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Characteristics of syngas combustion resulting from coffee husk biomass waste gasification process: Overview of automotive fuel alternatives

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This article contributes to:
7 AFFORDABLE AND CLEAN ENERGY
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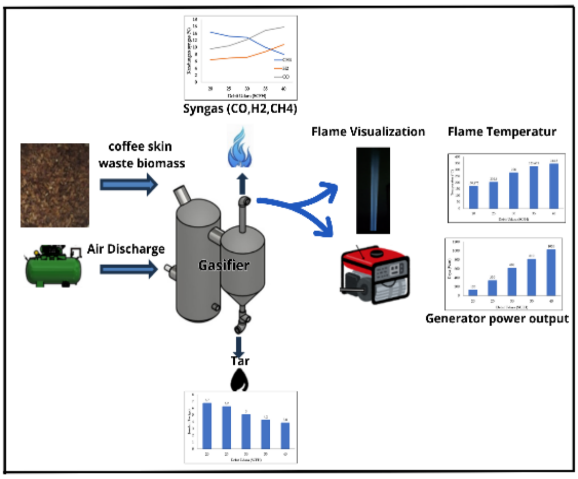

Highlights:

- Syngas production from coffee husk biomass waste has great potential as an alternative automotive fuel to replace fossils.
- Increasing air discharge increases CO and H_2, decreases CH_4, reduces tar content in syngas, and increases temperature, flame height, and generator power output.
- Syngas from coffee husk biomass waste is worth considering as an alternative automotive fuel.

Abstract

The production of syngas from coffee husk biomass waste as a raw material offers significant potential as an alternative automotive fuel source through the gasification process, considering the abundant resources available. Therefore, this study aimed to characterize the physical properties of the fuel initially, in order to observe the differences in these properties after the fuel underwent Ultra Fine Bubble treatment. The objective was to analyze the combustion characteristics of syngas derived from coffee husk biomass waste, to develop a sustainable alternative to fossil fuels for automotive applications. The results showed that with increasing air discharge, the concentration of CO and H_2 gases in gasified syngas increased while the concentration of CH_4 decreased. Additionally, higher air discharge resulted in lower tar content, higher flame temperature, higher flame height visualization, and higher generator power output as a review of the feasibility of alternative automotive fuels.

Keywords: Syngas; Gasifier; Coffee husk biomass; Combustion characteristics; Automotive alternative fuel

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1. Introduction

Indonesia possesses abundant biological energy sources with significant potential to be utilized as an alternative automotive fuel source [1]–[3]. In the context of global energy sustainability and climate change, the demand for alternative automotive fuel sources is increasingly important as renewable, sustainable, and alternative energy sources are needed to replace fossil fuels [4]–[10]. Among these solutions, gasification of coffee husk biomass waste has emerged as a promising clean and sustainable alternative energy solution [11]–[13]. Although classified as waste, coffee husk has significant potential as a biomass gasification feedstock, making it a viable source for automotive fuel or other energy applications. This process not only transforms coffee husk biomass into syngas but also significantly reduces greenhouse gas emissions and air pollutants compared to the direct combustion of biomass or the use of fossil fuels [14].

The development of coffee husk biomass gasification technology as a renewable energy source faces various challenge. The main problem is the formation of tar that occurs during the processes [15]–[17]. Tar is generated during the gasification process due to the condensation of volatile organic compounds [18], [19]. It has a low heating value, which leads to the loss of some biomass potential energy [20], [21]. Energy conversion efficiency from biomass to syngas may decrease because tar is less efficient as a fuel [14]. If tar is not removed efficiently, it may affect the final quality of the syngas product, which may have an undesirable composition [16]. Addressing these challenges is crucial to fully optimize the renewable energy potential of coffee husk biomass waste through biomass gasification processes.

Studies continue to be conducted to address the problem of tar in the gasification process. A commonly used method involves gasification at high temperatures, which helps reduce tar formation [22]. The use of catalysts has also proven effective in enhancing biomass conversion and minimizing tar formation [23], [24]. Fluidized bed reactor systems help reduce tar formation because biomass is well dispersed in the gas stream [11], [25]. Additionally, post-gasification purification methods, such as gas cleaning and cooling, can remove tar and other harmful organic compounds [26], [27]. Cooling syngas facilitates tar condensation and separation [28], [29], while physical filtration methods effectively extract tar from the gas [30], [31]. Optimal air-fuel regulation can prevent high tar formation [32]. Water vapor (H_2O) injection in the gasification system helps reduce tar formation [33]. Circulating reactors can optimize operational conditions and reduce tar [12]. These studies provide valuable information on the potential of biomass gasification as a renewable energy source. A focus on the combustion flame characteristics of syngas fuel from the gasification of coffee husk biomass waste can be a reference in applications as a renewable energy source, emphasizing optimizing several parameters.

Therefora, this study aims to contribute to the development of coffee husk biomass waste as an alternative automotive fuel source through gasification. To achieve this, the combustion of flame characteristics of syngas is analyzed, specifically focusing on flame temperature and visualization. The following parameters are used as controls including gasification process temperature (oxidation, pyrolysis, reduction, and drying temperatures), feedstock moisture content, humidity of the air entering the gasification system, and syngas moisture. Gasifier intake air discharge varied to obtain data on syngas content (hydrogen (H_2), carbon monoxide (CO), and methane (CH_4)), tar amount, flame temperature, flame visualization, and generator output power using syngas fuel, as a feasibility test for alternative automotive fuel sources. This approach is expected to address key technical challenges in the gasification process, thereby supporting the transition to a cleaner renewable energy system.

2. Methods

This study was conducted using an experimental method, namely direct observation of the characteristics of syngas combustion flame from the coffee husk biomass gasification process. Syngas was produced from the coffee husk biomass gasification process with a variation in the airflow rate entering the gasification system. The variations in the inlet air flow rate were conducted to optimize its effect on the combustion flame characteristics, focusing on flame temperature and the visualization of syngas combustion flame from the coffee husk biomass gasification process, using control data for analysis. Variations in air flow rate were carried out to understand the effect of the air-to-biomass ratio in the gasification process, which has direct implications for combustion efficiency, syngas content, and tar reduction. This objective allows the identification of optimal operating conditions to produce high-quality syngas. Gasification process temperature (control temperature), air and syngas humidity, tar content, and syngas content from gasification (H_2, CH_4, and CO), as well as a review of the generator output power.

The test equipment was designed to support the smooth running of the study process. **Figure 1** shows a schematic of the test equipment. The test equipment system includes a fuel and air intake system, a gasification system (gasifier), measuring and control instruments, and visualization equipment. The system components include a compressor, air flowmeter, air filter, water content meter (MC meter), gasifier, cyclone, tar reservoir, condenser, syngas filter, combustion chamber, thermocouple, data logger, laptop, camera, syngas sensor, generator, and a series of light bulbs. The test equipment is designed to ensure proper control of experimental parameters, including airflow, humidity, and gasification temperature. The components such as the syngas filter and condenser are selected to reduce tar interference in syngas measurements and ensure the consistency of combustion results. The biomass material used is coffee husk biomass waste, while the oxidizer is air. Biomass material is supplied to the gasifier hopper, while air is supplied from the air compressor tank.

a. Compressor, b. Air flowmeter, c. Air filter, d. MC meter 1, e. Gasifier, f. Cyclone, g. Tar reservoir, h. Condenser, i. Syngas filter 1, j. Syngas filter 2, k. MC meter 2, l. Combustor, m. Flame, n. Thermocouple, o. Data logger, p. Laptop, q. Camera, r. Syngas sensor, s. Generator, t. String of light bulb

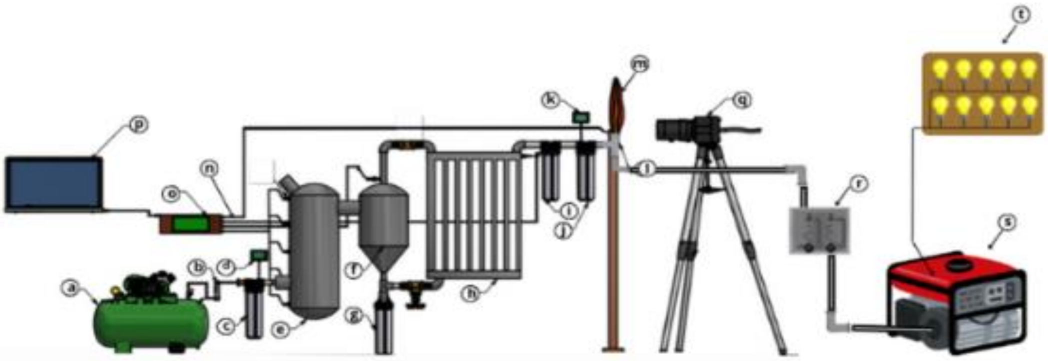


Figure 1. Schematic of test equipment

This study was conducted by observing the characteristics of syngas combustion flame resulting from the gasification process of coffee husk biomass waste with variations in the inlet air discharge in the reactor. The variations of the inlet air discharge are 20, 25, 30, 35 and 40 SFCH. The flame characteristics observed include flame temperature and flame visualization, which result from the combustion of syngas produced through the gasification of coffee husk biomass waste, supported by additional parameter data from the gasification process. The parameters measured included gas composition (CO, H_2, CH_4), tar content, flame temperature, flame height, and generator output power. This study prioritizes the relationship between these parameters and the efficiency of syngas use in automotive applications, providing new valuation information compared to previous biomass investigations. This treatment was carried out to determine the levels of syngas from gasification (CH_4, CO, H_2), the amount of tar, flame temperature, flame visualization, generator output power, reactor temperature, material water content, environmental water content, and syngas. The instruments used in the measurements include a Type-K thermocouple with a 10 cm stick length, Visi-Float® flowmeters by Dwyer for airflow measurement, and a grain moisture meter (AR991) for determining the moisture content of coffee husk biomass waste, as reported in reference [34]. An air-humidity acquisition device based on the DHT11 sensor, as reported in reference [35]. MQ-series syngas sensors, including CH_4 (MQ-4), CO (MQ-7), and H_2 (MQ-8), following the method described in reference [36], and a data logging system that integrates PLX-DAQ-v2 data acquisition Excel Macro and Arduino UNO boards, as reported in reference [37].

3. Results and Discussion

This study was conducted by observing the characteristics of syngas combustion flame produced from the gasification of coffee husk biomass waste, with variations in the inlet air flow rate into the reactor. The variations of the inlet air discharge are 20, 25, 30, 35 and 40 SFCH. The parameters of flame characteristics observed are flame temperature and visualization of syngas combustion flame resulting from the gasification process of coffee husk biomass waste, supported by additional parameter data from the gasification process. This treatment was carried out to determine the gasified syngas content, total tar, flame temperature, flame visualization, generator power output, reactor temperature, material moisture, environmental moisture, and syngas moisture. **Table 1** shows the supporting parameter data of the test results with variations in the reactor intake air discharge.

Based on **Table 1**, it is found that an increase in air discharge results in a higher temperature in the reactor, with the highest average temperature recorded at the 40 SCFH air discharge variation. Additionally, the moisture content of the feedstock plays a significant role in the gasification process in the reactor. The lower the moisture content of the raw material, the higher the heating value, which will affect the flame of syngas output.

Table 1. Moisture and temperature data in the reactor

Mass (Kg)	Discharge (SFCH)	MC Materials	Humidity Room	T Room	T Oxidation	T Reduction	T Pyrolysis	T Drying	MC Syngas	T Con in	T Con out
2	20	47	72	30	507.50	264.75	238.30	102.30	38	47.63	31.78
2	25	4.7	73	31	512.37	262.63	261.10	103.08	39	48.95	32.00
2	30	4.7	73	30	518.40	303.18	278.20	113.43	50	53.95	32.18
2	35	4.7	73	30.8	532.50	338.73	368.50	119.08	53	55.08	32.75
2	40	4.7	74	31	543.08	374.83	368.35	129.10	54	69.98	33.50

The variation in air discharge during coffee husk biomass waste gasification has a significant impact on the chemical reactions and the composition of the resulting syngas. This process is influenced by factors such as temperature, equivalence ratio (ER), and steam-fuel (SF) ratio, which in turn affect the yield and composition of syngas, including the concentrations of CO, H_2, and other gases. Understanding these variations is important for optimizing gasification processes to produce syngas with desirable properties. For example, higher gasification temperatures, such as 900 °C, increase syngas production and CO yield, while reducing char residue compared to lower temperatures such as 700 °C and 800 °C [38]. The thermal decomposition of coffee husk biomass waste is enhanced with highly preheated air, contributing to increased syngas production. Increasing both ER and SF ratios results in the production of syngas rich in H_2 and CH_4 but poor in CO, with the highest heating value observed at specific ER and SF conditions [39]. Higher ER and SF ratios also lead to mixtures rich in H_2 and carbon dioxide (CO_2), while reducing CO content [40]. The H_2/CO molar ratio improves with increased steam, enhancing syngas heating value [39]. When air is used as an oxidizing agent, it produces a different syngas composition compared to oxygen (O_2)-steam blends, with the latter increasing the yield of CO and H_2 [40]. Steam as an oxidizing agent favors H_2 evolution, while air tends to reduce CO evolution [39]. While the effects of air discharge variations on chemical reactions in coffee husk biomass waste gasification are well-documented, it is also important to consider the environmental and economic implications of these processes. The selection of oxidizing agents and operational parameters can influence not only the efficiency and output of the gasification process but also its sustainability and cost-effectiveness.

Environmental humidity and moisture content of coffee husk biomass waste feedstock can significantly influence the efficacy and yield of the gasification process [41]. Elevated humidity levels can lead to the condensation of syngas, particularly during or after the cooling phase of the gasification process. This condensation can negatively impact gas quality, as volatile compounds may become trapped in the produced tar. High-humidity environments can also alter the initial thermal conditions of the feedstock, requiring additional energy to evaporate moisture before the gasification reaction begins. This extra energy allocation can reduce the thermal efficiency of coffee husk biomass waste feedstock exhibiting elevated moisture content necessitating supplementary energy to vaporize water in the gasification process [42]. The power allocated to the vaporization of this water reduces the energy accessible for gasification reaction, thereby diminishing overall efficiency. The presence of moisture in the feedstock can also influence the syngas product ratio [43]. Certain portions of H_2O can engage in gasification reactions (e.g., steam reforming or the Boudouard reaction), resulting in increased H_2 production but concurrently decreasing the concentration of CO. A disproportionate ratio of H_2 to CO could adversely affect the advanced applications of syngas. Excessively wet feedstock can also impede material flow in gasification reactors, leading to process instability and potential operational disruptions [44].

3.1. Syngas Content

Table 2 presents data on syngas content produced during the gasification process using coffee husk biomass. Syngas content captured includes CH_4, H_2, and CO. This data shows that air discharge will affect the composition of syngas produced.

Table 2. Syngas content

Air Discharge (SCFH)	Syngas content (%)		
	CH_4	H_2	CO
20	14.36	6.43	9.56
25	13.18	6.93	10.46
30	12.81	7.17	12.26
35	10.00	8.79	14.86
40	8.01	10.80	15.80

Table 2 shows that among the three syngas contents obtained, CH_4 achieved the highest variation of 20 SCFH inlet air discharge with a concentration of 14.36%. The lowest CH_4 concentration was obtained in the variation of 40 SCFH air discharge with a concentration of 8.01%. In syngas H_2 content, the highest concentration was obtained in 40 SCFH air discharge variations with a concentration of 10.80%, while the lowest H_2 concentration was obtained in 20 SCFH discharge variations with a concentration of 6.43%. In CO syngas content, the highest concentration was obtained in 40 SCFH variations with a concentration of 15.80%, while the lowest CO concentration was found in 20 SCFH discharge variations with a concentration of 9.56%. Based on Table 2 and Figure 2, as the air discharge increases, the production of syngas levels in the form of CO and H_2 concentration levels increases. However, there is a decrease in the concentration of CH_4 gas levels. This is also reviewed from the gasification control parameters in Table 1. Increasing the intake airflow results in higher combustion (oxidation temperatures) in the reactor.

Increasing the airflow into the gasifier during the gasification process will increase the formation of H_2 and CO gas. This airflow refers to the volume of air entering the gasifier. An increase in air discharge provides more oxygen for the chemical reactions occurring in the gasifier. In the combustion process, enhanced airflow supplies additional oxygen to support more complete fuel combustion. This more complete combustion produces more energy, which in turn affects the gas composition. As combustion becomes more complete, CO levels increase due to the complete oxidation of carbon in the fuel. However, at some stage, more intensive combustion can also affect other reactions in the gasifier. When more air (and oxygen) is supplied, CO and H_2 formation reactions become more active. The additional oxygen accelerates these reactions, resulting in more CO and H_2 in the product gas [45].

Increased oxygen can increase CO production because oxygen oxidizes carbon to CO, and then the CO_2 formed can be returned to CO through a reversal reaction [46]. With more oxygen, H_2O reacts with carbon to produce CO and H_2. An increase in air discharge can also affect the formation of H_2 because the gasification process involves a reaction between H_2O and carbon. The balance between combustion and gasification reactions is very important. If too much air is introduced, excessive combustion may occur, which can reduce the amount of valuable gases such as H_2 and CO. If too much CO_2 is formed, conversely, if too little air is available, gasification process is not optimized, and the reaction becomes less efficient.

The decrease in CH_4 levels due to an increase in air discharge in the biomass gasification process can be viewed from the mechanism of chemical reactions in the gasifier. Biomass gasification involves the conversion of solid materials into gases such as CO, H_2, CH_4, and CO_2 through chemical reactions at high temperatures. Higher air discharge results in more oxygen being available for this process. CH_4 can be oxidized to CO_2 and H_2O when excess oxygen is present. When the air discharge increases, more oxygen is available for this reaction, thereby CH_4 undergoes more intensive oxidation. Higher air discharge provides more oxygen for these reactions. Methane can be oxidized to carbon dioxide (CO_2) and water vapor (H_2O) when excess oxygen is present. When the air discharge increases, more oxygen is available for this reaction, thereby methane undergoes more intensive oxidation. When more oxygen enters the gasifier, combustion reactions occur on the carbon in biomass and the gases produced, including methane. The excess oxygen spurs a more complete combustion reaction. Other reactions, such as the formation of CO_2 from CO, can also occur, contributing to further oxidation of CH_4. With more oxygen, reactions that produce gases such as CO_2 and H_2O will increase, changing the balance of gases in the gasifier. CH_4, a more stable gas, will be oxidized into more stable gases such as CO_2 and H_2O. Increasing the air discharge in the gasification process causes a decrease in CH_4 gas content because the additional oxygen accelerates the oxide reaction.

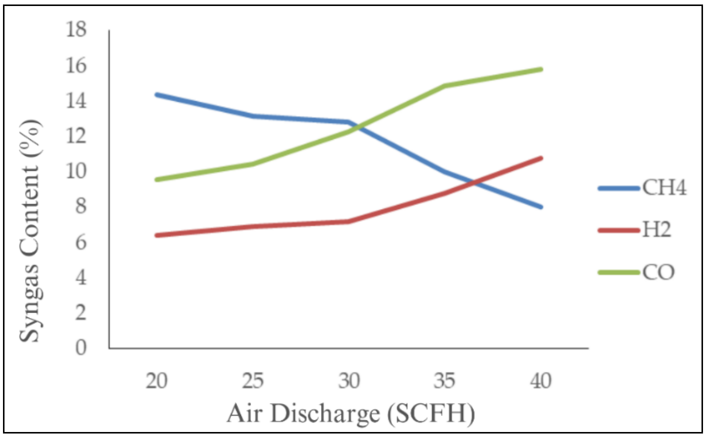


Figure 2. Syngas content against air discharge

3.2. Total Tar

In addition to syngas content produced in the gasification process, tar is also obtained in this process. Tar is a liquid waste that is concentrated in color and has a pungent odor. It is condensed through the cyclone and cooling pipes. The data on the amount of tar obtained is shown in **Table 3**. **Figure 3** shows that different variations in air discharge can affect the amount of tar produced. The data indicates that the highest tar content, measuring 6.7 grams, is observed at an air discharge variation of 20 SCFH. In contrast, the lowest tar content, measuring 3.8 grams, occurs at an air discharge variation of 40 SCFH.

Table 3. Tar count data

Air Discharge (SCFH)	Total tar (gr)
20	6.7
25	6.2
30	5.0
35	4.2
40	3.8

Based on **Table 3** and **Figure 3**, the total tar produced in the gasification process decreases as the inlet air discharge increases. Increased airflow into the gasifier during the gasification process reduces the tar produced [47], [48]. The addition of air increases the availability of oxygen, facilitating more intensive oxidation reactions. These reactions not only generate heat but also contribute to the breakdown of tar compounds. With more oxygen, most tar compounds are oxidized into gases such as CO_2 and H_2O, reducing the residual tar in the gas stream.

Increasing the inlet air discharge, which introduces a higher amount of oxygen, enhances the combustion rate in the reactor. This process generates additional heat, thereby raising the temperature of the gasification reactor. A higher reactor temperature increases the rate of thermal reactions in the gasification reactor. This process includes pyrolysis reactions, where solid fuels are broken down into simpler compounds, and carbon compounds are converted into gases such as H_2, CO, and CH_4. At higher temperatures, the complex organic compounds that makeup tar break down more easily into simpler molecules. For example, these compounds tend to remain stable at low temperatures, whereas at high temperatures, the chemical bonds in tar compounds can break, producing light gases such as CO, H_2, and CH_4. The devolatilization process will occur faster at high temperatures, producing less tar. Tar formed in the reactor undergoes thermal cracking at elevated temperatures, breaking down large tar molecules into smaller molecules and gases. Consequently, higher temperatures generally lead to a reduction in the amount of tar produced in gasification reactors.

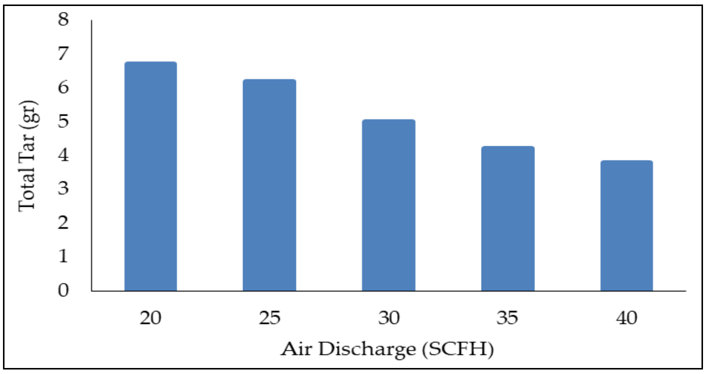
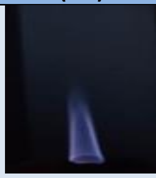
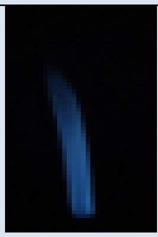
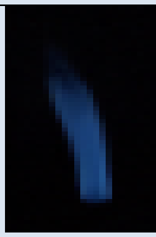
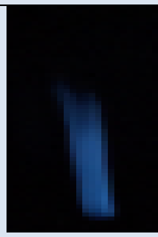
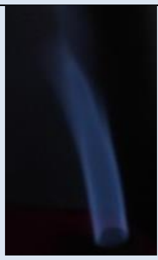
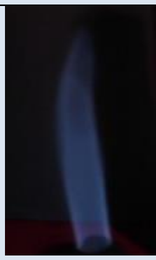
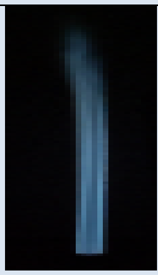
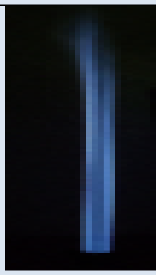
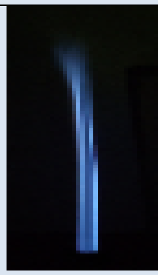
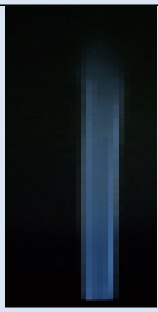
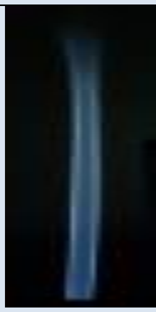
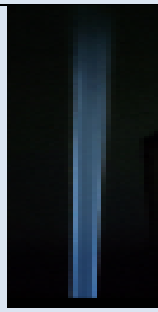


Figure 3. Amount of tar against air discharge

3.3. Flame Visualization

Flame height testing in crossdraft-type gasification is carried out with ImageJ software. The measured flame height is the height of the flame coming out of the syngas output hose. The visualization and flame height are presented in **Table 4**. **Figure 4** shows that the highest flame height visualization is found in 40 SCFH air discharge variations with a flame height of 30.94 cm. The lowest flame height visualization is obtained in 20 SCFH discharge variations with a flame height of 4.609 cm. Based on **Table 5** and **Figure 5**, the flame temperature increases as the incoming air discharge increases, resulting from the gasification process. Increasing the air discharge in the gasifier reactor in the gasification process led to higher flame temperature. More oxygen enters the gasification reactor with an increase in the incoming air discharge. The air entering the gasification reactor contains oxygen, a vital combustion component. In gasification, air is used for partial combustion of biomass solid fuels. Partial combustion of solid fuels is an exothermic reaction, which means that it produces heat. With more oxygen, this reaction becomes more intense, generating more heat in the reactor as more fuel is partially burned. This increase in heat speeds up the conversion of fuel to syngas and increases the overall temperature inside the reactor. Increasing the temperature in the reactor produces syngas with higher energy content as

Table 4. Flame visualization and flame height

Air Discharge (SCFH)	Flame Height (cm)			Average (cm)
20	 4.748	 4.372	 4.707	4.609
25	 10.090	 8.761	 8.03	8.960
30	 13.136	 12.952	 13.196	13.094
35	 22.998	 22.022	 21.547	22.189
40	 30.296	 30.052	 32.485	30.940

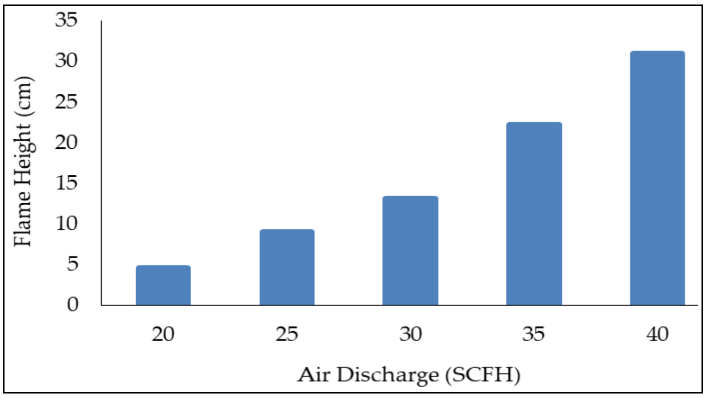


Figure 4. Flame height against air discharge

the proportion of high heating value combustible gases such as CO and H_2 increases. This high energy content syngas generates more heat when burned, increasing flame temperature [49], [50]. Both CO and H_2 components are combustible gases with high heating values, which can produce high flame temperatures when burned.

3.4. Flame Temperature

The flame temperature was measured using a K-type thermocouple, and testing flame temperature by placing it above 2 cm horizontally from the top of the flame base. The following is flame temperature data presented in **Table 5**. Flame temperature data is obtained against the air discharge. The highest flame temperature is found in 40 SCFH air discharge variation with a temperature of 344.5 °C. The lowest flame temperature is obtained at 170.88 °C in the air discharge variation of 20 SCFH.

Table 5.
Flame temperature data

Air Discharge (SCFH)	Flame Temperature (°C)
20	170.88
25	202.1
30	276
35	323.68
40	344.5

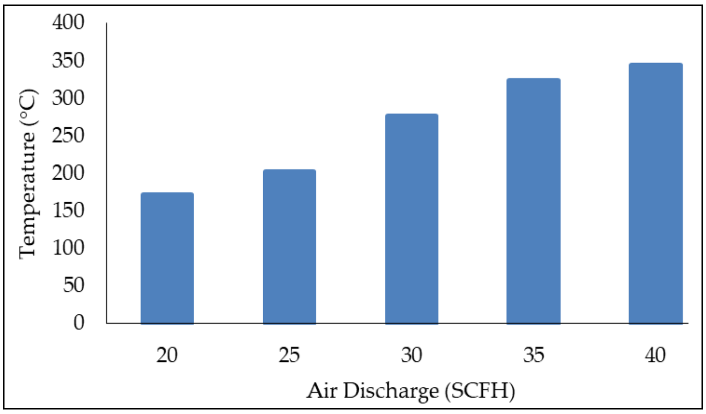


Figure 5.
Flame temperature against air discharge

Based on **Table 3** and **Figure 3**, the total tar produced in the gasification process decreases as the inlet air discharge increases. Subsequently, increased airflow into the gasifier during the gasification process reduces the tar produced [51], [52]. The addition of air enhances the availability of oxygen, enabling more intensive oxidation reactions. These reactions not only generate heat but also facilitate the breakdown of tar compounds. With more oxygen, most tar compounds are oxidized into gases such as CO_2 and H_2O, reducing the residual tar in the gas stream.

Increasing the inlet air discharge, which introduces a significant amount of oxygen, boosts the combustion rate in the reactor. This leads to greater heat production and an increase in gasification reactor temperature. A higher reactor temperature increases the rate of thermal reactions in the gasification reactor. This process includes pyrolysis reactions, where solid fuels are broken down into simpler compounds, and carbon compounds are converted into gases such as H_2, CO, and CH_4. At higher temperatures, the complex organic compounds that make up tar break down more easily into simpler molecules. For example, these compounds tend to remain stable at low temperatures, whereas at high temperatures, the chemical bonds in tar compounds can break, producing light gases such as CO, H_2, and CH_4. The devolatilization process will occur faster at high temperatures, producing less tar. In addition, tar formed tends to undergo thermal cracking at high temperatures, where the large molecules that make up the tar are broken down into smaller molecules and gases. As a result, higher temperatures tend to reduce the amount of tar formed in the gasification reactor.

3.5. Generator Power Output

Generator power output testing is carried out by flowing the results of syngas from gasification to the Gasoline Generator (2500 watts). The loading results in each variation are generated from the calculation between voltage x amperage (P = V x I), leading difference in loading. The following is the generated generator power output data, presented in **Table 6**.

Based on **Figure 6**, the highest generator power output is obtained at 40 SCFH air discharge variation with the highest power of 1020 watts (for the number of light bulbs on as many as 10), while the lowest generator power output is obtained at 20 SCFH air discharge variation with the power obtained at 120 watts (for the number of light bulbs on is 1).

Table 6.
Flame temperature data

Inlet Air Discharge (SCFH)	Ampere (A)	Voltage (V)	Generator power output (Watt)	Lamp loading (Pcs)
20	1.09	110	120	1
25	2.53	130	330	3
30	3.80	160	608	6
35	4.50	180	810	8
40	4.63	220	1020	10

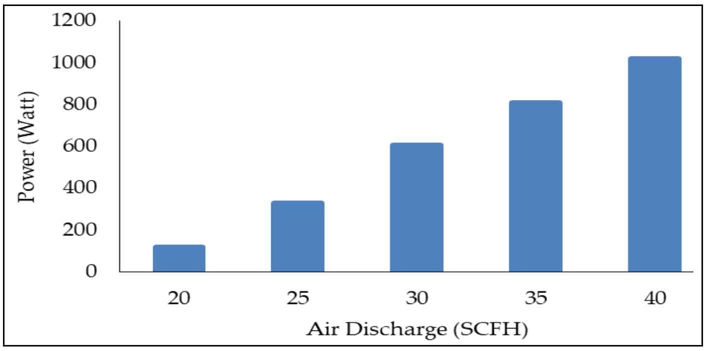


Figure 6. Flame temperature against air discharge

Based on **Table 6** and **Figure 6**, increasing the air discharge into the gasifier reactor in the gasification process results in greater generator power output. The air discharge entering the gasification reactor determines the amount of oxygen available. With increasing air discharge, more oxygen enters the reactor. With more oxygen available, the partial combustion reaction of the solid fuel becomes more intense. This partial combustion is an exothermic reaction, producing heat and breaking down the solid fuel into gaseous components. The increased combustion intensity enhances the efficiency of solid fuel conversion into syngas, resulting in a higher production rate of syngas. This increase often corresponds to syngas with a greater energy content. Syngas that are rich in CO and H_2 are highly flammable and generate substantial heat when combusted. Syngas produced from a gasification process with a higher air discharge have a higher content of CO and H_2, which are high heating value components. With high-quality syngas, combustion in the generator engine becomes more efficient [53]. More energy is produced from syngas combustion, increasing the efficiency of chemical energy conversion to electrical energy [54]. More efficient combustion (syngas entering the generator combustion chamber burns completely) also reduces energy waste and ensures that most energy is converted into electrical power [55]. Since more energy is generated from burning high-quality syngas, the generator's electrical power output also increases [56]. The engine can run at higher capacities without experiencing a drop in efficiency, producing more electricity per unit of syngas fuel used.

The potential to scale up the gasification process of coffee husk biomass waste is promising, given its availability and energy content as an alternative automotive fuel source. Coffee husk biomass waste, a by-product of coffee production, has been identified as a viable feedstock for gasification due to its high volatile content and calorific value comparable to woody biomass. However, challenges such as high tar and ash content and co-gasification with higher calorific materials such as coal must be overcome for efficient large-scale applications. Coffee husk biomass waste has a high volatile matter content (69.8%) and a higher heating value (HHV) of 18.3 MJ/kg, making it suitable for gasification processes similar to wood biomass [57]. Co-gasification of coffee husk biomass waste with coal has shown promising results, producing syngas with a lower heating value (LHV) of 5045.56 kJ/m³ when using 75% coffee husk biomass waste and 25% coal [58]. The thermochemical characteristics of coffee husk biomass waste, such as a volatile matter content of 66.85% and a fixed carbon content of 14%, favor its use in gasification [59]. The high ash content of coffee husk biomass waste, which is 9.2%, can negatively impact gasification systems and therefore requires careful management [57]. Inorganic elements such as potassium and sodium can cause defluidization in fluidized bed gasifiers, requiring feedstock pretreatment [59]. Moisture content in coffee husk, which can reach up to 60%, necessitates the use of proper drying technology to ensure efficient and effective gasification [55]. Integrating coffee husk biomass waste gasification into existing energy systems can improve bioenergy production and waste management, specifically in coffee-growing regions [59]. Utilizing coffee husk biomass waste in gasification, in combination with other biomass or coal, can enhance energy yield and improve the economic feasibility of the process [58], [60]. While the potential for large-scale application of coffee husk biomass waste gasification is considerable, overcoming the technical challenges associated with its high tar content and moisture content is imperative. Further study and development in pretreatment and co-gasification techniques could improve the feasibility and efficiency of this process on a larger scale to obtain an alternative automotive fuel source.

4. Conclusion

In conclusion, this study showed that increasing the inlet air flow rate significantly increased the CO and H_2 gas concentrations, reflecting better syngas quality. In addition, the tar content was reduced with higher air discharge, contributing to improved gasifier performance and reducing the potential for tar accumulation. These results confirmed the importance of optimizing air discharge parameters to improve gasification efficiency and produce cleaner syngas. However, there were limitations to this study, the analysis only included the effect of air discharge, while other operational parameters, such as feedstock variation and reactor design, were not evaluated. The laboratory scale used also limited direct applicability to the industrial scale. To address this, future investigations should examine the effect of moisture and feedstock type on syngas composition and tar reduction. Pilot or industrial-scale experiments would be essential to validate these results under real-world conditions. Implementing real-time monitoring and control systems could also help dynamically optimize gasifier performance. This study provided valuable information but overcoming these limitations and expanding the scope would improve the applicability of biomass gasification technology.

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Authors' Declaration

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