to heating in the absence of air. The volatile matter content was tested using a muffle furnace. One gram of each material (biomass and biochar) was used. The material was placed in a porcelain crucible, then heated to 950 °C in a furnace for 7 minutes. The percentage of volatile matter in the analyzed sample is obtained using Equation 3.

$$VM(\%) = \frac{Sample\ after\ heating\ (g)}{Sample\ before\ heating\ (g)} x100\% \quad (3)$$

Ash content is the percentage of non-volatile minerals that remain as a residue after combustion. One gram of each material is placed in a porcelain crucible and heated in a muffle furnace at 750°C for 1 hour. The ash content percentage of the analyzed sample is obtained using Equation 4.

$$AC(\%) = \frac{Ash\ weight\ (g)}{Control\ sample\ (g)} x100\% \quad (4)$$

Fixed carbon is the solid fraction remaining in the sample after reduction of volatile matter content and ash content. The percentage of fixed carbon in the analyzed sample is obtained using Equation 5.

$$FC(\%) = 100\% - (\%\mathrm{VM} + \%\mathrm{AC}) \quad (5)$$

2.5. Data Analysis

This research used descriptive data analysis. Descriptive analysis refers to a fundamental approach that emphasizes the systematic examination and interpretation of historical data to provide insights into past events within an organization. It involves the collection, aggregation, and presentation of data to reveal underlying patterns, trends, and relationships [33].

3. Results and Discussion

3.1. Changes in syngas composition during the gasification process

The gasification of coffee parchments produces a mixture of synthesis gas (syngas) containing carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), and oxygen (O_2). The composition of each gas changes over the course of the reaction due to the dynamics of oxidation and reduction reactions within the reactor. The average carbon monoxide (CO) obtained was 4.95%, while the average carbon dioxide (CO_2) was 5.81%. There was a difference between CO and CO_2 of 0.86% and an increase of 17.37%. This difference is clearly shown in Figure 4.

The decrease in CO gas content during the gasification process was caused by chemical reactions that occurred in the reactor, particularly the oxidation of CO into carbon dioxide (CO_2). In the gasification process, biomass or carbon-based fuel is heated with a limited supply of oxygen to form synthesis gas (syngas) containing CO, H_2, and CH_4 [34]. However, with an increase in oxygen or air supply (air-fuel ratio, AFR), CO undergoes oxidation, decreasing its concentration and converting it to CO_2, especially in the first 12 minutes. The high temperature in the reaction zone also accelerates the conversion of CO to CO_2 [34]. Therefore, a decrease in CO generally occurs when the AFR increases, and the gasification temperature reaches an optimal level, while increasing the CO_2 content due to oxidation. Other factors that influence this process are the thermodynamic conditions and chemical equilibrium in the reactor, which determine the composition of the gas formed. Regulating air supply, temperature, and reactor operating conditions is important for controlling the decrease in CO concentration during the gasification process.

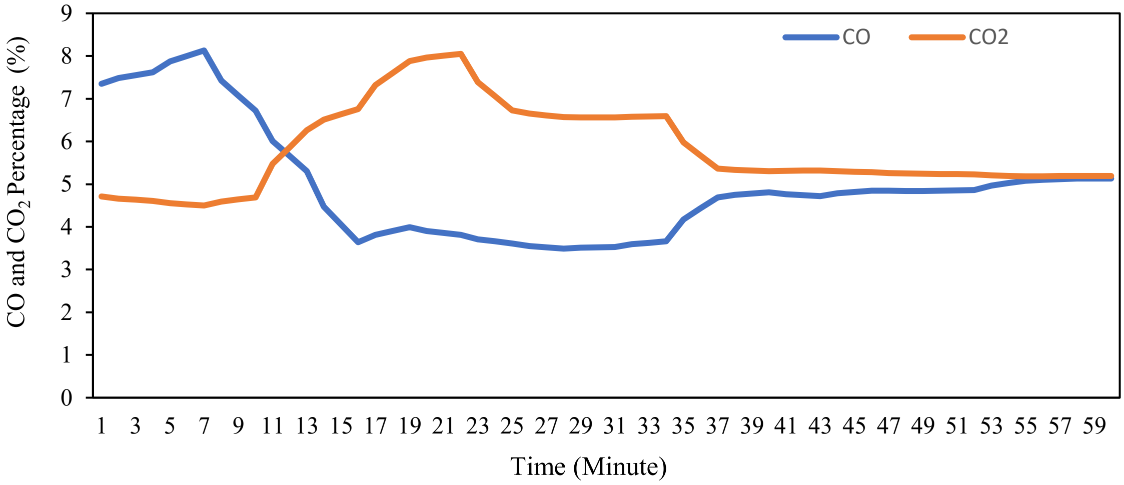

Figure 4. Graph showing changes in CO and CO_2 composition.

The methane (CH4) gas content increased from 0.31% to a peak of 0.76% at minute 19, then decreased and stabilized at minute 46 until the end of the process, as shown in Figure 5. The gasification temperature significantly affected methane formation in syngas. At low temperatures, the pyrolysis process produces more light hydrocarbon compounds, including methane. In contrast, at high temperatures, the reforming reaction becomes more dominant, thereby reducing the methane content by converting it into hydrogen and carbon monoxide. Methane variation during gasification is influenced not only by temperature but also by feedstock properties, such as carbon content, hydrogen-to-carbon ratio, and moisture content, as these factors affect reaction pathways and the resulting gas composition. [13,35,36].

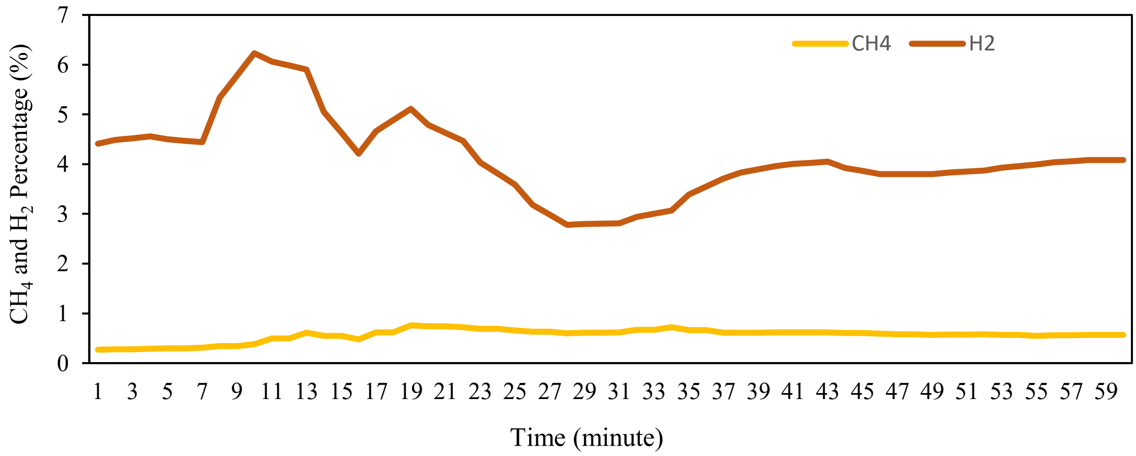

Figure 5. Graph showing changes in H_2 and CH_4 composition.

Hydrogen (H_2) is the lightest chemical element, with the symbol H and atomic number 1, and it typically exists as a colorless, odorless, tasteless, and highly flammable diatomic gas that is abundant in the universe [37,38]. Scientifically, H_2 is a molecule consisting of two hydrogen atoms bonded covalently. The percentage of hydrogen (H_2) produced during the 60-minute gasification process is shown in Figure 5. The hydrogen content changed more frequently than other gases, with stable initial conditions before increasing at 8 to 10 minutes, then fluctuating and slowly increasing until the end of the process.

Meanwhile, the oxygen (O_2) content fluctuated initially, then increased sharply to 13.76% before stabilizing (Figure 6). In the gasification process, the amount of oxygen (oxidizer) used greatly determines the efficiency and quality of the syngas produced. The correct air-fuel ratio (ER or AFR) is an important factor in the gasification process, enabling optimal operation and producing gas with the desired composition [39]. The airflow rate also determines the concentration of the formed gas. The higher the airflow rate, the greater the concentration of syngas (CO, H_2, and CH_4) produced. However, if the fuel amount does not match the increase in airflow, fuel consumption will occur more quickly, leading to a decrease in syngas (CO, H_2, and CH_4) concentration over time [40]. Research by Najib and Darsopuspito [41] also shows that an airflow rate that is not proportional to biomass mass results in an excess air supply in the reactor. This condition produces more O_2, N_2, and CO_2, while combustible gases (CO, H_2, and CH_4) decrease. The airflow rate through the inlet and outlet ducts of the gasifier should be optimized to ensure stable operation and to prevent interference with syngas production.

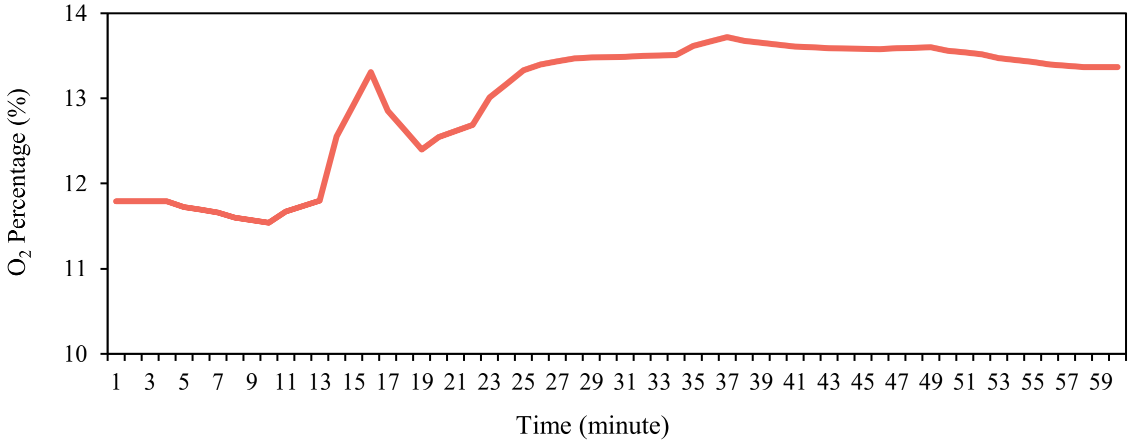

Figure 6. Graph of O_2 composition changes.

The average composition of syngas derived from coffee parchment consists of 4.95% CO, 5.81% CO_2, 0.56% CH_4, 4.14% H_2, and 12.99% O_2. In comparison with other studies, Pinto et al. [24] reported that syngas produced from rice husk contains 17% CO, 32% H_2, and 39% CO_2. In addition, Adnan et al. [25] reported that gasification of palm kernel shell produced syngas with compositions of 94.9% CO, 0% H_2, 1.8% CO_2, and 2% CH4. However, there is no information about the syngas of raw coffee parchment waste.

3.2. Effect of fuel on the lower heating value (LHV) of syngas

The lower heating value (LHV) of syngas during the gasification process is shown in Table 1 and Figure 7. The determination of bioenergy characteristics is greatly influenced by calorific value [42]. The calorific value from the combustion of coffee parchments was high until the 10 minutes, namely 417.19 kcal/m^3, then experienced a drastic, fluctuating decline between the 11 and 27 minutes, and rose slowly thereafter. The sudden spike in calorific value at the beginning of the gasification process is caused by an intense initial combustion reaction as the raw material interacts with oxygen. At this early stage, the fuel begins to burn exothermically, generating a large amount of heat, resulting in a very high calorific value. As the gasification process progresses, the combustible fuel is depleted, and the reaction shifts to the pyrolysis and gasification stages, where the reactions are more complex, usually slower, and less intense in generating heat [43].

The average lower heating value (LHV) of syngas produced from coffee parchment during the gasification process was 303.93 kcal/m^3. A study by Adnan et al. [25] reported that gasification using raw palm kernel shell produced an average LHV of 10.7 MJ/kg. Other studies utilizing pelletized biomass, such as betung bamboo pellets [32] and rubber wood pellets [44], reported average LHVs of 887.57 kcal/m^3 and 725.81 kcal/m^3, respectively.

Table 1. Calorific value (LHV) and temperature during the gasification process

No.	Time (minute)	LHV (kcal/m^3)
1	1-10	417.19
2	11-20	317.84
3	21-30	256.15
4	31-40	270.42
5	41-50	296.42
6	51-60	303.58

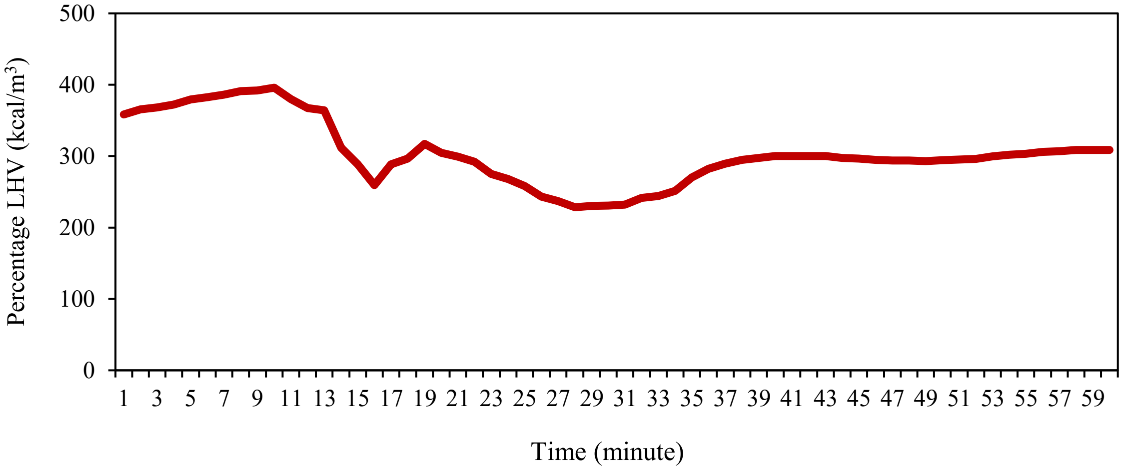

Figure 7. Graph showing changes in lower heating value (LHV).

3.3. Moisture content

Moisture content affects internal temperature changes in the fuel and reduces its calorific value, thereby decreasing conversion efficiency and engine performance, as some energy is used to evaporate the water [45]. In this study, moisture content was determined by oven-drying the samples for 24 hours at 100°C. Based on the oven-drying analysis results, several data points were obtained.

The average moisture content of the three biomass sample replicates was 14.85%, whereas that of the biochar sample was 26.85%. A study by Setiawan et al. [46] reported a moisture content of 10.44% for Gayo coffee parchment. Based on this, the moisture content of biomass is close to that of Gayo coffee parchment, but the biochar has a higher average. According to research by Shahabuddin et al. [47], high moisture content in gasification feedstock can reduce process efficiency and energy output. This is because some of the heat energy is used to evaporate water, rather than to support thermal reactions such as pyrolysis and reduction. This condition can also increase the formation of tar and ash, ultimately disrupting the stability and performance of the gasification process.

3.4. Proximate analysis of coffee parchments and solid by-product of gasification (biochar)

The characteristics of the gasification fuel were analyzed using proximate analysis. Proximate analysis is a test that includes volatile matter content, ash content, and fixed carbon content. This analysis was conducted twice using different materials: biomass and biochar from the gasification of coffee parchment. The results of the proximate analysis are shown in Table 2.

Table 2. Proximate analysis of coffee parchments and solid by-product of gasification (biochar)

Repetition No.	Biomass			Repetition No.	Biomass		
	AC (%)	VM (%)	FC (%)		AC (%)	VM (%)	FC (%)
1	11.79	5.62	82.59	1	8.40	6.36	85.24
2	11.82	4.41	83.77	2	8.09	7.42	84.49
3	12.23	4.54	83.23	3	9.41	6.67	83.92
Average	11.94	4.85	83.21	Average	8.63	6.81	84.56

Note: MC = Moisture content, AC = Ash content, VM = Volatile matter content, FC = Fixed carbon

3.4.1. Volatile matter content

The average volatile matter content of the three coffee parchment biomass samples tested was 11.94%. The average volatile matter content of coffee parchment biochar was 8.63% (Table 2). A study conducted by Setiawan et al. [46] stated that the volatile matter content of Gayo coffee parchments was 68.58%. Based on this study, the volatile matter content of the coffee parchments was very low compared to that of Gayo coffee parchments.

3.4.2. Ash content

The average ash content of biomass is 4.85%, while that of gasification biochar is 6.81% (Table 2). According to research by Setiawan et al. [46], the ash content of Gayo coffee parchments is 3.34%. This shows that the ash content of the research results from both materials is quite high. High ash and moisture content also contribute to a low calorific value [48]. Based on this, coffee material has low ash content, making it suitable for use as fuel.

3.4.3. Fixed carbon

Fixed carbon is used as an indicator to estimate the amount of charcoal that can be produced from fuel samples [47]. The fixed carbon value affects charcoal quality, where the higher the fixed carbon value, the better the charcoal quality [49]. Based on Table 2, the fixed carbon in coffee parchment biomass is greater than that in biochar. The average fixed carbon in biomass is 83.21%, while the average fixed carbon in biochar is 84.56%. The difference between the two fixed carbon contents analyzed is 1.35%.

Fixed carbon content is an indicator of the amount of solid material that remains after volatile components are released [50]. The higher the fixed carbon content in a fuel, the greater the calorific value produced. Conversely, a low fixed carbon content reflects poor fuel quality [51]. The fixed carbon content of coffee parchment indicates that it is of good quality when used as fuel.

3.5. Application of coffee parchment syngas as a renewable energy alternative

The syngas analysis results show that some of the syngas produced has a lower content than it should. This is especially true for combustible components such as carbon monoxide (CO), hydrogen (H_2), and methane (CH_4), which are smaller than other, more dominant components such as oxygen (O_2). The unsatisfactory syngas results may be caused by combustion under unstable airflow and by the raw material's moisture content, which affects the gas composition produced.

In contrast to the syngas results, the proximate analysis indicates that coffee parchment has potential as a fuel with a high carbon content but also a high moisture content. Measures need to be taken to increase the fuel potential of coffee parchment by reducing its moisture content. One method is to mix coffee grounds with other materials to produce processed products, such as pellets. In a study by Putri et al. [52], the effectiveness of mixing coffee husk (CH) with gamal wood to produce pellets was evaluated. The results showed that the optimal pellet composition to meet the specified standards was 75% gamal and 25% coffee husk. Another study by Iryani et al. [53] examined pellet production by mixing spent coffee grounds (SCGs) with wood powder at an optimal ratio of 75% wood powder and 25% SCGs, as well as several other ratios that were superior to the coffee husk mixture. The success of these two ratios is indicated by the proximate results and combustion, which produce high calorific values. This is not limited to other parts of the coffee plant, such as coffee parchment, which also contains similar components.

Converting it into pellets can be one solution to reduce the problems associated with coffee parchment. In line with the study by Prabawa et al. [54], pelletizing biomass offers several advantages, including increased bulk density, which reduces transportation costs, higher energy content, and extended shelf life due to reduced moisture content to approximately 10%. When the moisture content of coffee parchment is reduced, it can be used as an alternative fuel to its full potential. This can help rural communities living near forests, especially those based on a mixture of coffee crops. Converting coffee parchment waste into syngas can reduce waste for coffee farmers. Syngas can also be utilized by communities for household energy needs, serving as a substitute for fossil fuels. Therefore, developing alternative energy sources is essential to replace fossil fuels, whose availability continues to decline due to prolonged use [55]. This is consistent with the findings of Gao et al. [34], which indicate that syngas can be used as a fuel and as a feedstock for the production of other chemicals, such as synthetic natural gas, methanol, and petroleum products.

4. Conclusion

Based on the results of the study, it can be concluded that the gasification process of coffee parchment produces a synthesis gas (syngas) composition consisting of carbon monoxide (CO) of 3.62-7.52%, carbon dioxide (CO_2) of 5.2-7.02%, methane (CH_4) 0.31-0.66%, hydrogen (H_2), and oxygen (O_2) 12.44-13.6%, with oxygen dominating, indicating that the airflow in the gasification process was unstable, thereby accelerating fuel combustion. The lower heating value (LHV) of syngas ranged from 256.15 to 417.19 kcal/m^3, with significant fluctuations mid-process, reaching a low of 228.41 kcal/m^3 at 28 minutes, then stabilizing at around 300 kcal/m^3. Proximate analysis shows that the ash and volatile matter content are within the appropriate range, while the moisture content in biomass and biochar is relatively high. The high fixed carbon content indicates that coffee parchment has good potential as an alternative fuel. However, special treatment is needed to reduce moisture content and increase energy conversion efficiency. This treatment includes converting it into pellets using only raw parchment or mixing it with another biomass like wood chips and sawdust. Future research should focus on reducing the moisture content of coffee parchment to improve the quality of syngas produced from the gasification process.

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