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Effect of Ignition Point Location on Temperature Profile and Syngas Composition in Downdraft Gasification of Coconut Shell and Wood Sawdust

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ABSTRACT

The utilization of biomass waste as an energy source, such as for hydrogen and methane gas production, can be achieved through the gasification process. This study aims to analyze the performance of biomass gasification using coconut shells and wood sawdust for syngas production, by comparing the effects of different ignition point positions on process effectiveness. The gasification process was carried out using a down-draft type gasifier reactor. Two main variables were examined: the type of biomass (coconut shell and wood sawdust) and the ignition point location (upper and middle positions). The measured parameters included temperature profiles and syngas composition (H_2 and CH_4). The results showed significant differences based on the ignition point position. The upper ignition point only reached relatively low temperatures (72–262 °C) within six minutes, whereas the middle ignition point achieved a much higher operational temperature (825 °C) after 10 min of ignition. Syngas analysis revealed that wood sawdust produced a higher hydrogen content (4.46%) compared to coconut shell (1.79%), while coconut shell produced a higher methane content (3.4%) than wood sawdust (1.17%). These findings indicate that ignition location plays a critical role in controlling the thermal zone development and gasification efficiency. Optimizing ignition position can significantly improve syngas quality and reactor performance in downdraft gasification systems.

1. INTRODUCTION

The utilization of renewable energy has become one of the main focuses in addressing global challenges related to energy security and climate change mitigation. One of the renewable energy sources with great potential in Indonesia is biomass, including coconut shells and wood sawdust—agricultural residues that are abundantly available. Among various energy conversion technologies utilizing biomass waste, gasification is one of the most extensively developed processes today, offering a cleaner and more efficient energy conversion method compared to direct combustion. Through the gasification process, biomass can be converted into synthesis gas (syngas), which possesses a higher calorific value and can be utilized in various energy applications. The implementation of small-scale gasification systems has been rapidly expanding, particularly in rural areas with abundant biomass resources (Sharma *et al*., 2020). Moreover, not only biomass but also waste materials such as plastics can serve as feedstock in the gasification process (Fazil *et al*., 2022).

The gasification process (Figure 1) of biomass is a synthetic gas production process that consists of four main stages occurring sequentially along the reactor (Marčič *et al*., 2016). It consist of four stages as follow:

1. Drying using heat, during which the wet biomass undergoes a dehydration process. The moisture content in the biomass is evaporated, and this step is crucial because a high water content can significantly affect the efficiency of the gasification process (Naryanto *et al*., 2020). The temperature during the drying stage typically ranges from

100 to 199 °C (Mishra & Upadhyay, 2021).

2. Pyrolysis, in which the dried biomass is heated in the absence of oxygen. In this stage, the biomass undergoes thermal decomposition without oxygen, producing volatile gases (such as methane and tar) and a solid carbon residue (char). The pyrolysis products then move toward the combustion zone (Suliono, 2017). The main outputs of this stage are pyrolysis gases such as methane (CH_4) and tar (incompletely combusted organic residues). The pyrolysis behavior of biomass depends on its cellulose, hemicellulose, and lignin composition, generally occurring within a temperature range of 124–498 °C (Sansaniwal *et al*., 2017).
3. Oxidation, which involves the partial oxidation of gases produced during pyrolysis. In this stage, air or another oxidizing agent reacts with the carbon in the biomass, generating heat and producing gases such as carbon dioxide (CO_2) and water vapor (H_2O). This reaction is exothermic and plays a vital role in maintaining the optimal gasification temperature (Awais *et al*., 2022). The heat generated during this stage supports the pyrolysis and drying of the incoming biomass feed, with temperatures reaching up to 1000 °C (Mishra & Upadhyay, 2021; Sansaniwal *et al*., 2017).
4. Reduction, in which the oxidized gases undergo reduction reactions that convert carbon dioxide (CO_2) and water vapor (H_2O) into carbon monoxide (CO) and hydrogen (H_2). The final product of this stage is known as synthetic gas (syngas), which can be utilized as an alternative energy source (Pandey *et al*., 2022). The temperature during the reduction reactions can reach 1000–1200 °C (Mishra & Upadhyay, 2021; Samani *et al*., 2024).

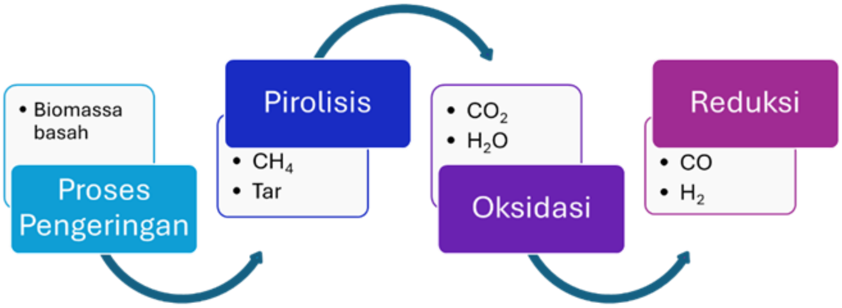


Figure 1. Stages of the biomass gasification process (Hoque *et al*., 2021)

A downdraft gasifier is a type of gasification reactor specifically designed so that the gas flow moves downward in the direction of gravity. In this system, air or an oxidizing agent is introduced into the middle section of the reactor, causing the produced gas to pass through the combustion and reduction zones before exiting. This configuration helps reduce the tar content in the resulting synthetic gas, making it cleaner compared to other types of gasifiers, such as the updraft gasifier (Pandey *et al*., 2022). The main advantages of the downdraft gasifier include its ability to produce synthetic gas with a lower tar content than that generated by an updraft gasifier and its flexibility in utilizing various types of biomass feedstock, including agricultural residues and wood (Yulistiani, 2015; Barontini *et al*., 2021; Montiel-Bohórquez & Pérez, 2022). Furthermore, it can be applied on a small to medium scale, for instance, in rural power generation or small industrial applications (Awais *et al*., 2022).

The efficiency of the gasification process is highly influenced by the moisture content of the biomass; therefore, feedstock with an appropriate moisture level (10–20%) is required to achieve optimal results (Naryanto *et al*., 2020). Biomass with a high ash content, such as municipal solid waste, can also be utilized for gasification through the optimization of operating conditions (Montiel-Bohórquez & Pérez, 2022; Trninić *et al*., 2020; Vikram *et al*., 2023). Other factors affecting gasification efficiency include temperature, particle size, air–fuel ratio, and the type of gasifying medium (Hoque & Rashid, 2021). Studies on feedstock with high moisture content have reported the production of synthetic gas with varying gas compositions and percentages (Styana *et al*., 2019). However, information regarding the optimal operating conditions for optimizing hydrogen-rich synthetic gas production, including the influence of ignition point location on temperature distribution and syngas composition in downdraft gasification, remains insufficiently explored. Moreover, under practical operating conditions, the placement of ignition is a critical factor that determines the continuity and overall success of the gasification process. Based on these considerations, this study aims to optimize the gasification process by determining the ignition point at the initial stage and comparing the gasification results of two types of biomass feedstock with different moisture characteristics. It is expected that the identified combustion point will lead to improved gas composition, particularly hydrogen (H_2) and methane (CH_4) content.

2. MATERIALS AND METHODS

The design of the downdraft gasifier reactor used in this study had a combustion chamber volume of 4 L. Figure 2 illustrates the schematic of the downdraft gasifier used in this study. The reactor consists of a feeding hopper, combustion zone, reduction zone, and ash chamber. Air is introduced through side nozzles, while the ignition point is varied at different vertical positions to investigate its effect on temperature distribution and syngas production. This laboratory-scale reactor operated in batch mode for biomass feeding. During gas sampling, all valves were closed, including the air inlet and the gas exhaust pipe. To anticipate pressure buildup due to gas accumulation inside the reactor, the excess gas was vented through the bottom outlet submerged in water, allowing gas to escape safely. The emitted gas was then tested for ignition by exposing it to a flame. If ignition occurred, the gas sample was collected in an aluminum gas bag for subsequent composition analysis using GC–MS.

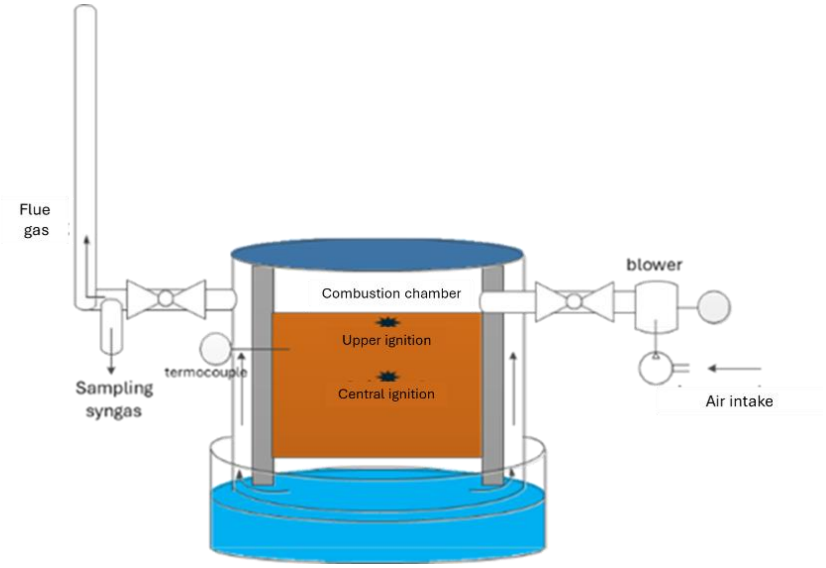


Figure 2. Design of the downdraft gasifier for start-up ignition-point experiments

The research was conducted at the Energy Conservation Laboratory, Department of Energy Conversion Engineering, Bandung State of Polytechnic. It took 7-month research from set up the gasifier to analyzing the experimental data results. The experimental procedures in this study consisted of several key stages, as follows:

1. Biomass preparation: In this stage, the biomass used—coconut shell and sawdust—was sun-dried for 2–3 days. Simultaneously, a downdraft gasifier was constructed, equipped with an air blower module featuring a speed and temperature monitoring system.
2. Gasifier testing: This stage aimed to ensure that all equipment operated properly and that the biomass feedstock could successfully produce synthetic gas, verified through an ignition test. The experiment was carried out as a single trial for each feedstock, after first verifying that ignition had been successfully initiated. The onset of gasification was identified through several indicators, namely a rise in temperature, the appearance of combustion smoke, and the capability of the generated gas to sustain ignition when exposed to an external flame.
3. Optimization of the gasification process: During this stage, the biomass feedstock was weighed, and the combustion chamber (fuel bed) was filled completely. Biomass samples were weighed before and after gasification. During the process, the airflow rate was maintained at 10,480 Nm^3/h, and the temperature rise was

recorded every minute using a digital K-type thermocouple. Two ignition points variations were tested: the upper ignition point (near the air blower inlet) and the middle ignition point. Two types of biomass were used to compare the process behavior and the composition of the resulting gases.

4. Biomass combustion and gas sampling: As the gas produced was able to sustain a flame upon ignition, gas sampling was performed using aluminum gas bags that are airtight and suitable for gas collection. The collected gas samples were then analyzed using Gas Chromatography–Mass Spectrometry (GC–MS) in ITB Chemical Engineering Labolatory. The composition of the produced syngas was analyzed using a Shimadzu GC-2014 gas chromatography system equipped with a Porapak Q column and helium (He) as the carrier gas. The instrument was operated with an oven temperature of 70 °C, an injector temperature of 150 °C, and a detector temperature of 200 °C. The analysed gases are H_2, CH_4, CO_2, and CO as products of gasification reactions, as well as N_2 (as a reference gas to account for air carried by the blower).

3. RESULTS AND DISCUSSION

3.1. Properties of Feedstock

Table 1 presents the physicochemical properties of coconut shell and wood sawdust. Coconut shell exhibits higher fixed carbon content, while wood sawdust has higher volatile matter, which is expected to influence the gasification behavior and syngas composition. The physical characteristics of the coconut shell and sawdust utilized in the gasification process involved particle size and water content. The chemical characteristics of feedstocks include volatile matters, fixed carbon, and ash content, which were determined based on several relevant references (Budi, 2011; Hoque & Rashid, 2021; Inayat *et al*., 2018). The density (kg/cm^3) of coconut shell is higher than that of sawdust when occupying the same combustion chamber volume. For this experiment, the amount of biomass used as feedstock was 460 g for each run.

Table 1. Physicochemical characteristics of coconut shell and sawdust

No.	Properties	Coconut Shell	Sawdust
1.	Particle size (cm^3)	2×0.3×3	0.5×0.05×2
2.	Water content (%)	7.92	5.01
3.	Volatile Matter (%)	67–81.69	78.6
4.	Fixed Carbon (%)	17.5–21.94	17.8
5.	Ash (%)	0.4–0.83	1.2
6.	HHV MJ/kg	19.43–20.58	18.23

3.2. Temperature Profile

The gasification experiments using coconut shell feedstock (Figure 3a) and sawdust feedstock (Figure 3b) demonstrated distinct temperature rise profiles during combustion, influenced by both the ignition point location and the type of biomass used. In the coconut shell gasification, the combustion temperature profile at the upper ignition point showed a temperature increase reaching 265 °C within the first 10 minutes of the process. However, the exhaust gas temperature subsequently decreased, peaking at 260 °C before dropping to 165 °C at the end of the gasification process. Ignition at the upper zone resulted in a lower temperature, but more uniform gradient. In contrast, using ignition at the center point, the combustion temperature continued to rise steadily throughout the process, reaching a maximum of 825 °C.

For the sawdust gasification (Figure 3b), both the combustion and exhaust gas temperatures initially increased, reaching 275 °C and 255 °C, respectively, within the first two minutes. However, the combustion temperature then dropped sharply to 200 °C, reaching its lowest point at 165 °C, before gradually rising again to 180 °C and stabilizing at 250 °C until the end of the six-minute gasification process. The exhaust gas temperature remained stable at 250 °C, later decreasing slightly to 225 °C and maintaining that level until completion. The temperature rise during gasification with ignition at the center point continued from the second to the 10 min, reaching a peak temperature of 825 °C. Using sawdust as feedstock, the peak temperature with ignition point at the center achieve 597.9 °C after six minute of combustion.

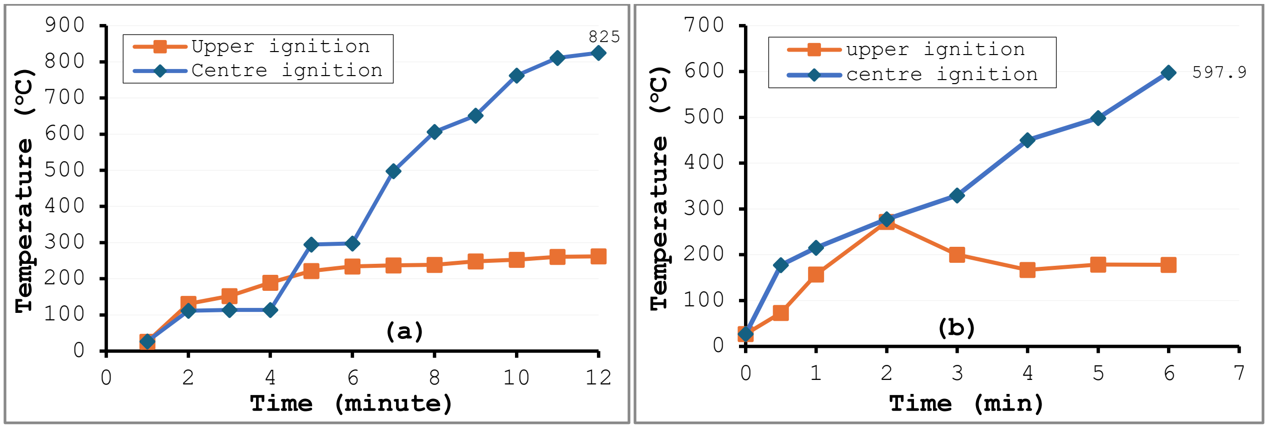


Figure 3. Temperature profiles in the gasification combustion chamber with upper and center ignition points: (a) sawdust, and (b) coconut shell

The difference in temperature rise between the upper ignition point (located near the air inlet) and the center ignition point can be attributed to variations in heat propagation behavior. Figures 3a and 3b illustrate the temperature evolution within the combustion chamber during downdraft gasification using coconut shell and wood sawdust as feedstocks, respectively. Each experiment was conducted using two ignition configurations, namely upper and centre ignition. The results clearly indicate that both ignition location and feedstock type significantly influence the thermal reactions occurring during the gasification process.

For both feedstocks, center ignition produced substantially higher temperatures compared to upper ignition. In the case of coconut shell (Figure 3a), the temperature under center ignition increased sharply after approximately 3 minutes and exceeded 800 °C, whereas the upper ignition configuration stabilized at around 250 °C. A similar trend was observed for sawdust (Figure 3b), where centre ignition reached approximately 600 °C, nearly twice the temperature achieved under upper ignition.

In a downdraft reactor, the reaction zones are typically arranged vertically and consist of drying, pyrolysis, oxidation (combustion), and reduction zones. When ignition occurs at the centre of the fuel bed, the oxidation zone develops within the bulk of the biomass matrix, enabling more uniform air–fuel contact and improved heat transfer to surrounding particles. This configuration enhances exothermic oxidation reactions, thereby increasing the local temperature. The elevated temperature subsequently promotes endothermic reduction reactions, which help sustain high thermal conditions within the reactor.

In contrast, upper ignition promotes the formation of a combustion zone concentrated only near the upper area. A portion of the generated heat is dissipated upward and outward rather than being effectively transferred downward through the reduction zone. Furthermore, upper ignition may induce premature devolatilization without sufficient development of a char bed beneath the oxidation zone, thereby limiting the extent of high-temperature reduction reactions. Similar resutls have been reported in several studies on stratified downdraft gasifiers (Zainal *et al*., 2002). Centre ignition facilitates the formation of a stable oxidation–reduction interface more effectively than upper ignition.

The timing and position of biomass particle ignition are strongly influenced by reactor temperature, particle size, and airflow rate. Ignition occurring closer to the air inlet promotes rapid oxidation and intense heat release in the upper zone of the reactor, while delayed ignition (further from the air source) allows devolatilization and reduction reactions to dominate, enhancing the formation of CO and H_2 gases while reducing tar production. Therefore, precise control of ignition timing and ignition location is a critical factor in optimizing syngas quality within a downdraft gasification system (Li *et al*., 2016).

In Figure 4, the temperature profile of the gasification process at the middle ignition point shows that the coconut shell reached a maximum temperature of 825 °C, which is higher than that of sawdust, which only reached 647 °C within the same time frame. During coconut shell gasification, the temperature remained relatively stable above 820

°C after reaching its peak. In contrast, the temperature of sawdust decreased sharply following its peak value. During coconut shell gasification, the temperature remained relatively stable above 820 °C after reaching its peak. In contrast, the temperature of sawdust decreased sharply following its peak value.

From the perspective of heat distribution, the sawdust gasification exhibited a slightly faster initial heating rate during the first three minutes. However, after the third minute, the coconut shell experienced a sharp and rapid temperature increase, significantly surpassing the temperature achieved by sawdust. The density (kg/cm³) of coconut shell is higher than that of sawdust when occupying the same combustion chamber volume. A denser fuel bed promotes enhanced char formation and stronger oxidation reactions due to the development of a more stable and compact zone of combustion. In contrast, sawdust typically exhibits lower bulk density and higher porosity, which may result in channeling effects and uneven air distribution. Such conditions reduce local combustion intensity and consequently lower the peak temperature.

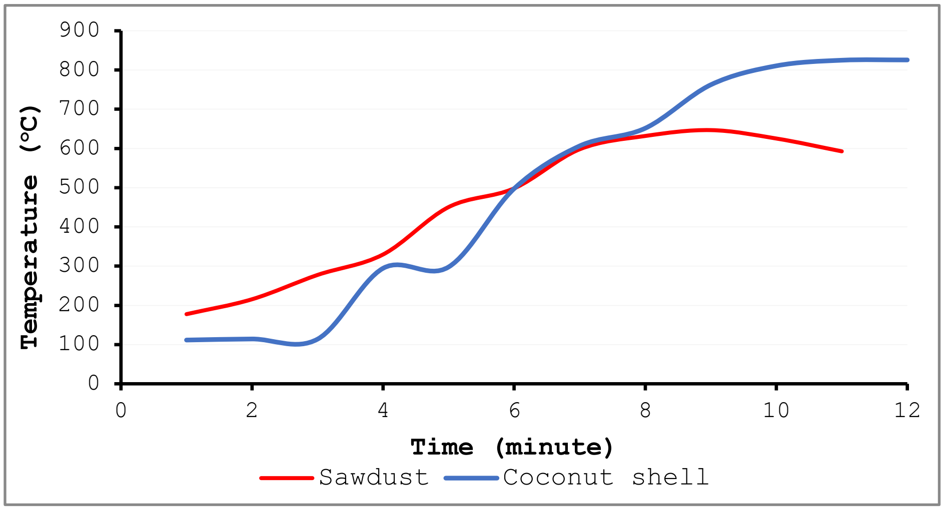


Figure 4. Temperature profiles of the gasification process using coconut shell and sawdust feedstock

In addition, coconut shell contains higher fixed carbon and lower volatile matter compared to sawdust. A high fixed carbon content supports sustained char oxidation (and char–gas reactions in the reduction zone, leading to higher operating temperatures. Sawdust, with its higher volatile content, undergoes rapid devolatilization, which may initially contribute to combustion but can also lead to rapid heat release followed by reduced char availability, thereby limiting prolonged high-temperature.

Differences in ash composition may also influence reactivity and thermal behavior. Alkali and alkaline earth metals present in biomass can catalyze char gasification reactions; however, excessive ash may hinder heat transfer and obstruct airflow. Coconut shell typically contains relatively low ash content compared to certain wood residues, contributing to more efficient high-temperature operation.

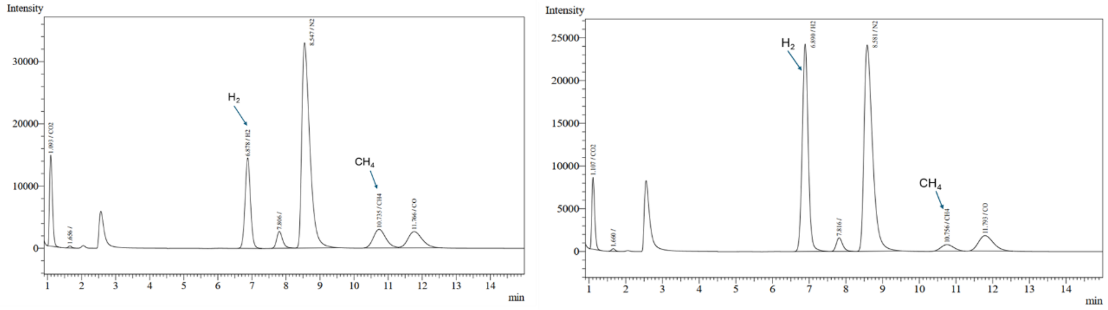
Moreover, sawdust particles are smaller and more loosely packed than coconut shell, where the particle size for coconut shell is 1.8 cm³, while it is only 0.05 cm³ for sawdust (Table 1). While smaller particles increase surface area, they may also reduce bed permeability and cause variations in pressure drop, thereby affecting air distribution and local equivalence ratio. The resulting heterogeneous combustion conditions may restrict the development of maximum temperature within the reactor (Trejo, 2025).

Moreover, coconut shell contains a higher proportion of fixed carbon and lignin, along with lower volatile matter content compared to sawdust. This composition enables coconut shell to produce a higher calorific value (approximately 18–20 MJ/kg) and sustain a longer and more stable combustion process, primarily due to the dominance of the solid carbon combustion phase (char combustion), which requires a longer oxidation time (Prasetyadi & Sutapa, 2023).

In contrast, sawdust, which has a higher volatile matter content, ignites more easily but burns out more rapidly, resulting in a shorter flame duration and a lower peak temperature. Moreover, the greater density of coconut shell compared to sawdust increases the fuel mass per unit volume, thereby enhancing the total energy released during combustion. Previous studies (Waluyo *et al*., 2023) have also reported that biochar derived from coconut shell exhibits higher fixed carbon content and a greater Higher Heating Value (HHV) than that of wood. Both findings confirm that, from a chemical and thermal standpoint, coconut shell is more efficient and durable in combustion processes compared to sawdust when using an equivalent fuel volume.

3.3. Syngas Composition

At the highest recorded temperature, a flame ignition test was conducted on the produced gas. Both types of feedstock generated flammable gas, after which gas samples were collected prior to combustion for composition analysis. The results, obtained through Gas Chromatography–Mass Spectrometry (GC–MS) analysis, are presented in Table 2, which shows the gas composition from the gasification of coconut shell and sawdust, while Figure 5 illustrates the corresponding GC–MS chromatogram.



(a)

(b)

Figure 5. GC-MS data results of gasification using: (a) coconut shell, and (b) sawdust

Table 2. Syngas composition resulted from gasification of coconut shell and sawdust as feedstocks with central ignition point

Gas	Coconut shell	Sawdust
H_2	1.79	4.46
CH_4	3.40	1.17
CO_2	13.28	10.27
CO	12.10	11.58
N_2	69.42	72.53
LHV (MJ/kg)	5.07	7.11

The lower H_2 composition observed in the gasification of coconut shell can be attributed to several factors, including the feedstock composition (percentages of volatile matter, hydrogen, and carbon content), gasification temperature, residence time, and variations in the air ratio (equivalence ratio, ER). The relatively small difference in H_2 yield between the two feedstocks may indicate that neither biomass type reached the optimal temperature for the reduction stage.

In the case of CH_4, the coconut shell feedstock produced a slightly higher concentration (3.40%) compared to sawdust, which may also be associated with the fact that both materials did not achieve the optimal temperature required for the reduction reactions that predominantly generate H_2. Higher operating temperatures in the range of 700–900 °C are generally favorable for tar cracking and enhanced production of CO and H_2 through endothermic reduction reactions ($C + H_2O$ and $C + CO_2$ reactions). Therefore, the higher temperatures achieved under centre ignition –particularly with coconut shell– are expected to yield syngas of improved quality, characterized by higher CO and H_2 concentrations and lower tar content. In contrast, the lower temperatures observed under upper ignition may result in incomplete tar cracking and reduced gas calorific value.

The difference in CO_2 and CO concentrations shows that coconut shell generated a slightly higher CO_2 content, possibly due to partial oxidation of carbon into CO_2 (rather than CO) or a relatively higher oxygen ratio. This condition is typical when the equivalence ratio (ER) or airflow rate is elevated, causing part of the reaction to proceed toward combustion rather than pure gasification. In a previous study (Hoque *et al*., 2021) employing a downdraft gasifier, the reactor temperature reached approximately 875 °C, yielding an average gas composition of 8.84% H_2 and 1.13% CH_4. These values are higher than those obtained in the present study, primarily due to the higher gasification temperature achieved in that experiment.

The syngas composition obtained in this study is characterized by a notably high nitrogen (N_2) fraction, accompanied by relatively lower concentrations of combustible gases such as CO, H_2, and CH_4, which is a typical feature of air-blown gasification systems due to the use of atmospheric air containing approximately 79% nitrogen. As a result, nitrogen behaves as an inert diluent and significantly reduces the calorific value of the produced gas. Similar observations have been reported in experimental studies of biomass gasification, where increasing the equivalence ratio (ER) leads to higher nitrogen dilution and a corresponding decrease in combustible gas concentrations. In a bubbling fluidized bed gasifier, increasing ER resulted in a higher N_2 fraction and reduced CO and H_2 content (Bandara *et al*., 2021).

In general, ER values for air-blown gasification range from 0.15 to 0.45, with optimal performance typically achieved between 0.20 and 0.30, where a balance between oxidation and reduction reactions is maintained (Rupesh *et al*., 2015). At higher ER values, excessive air supply not only increases nitrogen content but also enhances the conversion of CO and H_2 into CO_2 and H_2O, leading to a decline in the lower heating value (LHV) of the syngas. Additionally, hydrodynamic factors such as particle size and bed permeability may further contribute to non-uniform air distribution, resulting in localized variations in ER and heterogeneous reaction zones, which hinder the formation of combustible gases.

4. CONCLUSIONS

Based on the experimental results, we concluded that ignition point location significantly affects temperature distribution and syngas composition. Upper ignition positions promote stable thermal zones and higher CO and H_2 production, while lower ignition leads to inefficient gasification. Optimizing ignition location is essential to improve reactor performance. The final temperature at the middle ignition point was approximately three times higher than that at the upper ignition point. The results suggest that ignition initiated at the middle position promotes a more effective pattern of heat propagation, which in turn facilitates a faster gasification process. In the gasification of both feedstocks using the middle ignition configuration, sawdust produced a higher hydrogen (H_2) concentration of 4.46%, compared to 1.79% for coconut shell. Conversely, coconut shell generated a higher methane (CH_4) concentration of 3.40%, compared to 1.17% for sawdust and higher carbonmonoxide (CO) concentration of 12.8%, compared to 11.58% for sawdust. However, the heating caloric value of sawdust is 2.4% higher than coconut shell. This experiment results possible lead to several future experiments to identify the combination of equivalence ratio (ER), residence time (airflow), and reactor temperature that maximizes H_2 for each feedstock.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
TMG	✓	✓		✓						✓				
PI					✓	✓	✓		✓	✓			✓	
YS										✓	✓			

C: Conceptualization
M: Methodology
So: Software
Va: Validation
Fo: Formal Analysis
I: Investigation
D: Data Curation
R: Resources
O: Writing - Original Draft
E: Writing - Review & Editing
Vi: Visualization
Su: Supervision
Fu: Funding Acquisition
P: Project Administration

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