Research Article

# Gasification performance of sawdust, pelletized sawdust and sub-bituminous coal in a downdraft gasifier

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**Abstract**
The paper is an experimental study of the gasification process of sawdust (SW), sawdust pellet (SWP) and sub-bituminous coal (SBCoal) by using downdraft gasifier. The gasification was undertaken in a lab-scale fixed-bed gasifier operating under air as an oxidizing agent. The comparison on the raw biomass, treated biomass and coal was assessed in term of the product gas and gasification performance at a fixed condition of gasification temperature of 750 °C and equivalence ratio of 0.25. The gasification performance was tabulated in the form of calorific value of the syngas ($HHV_{syngas}$), gasification efficiency ($X_{CGE}$) and carbon conversion efficiency ($X_C$). It was denoted that SWP produces the highest $H_2$ and the lowest $CO_2$. Furthermore, SBCoal possesses the highest gasification performance among the three feedstocks. Besides, the influence of the temperature between SW, SWP and SBCoal was evaluated at the equivalence ratio of 0.25. The findings demonstrate that rising the temperature, $H_2$ and CO for SW, SWP and SBCoal are increase. The volume of the $CO_2$ is constant as the temperature increases. In contrast, the $CH_4$ decreases with increase in the gasification temperature. As the gasification temperature increases, $HHV_{syngas}$ and $X_{CGE}$ of SW and SWP are increasing; meanwhile, SBCoal shows the opposite results. Simultaneously with rising gasification temperature, the $X_C$'s of the SW, SWP and SBCoal are increasing.

**Keywords** Gasification · Pelletization biomass · Calorific value · Gasification efficiency · Carbon conversion efficiency

## 1 Introduction

The possible depletion of the conventional fossil fuels in the future, as well as environmental pollution, has been brought upon due to extreme usage. This phenomenon has ignited the countries to search for the promising solution that is renewable, environmentally friendly, sustainable, economically and lessen the current environmental issues. In recent years, it has been discovered that biomass have been used widely as renewable energy and accounted for about 14% of the total energy consumption [1]. Regards to this, gasification of the biomass and coal seems to be attractive technology that produce the energy-rich gaseous product that can be used further for power generations [2]. The substitution from combustion to gasification is due to the combustion process that resulted severe air pollution problems by emitted a vast amount of carbon dioxide, particularly in the coal-fired power plants. Hence, it is essential to operate it more cleanly. Gasification play an important role in the implementation the clean coal technology by transformed the coal into syngas ($H_2$, CO, $CH_4$ and $CO_2$) in an insufficient oxygen environment. Sawdust, which is the abundant waste resources obtained from the wood industries, have been approved its potential on the syngas composition and gasification performance [3, 4]. Gasification of coal also have been carried out on the several types of coal that concluded each different types of coal properties

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gave influence on the gasification performance [5]. Generally, biomass has low energy density and is widely spread properties resulted in an adverse effect in terms of collection and transport cost. Tumuluru et al. [6] proposed that pre-treated of the feedstock is capable of overcoming the biomass limitations and resistance in the biofuels production, eventually aids in enhance the physical and chemical properties of the feedstock to allow higher percentages of feedstock in the fuel application. Furthermore, the authors also found out that the torrefaction and densification of torrefied feedstock of the biomass for bioenergy utilizations capable of performing similarly like coal in terms of physical, grinding, chemical, and storage properties with the higher volatiles content [7].

Gasification of pellet fuel has widely been applied in the commercial gasification [8] that produce the syngas composition in much more stable condition by maintaining the gasification more steady and efficient. The uniform shape and density of the pellet fuels ease during the feeding operation thus provide less of a biomass bridge and gasification reactions [9]. The results denoted that pellet fuels improve the gasification performance such as higher syngas heating value, higher cold gas efficiency and others when comparing with its raw biomass. Based on these merits, pelletized biomass is frequently applied in gasification, especially in fixed-bed gasifiers where, mechanically substantial fuel particles of limited size are required for successful operation [10]. A handful of studies have been carried out on the potential of the fuel pellets on its effect towards the syngas composition and gasification performance that resulted in different perspectives. Erlich et al. [11] highlighted that pelletized biomass generally not suitable for gasification than raw materials. The authors are taken into account the influence of the equivalence ratio and analyse the evolution of the pelletized material together with the influence on the gas pressure drop across the char bed. Simone et al. [12] also utilized the several pelletized biomass in a pilot-scale downdraft gasifier to investigate the feasibility and reliability of the gasification and provide new process data set on the gasification performance. The results denoted that pelletized biomass is unfavourable for downdraft gasifiers. This is due to high-pressure drops, difficult gasifier control and fragmentation of the gasification residues. On the contrary, the syngas composition and gasification performance were relatively good and can be served as complementary feedstock to enhance the energy content per unit volume and minimize the moisture content of the biomass. Overtime, Aydin et al. [13] demonstrate gasification between pine cone particle and wood pellet in a fixed bed downdraft gasifier. It is apparent that the cold gas efficiency of the wood pellet possesses 80% higher than pine cone particle, 60%. Moreover, the optimal gasification temperature interval for the wood pellet is much lower than the pine cone particle at 850–900 °C; meanwhile, the pine cone particles is at 900–950 °C. Even though the pelletized biomass has been utilized as a feedstock in gasification or combustion system; however, there is no reliable and precise data on the utilization of fuel pellet potential with the reason for the improvement in the efficiency of the pelletized case gasification is not apparent [14]. To the author knowledge, there is still a lack of the studies in comparing the gasification performance of pelletized biomass with its parent biomass [15]. Hence, there is a need to investigate the potential of the fuel together with the fuel in the pellet form and coal comparatively to strengthen the biomass utilization potential besides contributing towards development of the sustainable bioenergy network.

In the present study, gasification of the raw biomass (sawdust, SW), densification biomass (sawdust pellet, SWP) and sub-bituminous coal (SBCoal) were investigated in the fixed-bed downdraft gasifier. The syngas composition and gasification performance were evaluated. The gasification performance that was investigated are the calorific value of the syngas ($HHV_{syngas}$), gasification efficiency ($X_{CGE}$) and carbon conversion efficiency ($X_C$). Furthermore, the syngas composition and gasification performance between SW, SWP and SBCoal are compared at different gasification temperature at 650 °C, 750 °C and 850 °C.

This paper is structured as follows. Section 2 introduces the feedstock involved as well as the experimental setup for the evaluation of the gasification process. Section 3 revealed the characteristics of the feedstock, the syngas composition and gasification performance. The influence of the various gasification temperature on syngas composition and gasification performance was covered in Sect. 3.3.1 and Sect. 3.3.2, respectively. Finally, Sect. 4 presents the conclusions.

## 2 Material and methods

### 2.1 Feedstock material and characterization

The feedstock used in this study were sawdust (SW) obtained from the wood industry located in Penang in Malaysia, and sawdust pellet (SWP) were also produced from the same factory without the addition of the binder. The sawdust which is in the powder form, is dried and then fed into the extruder pellet machine. The pellets then were produced and cooled with an air cooling process before proceeding to manufacture. Meanwhile the sub-bituminous coal (SBCoal) is received from the electric utility company in Malaysia through the third-party company. Figure 1 shows the photograph of the feedstock. The characteristics of the feedstock

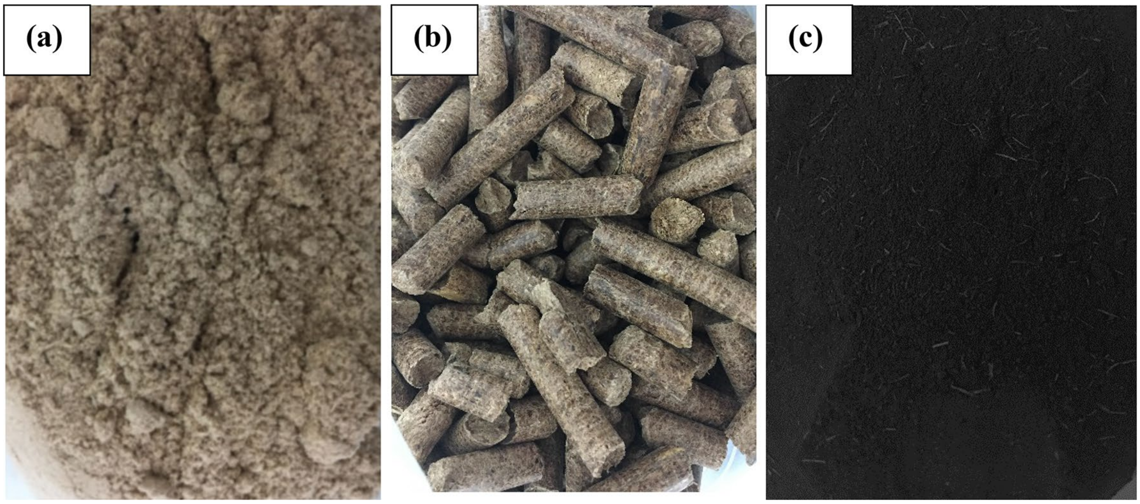


**Fig. 1** The picture of sawdust, sawdust pellets and sub-bituminous coal

in terms of the proximate analysis and ultimate analysis was determined according to the ASTME1131 [16] and ASTM D3176 [17], respectively. Furthermore, the heating value of each feedstock was investigated using bomb calorimeter branded IKA C200.

## 2.2 Gasification experiment

Figure 2 shows the schematic diagram of the gasification system used throughout the whole gasification process for each feedstock that located at the biomass laboratory, under Department of Mechanical Engineering, Universiti Teknologi Petronas (UTP), Perak. The gasification system was comprised into three main units: the gasifier reactor,

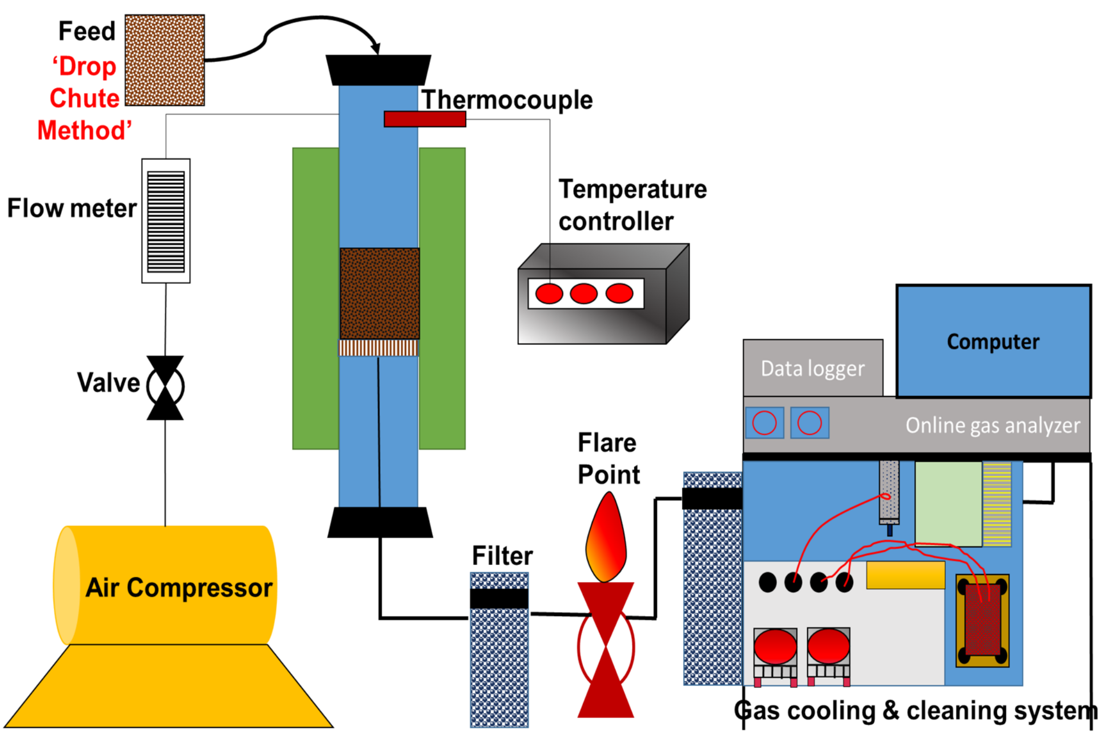


**Fig. 2** The schematic diagram of the lab-scale downdraft fixed bed gasification system

the gas cleaning and cooling machine and gas analyzer. The total height of the gasifier reactor is 500 mm with the internal diameter of 80 mm. The air was introduced into the gasifier reactor as an oxidizing agent by the compressed air from the top side of the gasifier reactor. Furthermore, the rotameter was attached beside the gasifier reactor functioning to measure and control the airflow rate. An electric furnace was enclosed around the gasifier reactor to generate heat to the reactor. The remaining solids of the feedstock that falls to the lower part of the grate was collected at the opening bottom together with the gas discharge hole that located in the low end part of the gasifier reactor.

To operate the gasification system, the air compressor was flushed with the desired amount of volume for 10 min before the experiment to achieve a stable state. Consequently, the gasifier reactor was heated to desire gasification temperature. When the gasifier reactor achieved a stable state with the desired gasification airflow rate and temperature, approximately 100 g of feedstock was loaded at the top of the gasifier reactor by applying drop-chute method. In order to make the equivalence ratio, ER fixed at 0.25; different airflow rate was introduced for each feedstock. The airflow rate fixed for SW, SWP and SBCoal was at 2.8055 L/min, 2.7178 L/min and 3.5230 L/min, respectively. ER is defined as the ratio between the amounts of air introduced into the gasifier reactor with the stoichiometric oxygen needed for complete combustion of the feedstock. The syngas produced was flowed through the gas cleaning and cooling system that associated with the gas analyzer. Generated syngas compositions for about 15 mins were collected in the data logger for further analysis. After the end of the gasification process, the electric furnace and air compressed was switched off, and the gasifier was left to cool until it reaches the ambient temperature or safe to be handled for the next experiment. Furthermore, the collected remaining residue was weighed using a precision weight balance once it reached the room temperature.

The gasification among the sawdust (SW), pelletized sawdust (SWP) and sub-bituminous coal (SBCoal) were investigated on the syngas composition ($H_2$, CO, $CH_4$ and $CO_2$) and gasification performance. The gasification performance in term of the calorific value of the syngas ($HHV_{syngas}$), gasification efficiency ($X_{CGE}$) and carbon conversion efficiency ($X_C$) were calculated and tabulated. The calorific value of the syngas ($HHV_{syngas}$) was calculated as it is an essential parameter that defines the quality of syngas produced from gasification in terms of energy content per unit volume or mass. The calorific value of the syngas ($HHV_{syngas}$) was calculated by taking into account the volume percentage of combustible gas components in the syngas (CO, $H_2$ and $CH_4$) produce from the co-gasification experiment with their specific calorific value according the US National Renewable Energy Laboratory (NREL) in the unit of MJ/Nm$^3$ as per standard value, expressed in the following Eq. (1) [18].

$$HHV_{syngas} = \left(V_{CO} \times 12.63\right) + \left(V_{CH_4} \times 39.82\right) + \left(V_{H_2} \times 12.74\right) \quad (1)$$

where V is defined as the volumetric percentage for each of CO, $CH_4$ and $H_2$ obtained from online gas analyzer measurements. In addition, the gasification efficiency ($X_{CGE}$) is defined as the ratio between chemical energy leaving the system associated with the cold and tar-free syngas and the chemical energy entering the system related to the biomass in the unit of percentage [19]. Generally, the $X_{CGE}$ was calculated by considering the specific gas production and the energy content of the biomass by following the Eq. (2).

$$X_{CGE} = \frac{HHV_{syngas}}{HHV_{feed} + Q} \times 100 \quad (2)$$

where $HHV_{syngas}$ is the calorific value of the syngas in the unit of MJ/Nm$^3$ divided by the $HHV_{feed}$ calorific value of the feedstock in the unit of MJ/kg. Meanwhile, the carbon conversion efficiency ($X_C$) was calculated to measure the amount of carbon in the feedstock that converted into gaseous [20]. The $X_C$ was calculated as following Eq. (3) [21].

$$X_C = \frac{12 \times A}{m_{feed} \times x_c} \times 100 \quad (3)$$

where A is the total number of moles of carbon-bearing components taken into account in the production of the syngas which are CO, $CH_4$ and $CO_2$; $m_{feed}$ is the mass of feedstock introduced to the reactor and $x_c$ is the mass fraction of carbon in the ultimate analysis of each feedstock.

## 3 Result and discussion

### 3.1 Feedstock characteristics

Table 1 presents the proximate, ultimate, and heating value analysis of each feedstock. It has been discovered that the value of the proximate analysis for each gasification feedstock are in the range of data recorded by other researchers [22–24]. As expected, the moisture content in SWP (9.19%) reduced from 11.80% (SW) due to thermal pre-treatment process in densification that is subjected to mechanical force during the manufacturing process [6]. The volatile matter of the biomass (SW and SWP) are marked almost twice of the SBcoal as reported by Long and Wang [25] and Thengane et al. [26]. SBCoal possesses the highest ash content that explained it partly attributed

**Table 1** The proximate, ultimate, heating value and the dimensions of SW, SWP and SBCoal

| | Sawdust (SW) | Sawdust pellet (SWP) | Sub-bituminous coal (SBCoal) |
|---|---|---|---|
| Proximate analysis (wt%) | | | |
| Moisture content | 11.8 | 9.19 | 8.18 |
| Volatile matter | 68.05 | 79.00 | 39.79 |
| Fixed carbon[a] | 19.05 | 10.16 | 33.81 |
| Ash content | 1.10 | 1.65 | 18.22 |
| Ultimate analysis (wt%) | | | |
| Carbon | 44.11 | 44.28 | 52.58 |
| Hydrogen | 5.53 | 6.09 | 5.90 |
| Nitrogen | 2.14 | 1.05 | 1.49 |
| Oxygen[a] | 45.52 | 48.62 | 38.90 |
| Sulfur | 2.70 | 0.28 | 1.14 |
| Heating value (MJ/kg) | 17.17 ± 0.089 | 17.46 ± 0.085 | 20.19 ± 0.082 |
| Dimensions (mm) | 0.00362 | 10–50 | 0.00747 |

[a]By difference

to the multiple catalytic components in the ash that promote char gasification within the gasification process [27]. Meanwhile, the carbon content in SBCoal is much highest at 52.58% compared to SW and SWP with 44.11% and 44.28% respectively. This was expected due to the nature properties of the SBCoal that formed about 300 million years ago at the right heat and pressure by extracting out the oxygen and hydrogen and eventually produced carbon-rich combustible mineral. Furthermore, SWP denoted much lower N and S content than SW and SBCoal. Significantly, the highest sulfur content in feedstock is unfavorable as it might cause corrosion on the metallic parts of the gasification installation and produce syngas that adverse for methanol synthesis. It can be seen that decreasing order of HHV from SBCoal ˃ SWP ˃ SW with the amount of HHV for each CL, SD and WP are also in the range with other researchers [28, 29]. Furthermore, SWP recorded the large sizes at 10–50 mm due to its pelletized form followed by the SBCoal (0.00747 mm) and SW (0.00362 mm) in which existed in the powder form.

### 3.2 Syngas composition

Figure 3 displays the profile for each fuel sample (a-b) as well as the average volume percentage of $H_2$, CO, $CH_4$ and $CO_2$ in syngas composition calculated for 15 min from the three fuels (d) under the operating condition of the gasifier where gasification temperature at 750 °C and ER at 0.25. Generally, for all the syngas composition for each feedstock are in the decreasing order from $CO_2$ ˃ $H_2$ ˃ CO ˃ $CH_4$. For the SW, the volume of the $H_2$ is deficient than SWP and SBCoal might be due to most of the atomic hydrogen in the raw biomass is converted to $H_2O$ [30]. When gasified the pelletized sawdust, the $H_2$ is raised significantly at 11% whereas the CO formation is close to that of the SBCoal's value. This results clearly marked that densification is capable of facilitating syngas formation from biomass gasification, and this phenomenon is qualitatively in-line with the results obtained from Aydin et al. [13]. Moreover, this is due to the fact that the pelletization process of the SWP reduce the moisture content of the SW making the biomass structure regularly and enhance the gasification process much more stable as compared to the powdered SW and SBCoal [31]. The irregular shape and powdered SW and SBCoal are difficult to handle as it is easier to disperse to the atmosphere especially during the loading stage. This resulted solely small amount of the SW and SWP in contact with the oxidizing agent. For the coal gasification, the $H_2$ formation is found at 8%. Both the SWP and SBCoal shows significantly high $CO_2$ as most of the CO is transformed to $CO_2$ during the water–gas shift reactions within the gasification process. $CH_4$ for SW, SWP and SBCoal marked the lowest percentage averagely 5% for the syngas composition.

### 3.3 Gasification performance

The gasification performance in terms of the $HHV_{syngas,}$ $X_{CGE}$ and $X_C$ between the SW, SWP and SBCoal is exhibited in Fig. 4. The increasing order of the $X_{CGE}$ is from SW < SWP < SBCoal with the highest $X_{CGE}$ is calculated at 24%. In contrast, the $X_{CGE}$ for the SW and SWP are close to each other approximately 20%. It can be seen that the difference between biomass and coal is around 5%. The value of the $X_C$ possesses the same order as $X_{CGE}$. The $X_C$ of the SW is boost by a factor 0.90 after undergoes pelletization.

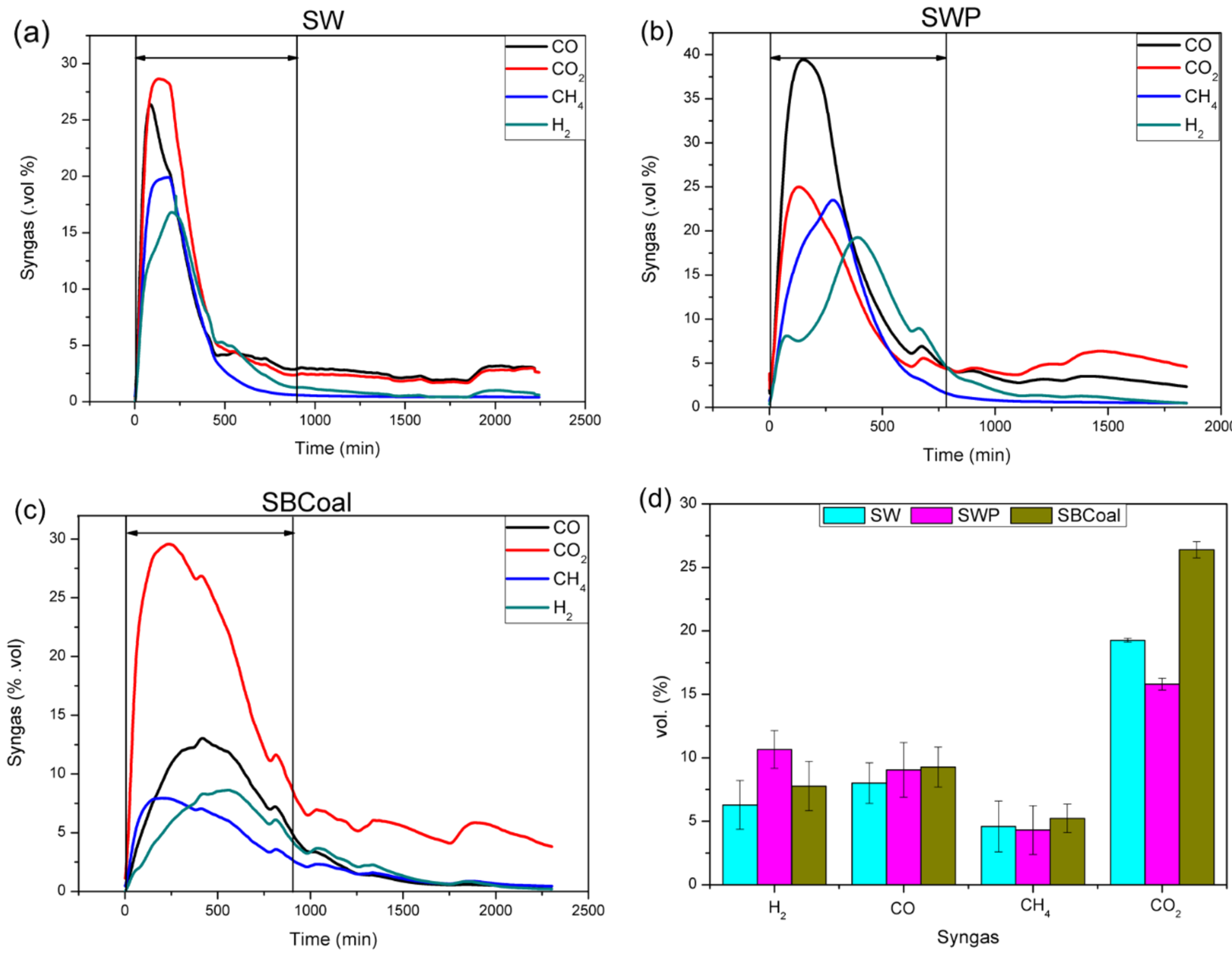


**Fig. 3** The syngas composition for **a** SW, **b** SWP, **c** SBCoal against time with the **d** average volume percentage for 15 min of $H_2$, CO, $CH_4$ and $CO_2$ in syngas composition at gasification temperature and ER fixed at 750 °C and 0.25, respectively

The lowest $X_{CGE}$ and $X_C$ of the raw sawdust are due to the highest formation of $CO_2$ as well as to the lowest production of the $H_2$ and CO in the syngas composition. Meanwhile, the difference in the $X_C$ between SW and SBCoal is around 30%. However, it should be pointed out that a high $X_C$ value does not account certainly resulted in better gasification performance. Despite that, $X_C$ of the SW is increased by 20% from the pelletization process that removes the moisture content from the mechanical force eventually forms the highest $H_2$ in syngas composition. These results agree well with the findings of Yoon et al. [9]. Nevertheless, the $HHV_{syngas}$ are also possessed the same order as both $X_{CGE}$ and $X_C$. The $HHV_{syngas}$ of the SW is amplified by 15% when undergoes pelletization. Both of the $HHV_{syngas}$ for SWP and SBCoal are almost the same calculated at 4.2152 MJ/Nm$^3$ and 4.2423 MJ/Nm, respectively. Despite the high $H_2$ yield from the SWP gasification, the $HHV_{syngas}$ of the SBCoal recorded slightly highest than SWP probably due to the slightly higher of the CO and $CH_4$ calculated from the average syngas components from the SBcoal gasification.

### 3.3.1 Syngas composition at various gasification temperature

The influence of the gasification temperature on the three feedstock with the syngas composition is presented in Fig. 5. Obviously, the rise of the gasification temperature resulted in the increasing of the $H_2$ and CO for SWP and SBCoal. The $H_2$ and CO are in the range of 5–12% and 6–11%, respectively. Both of the highest $H_2$ and CO are produced from the gasification of SWP. Meanwhile, $CO_2$ generates a constant value as the temperature increase. It is apparent that by increasing the gasification temperature, the $CO_2$ was dissipated through the Boudouard reaction, thereby increasing the production of CO gasification

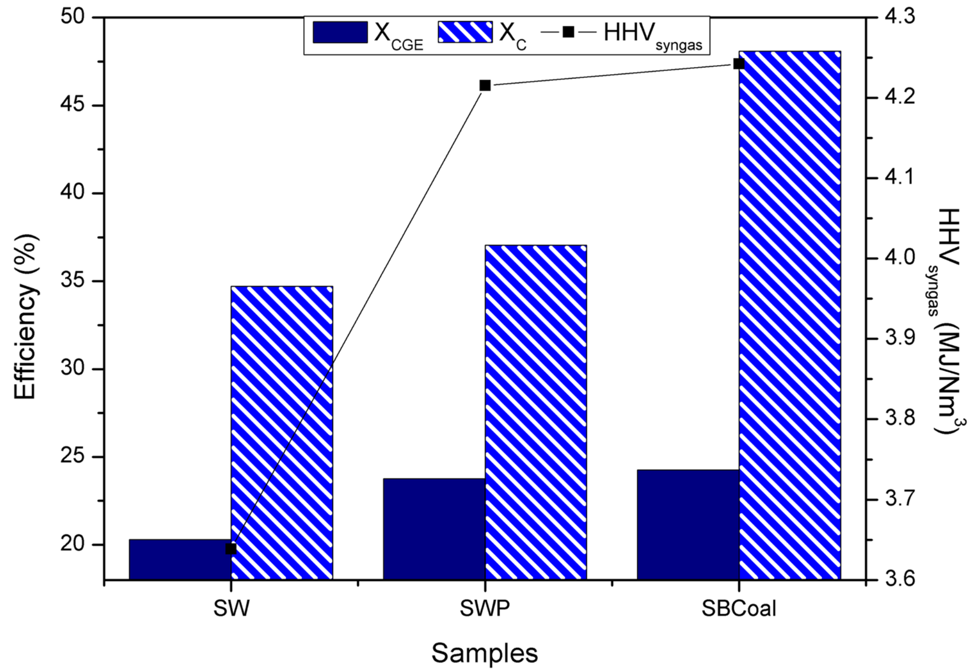


**Fig. 4** HHV$_{syngas}$, $X_{CGE}$ and $X_C$ for SW, SWP and SBCoal with the gasification temperature and ER fixed at 750 °C and 0.25, respectively

[32]. However, for the SWP, it can be found that at 750 °C, the $CO_2$ show a little dropped down and rise back as the temperature increase. This might be some reaction error that occurs during the experimental process within the gasifier reactor. Despite the adverse, throughout the experiment, the syngas production from SWP showed higher stability over time without critical variation. This is because the SWP enhanced the energy density per unit volume, uniformity and defined form of fuels. In contrast, $CH_4$ is decreased as the gasification temperature increased.

### 3.3.2 Gasification performance at various gasification temperature

Figure 6 displays the gasification performance against the various temperature. The HHV$_{syngas}$ was ranged from 3.3029 to 4.6523 MJ/Nm$^3$, and these values agreed well with that reported in the literature [33–35]. It can be seen that as the temperature raised, the HHV$_{syngas}$ of the biomass is increased with the highest HHV$_{syngas}$ achieved by SWP at 850 °C. On the other hand, the HHV$_{syngas}$ of the SBCoal marked down with the increasing of the temperature. This is strongly associated with the fuel properties, particularly due to the high ash content together with the lowest volatile content of the SBCoal [22]. Thus, it results in the low calorific value and syngas productions at temperature of 850 °C. Similarly, Adeyemi et al. [36] stated that the increase of the HHV$_{syngas}$ is related to the higher gasification temperature due to the endothermic gasification reactions. As a consequence, more heat losses to the system and enhanced the syngas production from the pyrolysis, steam reforming, gasification and cracking reactions that occur inside the gasifier reactor. This emphasized that SWP can be substitute with SBCoal at highest gasification temperature. It also can be seen that $X_{CGE}$ follows the same patterns as HHV$_{syngas}$. Increasing the gasification temperature resulted in the increasing of the SW and SWP instead for SBCoal conditions. As the $X_{CGE}$ related to the ratio between the calorific value of the syngas production and biomass, the lowest HHV$_{syngas}$ of the SBCoal at 850 °C leads to the lowest value of the $X_{CGE}$. The $X_{CGE}$ was ranged from 17 to 28% with the highest and lowest $X_{CGE}$ were achieved by SWP and SW, respectively. The values are in-line with the study conducted by Simone et al. [12] on the various biomass pellet by the factor of 1.5 as the authors perform the gasification in the pilot-scale. In the view of the $X_C$, all the feedstock possesses the same pattern in which increasing of the gasification temperature leads to the increased of the $X_C$. The $X_C$ was ranged from 20 to 50% in which the SBCoal achieved the highest. This might be due to the vast production of $CO_2$ at 850 °C and its nature properties. In additional, Taba et al. [37] highlighted that $X_C$ increase with increasing of the temperature due to the oxidation and gasification reactions that resulted in the highest yield of gases from the fuels. It can be noted that the value of the $X_C$ that consider the amount of carbon-mole production in the syngas composition of the SW and SWP are almost the same. The amount of CO, $CO_2$ and $CH_4$ production in the syngas composition for both SW and SWP are in the ranged of 7–11%, 15–19% and 4–6%, respectively.

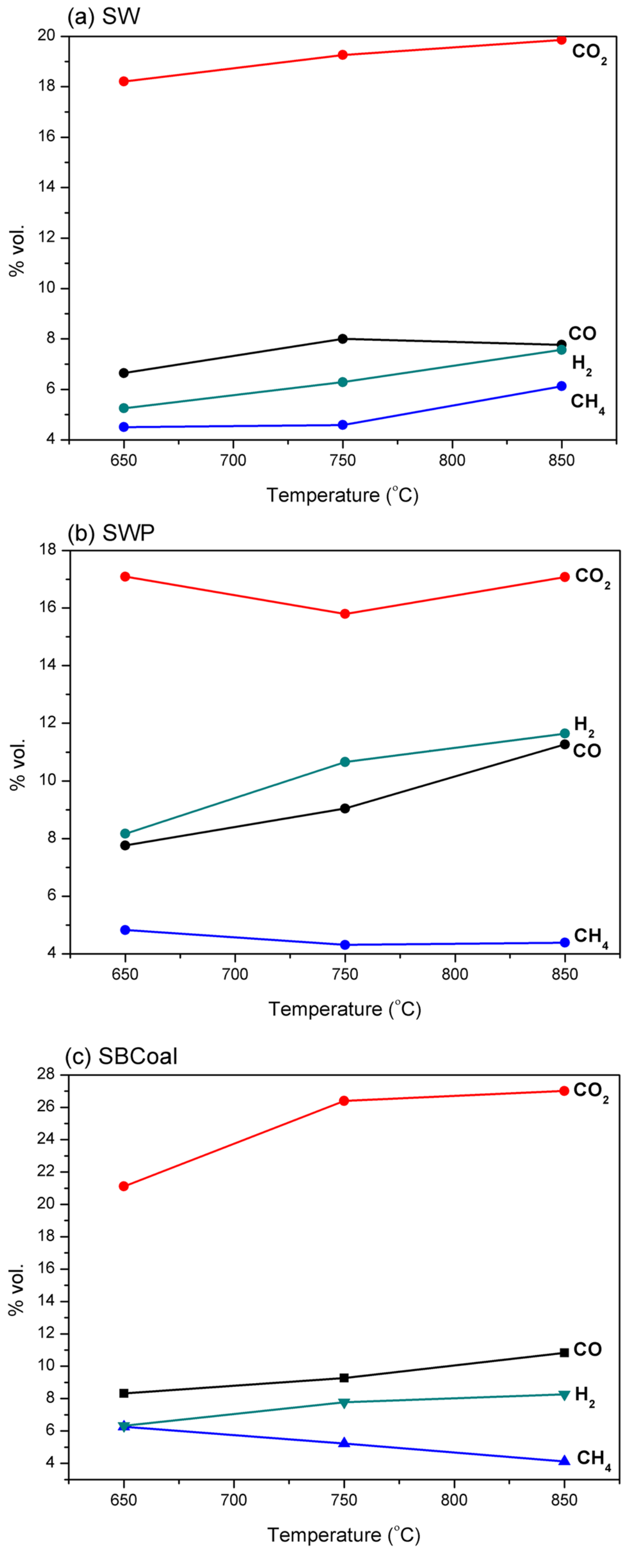


**Fig. 5** Variations of syngas composition from the gasification **a** SW, **b** SWP, and **c** SBCoal versus gasification temperatures

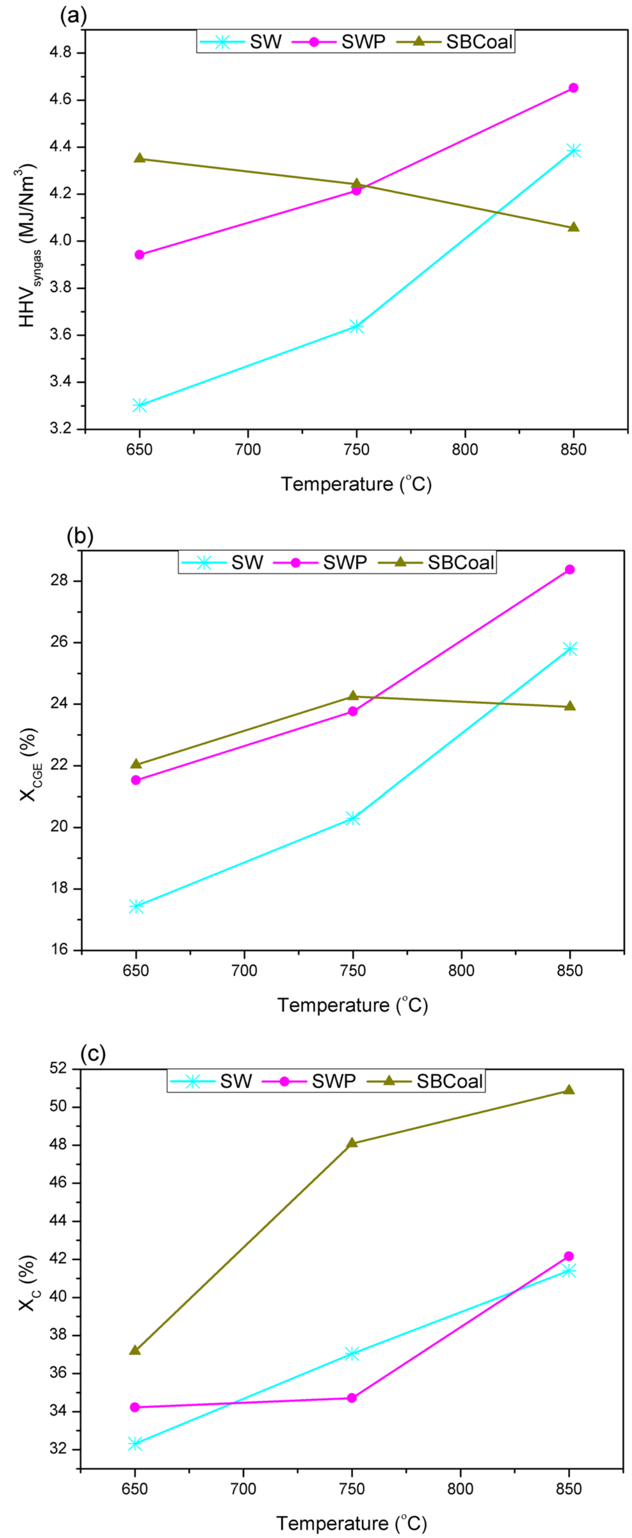


**Fig. 6** Distribution of the **a** $HHV_{syngas}$, **b** $X_{CGE}$ and **c** $X_C$ at various gasification temperature with ER fixed at 0.25

## 4 Conclusions

The syngas composition and gasification performance of three different fuels, including sawdust (SW), pelletized sawdust (SWP), and sub-bituminous coal (SBCoal) in the fixed bed downdraft gasifier are investigated. The syngas composition and gasification performance at the fixed gasification temperature and ER of 750 °C and 0.25 were determined. SWP resulted in the highest syngas production of $H_2$ and CO at 11% and 9%, respectively. Meanwhile, SW recorded the lowest $H_2$ and CO at 6% and 8%, respectively. In term of the gasification performance, SBCoal calculated the highest $HHV_{syngas}$, $X_{CGE}$ and $X_C$ at 4.2423 MJ/Nm$^3$, 24% and 48%, respectively. Meanwhile, the second-order highest is achieved by SWP at $HHV_{syngas}$, $X_{CGE}$ and $X_C$ calculated at 4.2152 MJ/Nm$^3$, 24% and 37%, respectively. To sum up, SWP has the potential to acts as a complementary fuel for coal. The syngas composition and gasification performance of the SW, SWP and SBCoal at various gasification temperature from 650 to 850 °C with ER fixed at 0.25 was also evaluated. In view of the syngas composition, $H_2$ and CO for all feedstock show the increasing volume percentage as the temperature increased. The CO shows constant value with the rising of gasification temperature. Meanwhile rising the gasification temperature, the $HHV_{syngas}$ and $X_{CGE}$ of the biomass are increasing, in contrast to the SBCoal. SBCoal calculated the lowest $HHV_{syngas}$ and $X_{CGE}$ at 850 °C at 4.0568 MJ/Nm$^3$ and 24%, respectively. The $HHV_{syngas}$ and $X_{CGE}$ of the SW were increased by 15% and 19%, respectively as it pre-treated to pellet fuel. Conversely, increasing the gasification temperature, the SW, SWP and SBCoal indicated the increase of the $X_C$. SBCoal recorded the highest $X_C$ at 850 °C with 50%. Meanwhile, the $X_C$ of the SW increased averagely by 6% as it pre-treated to SWP. Looking ahead, several parameters such as moisture content gasifier types, etc. need to be addressed to emphasize the potential of the pellet fuel with the fossil fuels for generating energy. Meanwhile, the major challenges emerging from the current work, which must receive significant attention, are the adaptation of the continuous mode for the gasification process to investigate the efficiency of the selected material for a period of time to simulate the actual principle in a power plant.

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### Compliance with ethical standards

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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