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ORIGINAL ARTICLE

Experimental Studies on Gasification Performance of Sawdust and Sawdust Pellet in a Downdraft Biomass Gasifier

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ABSTRACT – In this work, a comparative analysis of the gasification process of sawdust (SW) and sawdust pellet (SWP) utilizing a downdraft gasifier was performed. The gasification was conducted in a research-scale fixed-bed gasifier applying air as an oxidizing agent. The comparison between the raw (sawdust, SW) and treated biomass (sawdust pellet, SWP) was investigated for the syngas composition and gasification performance at the fixed condition of gasification temperature at 750 °C and equivalence ratio of 0.25. The gasification performance was tabulated in the form of heating value of the syngas (HHV_{syngas}), gasification efficiency (η_{GE}) and carbon conversion efficiency (η_{CCE}). It was found out that SWP produced the highest H_2 and the lowest CO_2. Furthermore, SWP also present the better gasification performance than SW. SWP achieved the high HHV_{syngas}, η_{GE}, and η_{CCE} at 4.2152 MJ/Nm^3, 24% and 37%, respectively.

KEYWORDS
gasification
pelletization biomass
heating value
gasification efficiency
carbon conversion efficiency

INTRODUCTION

The demand for energy sources for human need has tremendous increase. Hence, possible depletion of the conventional fossil fuels in the future, as well as environmental pollution, has been brought upon due to extreme usage. There is an urgency to search for the promising solution that is renewable, environmentally friendly, sustainable, economically and lessen the current environmental issues. Given these circumstance, biomass have been consume widely as renewable energy and accounted for about 14% of the total energy consumption (IRENA, 2012). Regarding to this issue, gasification of the biomass seems to be attractive technology that generate the energy-rich gaseous product that can be used further for power generations (Mallick et al., 2018). Gasification play an important role converting the biomass fuel into syngas (H_2, CO, CH_4 and CO_2) or combustible gas mixture (Wasinarom & Charoensuk 2019) in an insufficient oxygen environment. Sawdust, which is the abundant waste resources acquired from the wood industries, have been agreed for its potential on the syngas composition and gasification performance (Mansur et al., 2019; Mishra and Mohanty 2018; Susastriawan et al., 2019). Biomass which is present in the low energy density and widely spread properties resulted in an opposing consequences for collection and transport cost. Thus, Yang and Kumar (2018) proposed that pre-treated of the fuels is capable of solving the biomass limitations and resistance in the biofuels production and significantly aids in enhance the physical and chemical properties of the biomass thus allow higher usage of biomass in the fuel industry. It have been highlight that pretreatment is defined as all intermediate process steps that taken on the biomass resources being modified either by physical or chemical characteristics before used in the final conversion (Stapf et al., 2019). The process are including sorting, separation, mechanical size reduction and biological treatment.

Gasification of pellet fuel has widely been used in the commercial gasification (Djatkov et al., 2018; Kumar et al., 2017; Puig-Arnavat et al., 2016) that the syngas composition produced are much more stable as well as the gasification are much more steady and efficient. This is due to the uniform shape and density of the pellet fuels ease during the feeding operation thus provide less of a biomass bridge and gasification reactions (Yoon et al., 2012). This resulted that pellet fuels enhance the gasification performance such as higher syngas heating value, higher cold gas efficiency and others when comparing with its raw biomass. Based on these qualities, 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 (Hu et al., 2017). 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. Simone et al., (2012) 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. It has been found out that the syngas composition and gasification performance were comparatively good and can be served as complementary feedstock to enhance the energy content per unit volume and minimize the moisture content of the biomass. Moreover, Sarkar et al., (2014) also found out that the torrefaction and densification of torrefied biomass for bioenergy utilizations capable of

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performing similarly like coal in terms of physical, grinding, chemical, and storage properties with the higher volatiles content. Additionally, Aydin et al., (2019) performed the gasification between pine cone particle and wood pellet in a fixed bed downdraft gasifier. The results revealed that the cold gas efficiency of the wood pellet possesses 80% higher than pine cone particle, 60% with the optimal gasification temperature interval for the wood pellet is much lower than the pine cone particle. The optimal gasification temperature for wood pellet is set at 850-900 °C; in contrast, the pine cone particles is at 900-950 °C. Despite the fact the pelletized biomass has been utilized as a feedstock in gasification or combustion system; yet, there is no reliable and precise data on the consumption of fuel pellet potential with the reason for the improvement in the efficiency of the pelletized case gasification is not apparent (Pradhan et al., 2018). To the author knowledge, there is scarce of the studies in comparing the gasification performance of pelletized biomass with its parent biomass (Yang & Kumar 2018).

In the present study, gasification of the raw biomass (sawdust, SW) and densification biomass (sawdust pellet, SWP) were investigated in the fixed-bed downdraft gasifier. The syngas composition and gasification performance were evaluated. The gasification performance that was investigated are the heating value of the syngas (HHV_{syngas}), gasification efficiency (η_{GE}) and carbon conversion efficiency (η_{CCE}).

MATERIALS AND METHODS

Materials & characterization Chemicals

The fuel used in this study were sawdust (SW) and sawdust pellet (SWP) shown in Figure 1 obtained from the wood factory at Nibong Tebal located in northern area of Malaysia. The SWP was produced in the factory without the addition of the binder using the extruder pellet machine and undergoes air cooling process before proceeding to manufacture. The proximate analysis and ultimate analysis of the fuel was investigated based on the ASTME1131 (ASTM E1131-98, 1998) and ASTM D3176 (ASTM D3176-09, 2009), respectively. Moreover, the heating value of each fuel was performed using bomb calorimeter typed IKA C200.

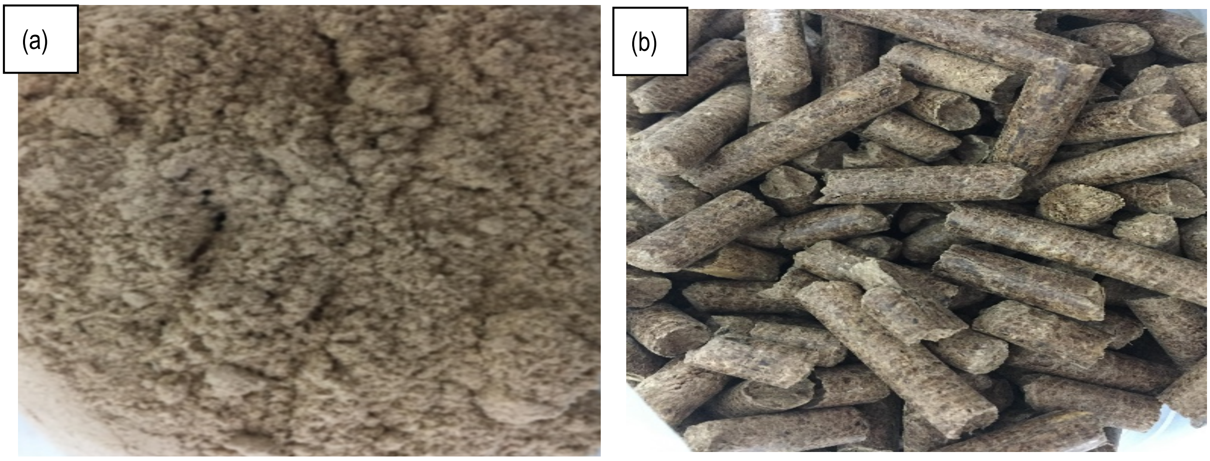

Figure 1. The picture of (a) SW and (b) SWP.

Gasification experiment

The gasification system used throughout the whole gasification process is displayed in Figure 2 that located at the biomass laboratory, under Department of Mechanical Engineering, Universiti Teknologi Petronas (UTP), Perak. The gasification system was consist of three main units: the gasifier reactor, the gas cleaning associated with cooling machine and gas analyzer. The gasifier reactor had an inner diameter of 80mm and a height of 500mm and was covered with 50mm of ceramic fiber to avert heat dissipation. Air acts as oxidizing agent was introduced at the top side of the reactor into the gasifier reactor using the compressed air located at the bottom side of the gasifier reactor. In additional, the attached rotameter beside the gasifier reactor was used to measure and control the airflow rate. The electric furnace was enclosed around the gasifier reactor was operated to generate heat to the reactor. Meanwhile, the remaining solids of the fuel that produced was collected at the low end part together with the gas discharge hole of the gasifier reactor.

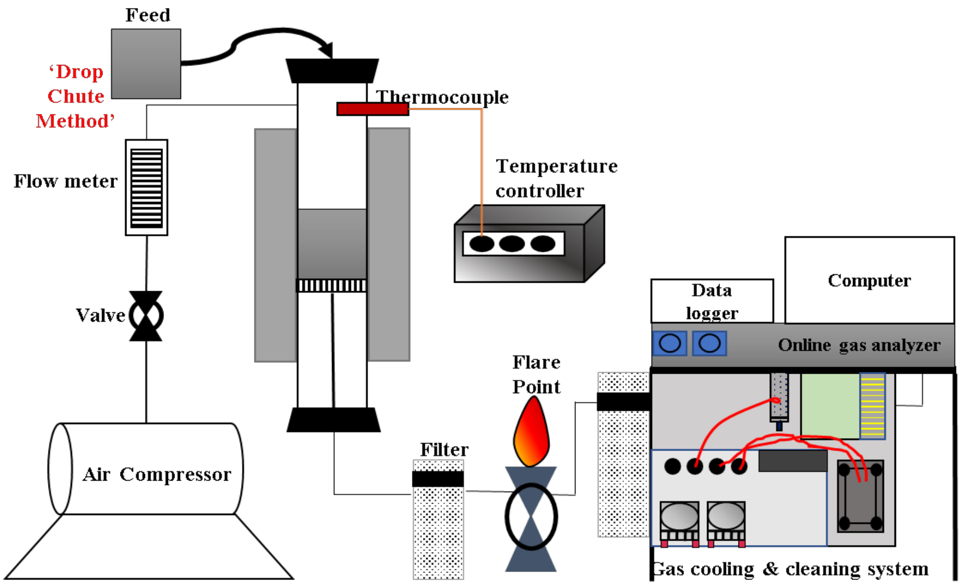

Figure 2. The schematic diagram of the lab-scale downdraft fixed bed gasification system.

Firstly, air was introduced and temperature was adjusted at the desired amount for 10 min before the experiment to achieve a stable state. Once, the gasifier reactor achieved the stable state with the desired gasification airflow rate and temperature, then, approximately 100 g of fuels was poured at the top of the gasifier reactor by applying drop-chute method. The temperature of the gasification process are set at 750 °C as it was the optimal temperature obtained from the preliminary experiment. As the equivalence ratio, ER fixed at 0.25; different airflow rate was introduced for each fuel which for the SW was at 0.2062 L/min, while for the SWP was at 0.1998 L/min. It is noted that 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 fuels. The syngas produced was flowed downward to the gas cleaning and cooling system that associated with the gas analyzer. The composition of the syngas produced was recorded and collected from the data logger for further analysis. The solid remaining residue were collected after the gasifier reactor was switched off and left to cool. The mass of the remaining solid residue were weighed using a precision weight balance and recorded.

The gasification of the sawdust (SW) and pelletized sawdust (SWP) were investigated on the syngas composition (H_2, CO, CH_4 and CO_2) and gasification performance. The gasification performance was evaluated for the heating value of the syngas (HHV_{syngas}), gasification efficiency (η_{GE}) and carbon conversion efficiency (η_{CCE}). The heating value of the syngas (HHV_{syngas}) was defines as the quality of syngas produced from gasification in terms of energy content per unit volume or mass. Moreover, the heating value of the syngas (HHV_{syngas}) was calculated by considering the volume percentage of combustible gas components in the syngas (CO, H_2 and CH_4) produce from the gasification experiment with their specific heating value according the US National Renewable Energy Laboratory (NREL) in the unit of MJ/Nm^3 as per standard value, expressed in the following Equation (1) (Basu, 2010).

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

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 (η_{GE}) 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 expressed in the unit of percentage (Shi, 2016). Basically, the η_{GE} was calculated by taken into account the specific gas production and the energy content of the biomass by following the Equation (2).

$$\eta_{GE} = \frac{HHV_{syngas}}{HHV_{fuel}} \times 100 \quad (2)$$

Where HHV_{syngas} is refer to the value of the syngas in the unit of MJ/Nm^3 divided by the HHV_{fuel} heating value of the fuels in the unit of MJ/kg. The HHV_{fuel} was obtained from the properties of SW and SWP. Furthermore, the carbon conversion efficiency (η_{CCE}) was calculated to determine the amount of carbon in the fuel that transformed into gaseous (Nam, Maglinao, Capareda, & Rodriguez-Alejandro, 2016). The η_{CCE} was calculated following Equation (3) (Rodrigues et al., 2017).

$$\eta_{CCE} = \frac{12 \times A}{m_{fuel} \times x_C} \times 100 \quad (3)$$

Where A refer to the total number of moles of carbon-bearing components of the syngas produced which are CO, CH_4 and CO_2; m_{fuel} refer to the mass of fuel at 100 g whereas x_c is the mass fraction of carbon of SW and SWP obtained from ultimate analysis.

RESULTS AND DISCUSSIONS

Fuel characteristics

Table 1 displayed the proximate, ultimate, and heating value analysis of SW and SWP. It was found out that the value of the proximate analysis for each fuels are inconsistent with the range of data recorded by other researchers (Frau et al., 2015; George et al., 2019). It was expected that 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 (Tumuluru et al., 2012). In term of ultimate analysis, it can be seen that SWP denoted much lower N and S content than SW. The highest sulfur content in fuels is unfavorable resulted adverse effect such as the corrosion on the metallic parts of the gasification installation and generate syngas that opposing for methanol synthesis purpose. Furthermore, it can be noted that the HHV_{fuel} of SWP as slightly higher than SW with the amount of HHV_{fuel} are also in the range with other researchers (Jeong et al., 2017).

Table 1. The proximate, ultimate and heating value of SW and SWP.

	Sawdust (SW)	Sawdust pellet (SWP)
Proximate analysis (wt. %)		
Moisture content	11.8	9.19
Volatile matter	68.05	79.00
Fixed carbon*	19.05	10.16
Ash content	1.10	1.65
Ultimate analysis (wt. %)		
Carbon	44.11	44.28
Hydrogen	5.53	6.09
Nitrogen	2.14	1.05
Oxygen*	45.52	48.62
Sulfur	2.70	0.28
Heating value (MJ/kg)	17.17 ± 0.089	17.46 ± 0.085

*By difference

Syngas composition

The profile of volume percentage of H_2, CO, CH_4 and CO_2 in syngas composition of the SW and SWP under the operating condition of the gasification temperature at 750 °C and ER at 0.25 is presented in Figure 3. It can be seen that there is clear trend of decreasing for all the syngas composition for SW and SWP from CO_2 > H_2 > CO > CH_4. For the SW, the volume of the H_2 is lower than SWP may be explained that most of the atomic hydrogen in the SW is converted to H_2O (Chen et al., 2013). Meanwhile, when the SWP is gasified, the H_2 is raised at 11%. This results supported that densification have the potential to facilitate the syngas formation (Aydin et al., 2019). The observed increase of CO_2 in SW could be attributed that most of the CO is transformed to CO_2 during the water-gas shift reactions within the gasification process. Subsequently, CH_4 for both SW and SWP recorded the lowest percentage averagely 5% for the syngas composition.

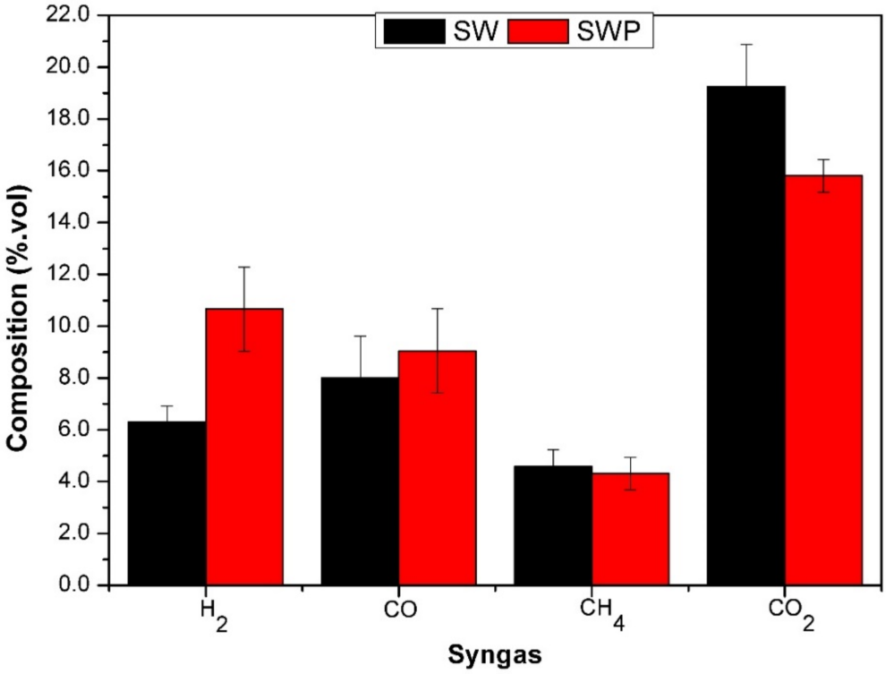

Figure 3. Profile of volume percentage of H_2, CO, CH_4 and CO_2 in syngas composition at gasification temperature and ER fixed at 750 °C and 0.25, respectively.

Gasification performance

The gasification performance in terms of the HHV_{syngas}, η_{GE} and η_{CCE} of the SW and SWP is illustrated in Figure 4. It is apparent from the figure that SWP achieved the high HHV_{syngas}, η_{GE} and η_{CCE} than the SW. The HHV_{syngas} of the SW is amplified by 15% when undergoes pelletization in which HHV_{syngas} for SW and SWP are calculated at 3.6386 ± 0.87 MJ/Nm^3 and 4.2152 ± 0.79 MJ/Nm^3, respectively. The η_{GE} of the SW is boost by a factor 0.90 after undergoes pelletization. The lowest η_{GE} and η_{CCE} of the SD are associated to the highest production of CO_2 as well as to the lowest formation of the H_2 and CO in the syngas composition. Meanwhile, the η_{CCE} of the SW is increased by 20% from the pelletization process that eliminates the moisture content by applying the mechanical force ultimately generates the highest H_2 in syngas composition (Yoon et al., 2012).

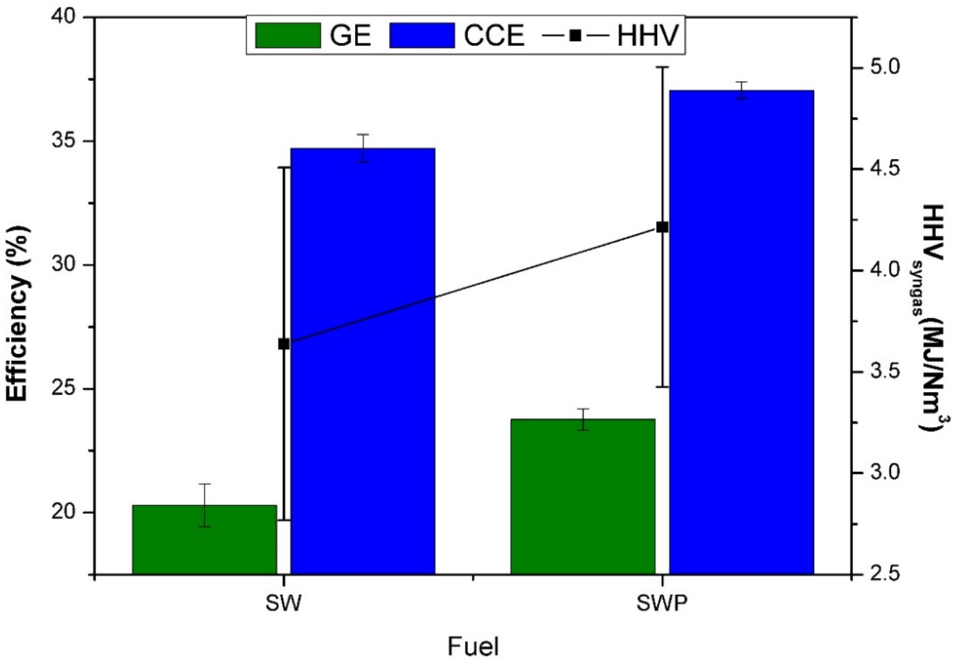

Figure 4. HHV_{syngas}, η_{GE} and η_{CCE} for SW and SWP with the gasification temperature and ER fixed at 750 °C and 0.25, respectively.

CONCLUSION

The syngas composition and gasification performance of sawdust (SW) and pelletized sawdust (SWP) 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 high syngas production of H_2 and CO at 11% and 9%, respectively. In contrast, SW recorded the lowest H_2 and CO at 6% and 8%, respectively. In term of the gasification performance, followed the same pattern, SWP achieved the high HHV_{syngas}, η_{GE} and η_{CCE} calculated at 4.2152 MJ/Nm^3, 24% and 37%, respectively.

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REFERENCES

ASTM D3176-09. (2009). *Standard Practice for Ultimate Analysis of Coal and Coke*. Retrieved from www.astm.org

ASTM E1131-98. (1998). Standard Test Method for Compositional Analysis by Thermogravimetry. In *ASTM International*. Retrieved from www.astm.org

Aydin, E. S., Yucel, O., & Sadikoglu, H. (2019). Experimental study on hydrogen-rich syngas production via gasification of pine cone particles and wood pellets in a fixed bed downdraft gasifier. *International Journal of Hydrogen Energy*, (xxxx). https://doi.org/10.1016/j.ijhydene.2019.02.175

Basu, P. (2010). *Biomass Gasification and Pyrolysis Handbook*. https://doi.org/http://dx.doi.org/10.1016/B978-0-12-374988-8.00001-5

Chen, W. H., Chen, C. J., Hung, C. I., Shen, C. H., & Hsu, H. W. (2013). A Comparison of Gasification Phenomena among Raw Biomass, Torrefied Biomass and Coal in An Entrained-Flow Reactor. *Applied Energy*, *112*, 421–430. https://doi.org/10.1016/j.apenergy.2013.01.034

Djatkov, D., Martinov, M., & Kaltschmitt, M. (2018). Influencing parameters on mechanical-physical properties of pellet fuel made from corn harvest residues. *Biomass and Bioenergy*, *119*(January), 418–428. https://doi.org/10.1016/j.biombioe.2018.10.009

Frau, C., Ferrara, F., Orsini, A., & Pettinau, A. (2015). Characterization of several kinds of coal and biomass for pyrolysis and gasification. *Fuel*, *152*, 138–145. https://doi.org/10.1016/j.fuel.2014.09.054

George, J., Arun, P., & Muraleedharan, C. (2019). Experimental investigation on co-gasification of coffee husk and sawdust in a bubbling fluidised bed gasifier. *Journal of the Energy Institute*, 2–11. https://doi.org/https://doi.org/10.1016/j.joei.2018.10.014

Hu, J., Shao, J., Yang, H., Lin, G., Chen, Y., Wang, X., … Chen, H. (2017). Co-gasification of coal and biomass: Synergy, characterization and reactivity of the residual char. *Bioresources Technology*, *5*(1), 1–7. https://doi.org/10.1017/CBO9781107415324.004

IRENA. (2012). Biomass for Power Generation. In *Renewable Energy Technologies: Cost Analysis Series* (Vol. 1). Abu Dhabi: International Renewable Energy Agency (IRENA).

Jeong, H. J., Hwang, I. S., Park, S. S., & Hwang, J. (2017). Investigation on co-gasification of coal and biomass in Shell gasifier by using a validated gasification model. *Fuel*, *196*, 371–377. https://doi.org/10.1016/j.fuel.2017.01.103

Kumar, L., Koukoulas, A. A., Mani, S., & Satyavolu, J. (2017). Integrating torrefaction in the wood pellet industry: A critical review. *Energy and Fuels*, *31*(1), 37–54. https://doi.org/10.1021/acs.energyfuels.6b02803

Mallick, D., Buragohain, B., Mahanta, P., & Moholkar, V. S. (2018). Gasification of Mixed Biomass: Analysis Using Equilibrium, Semi-equilibrium, and Kinetic Models. In *Coal and Biomass Gasification: Recent Advances and Future Challenge* (pp. 223–241). https://doi.org/10.1007/978-981-10-7335-9_9

Mansur, F. Z., Faizal, C. K. M., Samad, N. A. F. A., Atnaw, S. M., & Sulaiman, S. A. (2019). Performance modelling and validation on co-gasification of coal and sawdust pellet in research-scale downdraft reactor. *IOP Conference Series: Materials Science and Engineering*. https://doi.org/10.1088/1757-899X/702/1/012023

Mishra, R. K., & Mohanty, K. (2018). Pyrolysis kinetics and thermal behavior of waste sawdust biomass using thermogravimetric analysis. *Bioresource Technology*, *251*(December 2017), 63–74. https://doi.org/10.1016/j.biortech.2017.12.029

Nam, H., Maglinao, A. L., Capareda, S. C., & Rodriguez-Alejandro, D. A. (2016). Enriched-Air Fluidized Bed Gasification Using Bench and Pilot Scale Reactors of Dairy Manure with Sand Bedding Based on Response Surface Methods. *Energy*, *95*, 187–199. https://doi.org/10.1016/j.energy.2015.11.065

Plis, P., & Wilk, R. K. (2011). Theoretical and Experimental Investigation of Biomass Gasification Process in a Fixed Bed Gasifier. *Energy*, *36*, 3838–3845. https://doi.org/10.1016/j.energy.2010.08.039

Pradhan, P., Mahajani, S. M., & Arora, A. (2018). Production and utilization of fuel pellets from biomass: A review. *Fuel Processing Technology*, *181*(September), 215–232. https://doi.org/10.1016/j.fuproc.2018.09.021

Puig-Arnavat, M., Shang, L., Sárossy, Z., Ahrenfeldt, J., & Henriksen, U. B. (2016). From a single pellet press to a bench scale pellet mill - Pelletizing six different biomass feedstocks. *Fuel Processing Technology*, *142*, 27–33. https://doi.org/10.1016/j.fuproc.2015.09.022

Rodrigues, S., Almeida, A., Ribeiro, A., Neto, P., Ramalho, E., & Pilão, R. (2017). Influence of temperature on the gasification of cork wastes. *Energy Procedia*, *136*, 127–132. https://doi.org/10.1016/j.egypro.2017.10.298

Sarkar, M., Kumar, A., Tumuluru, J. S., Patil, K. N., & Bellmer, D. D. (2014). Gasification performance of switchgrass pretreated with torrefaction and densification. *Applied Energy*, *127*, 194–201. https://doi.org/10.1016/j.apenergy.2014.04.027

Shi, Y. (2016). *Biomass Gasification in a Pilot-Scale System*. University of Iowa.

Simone, M., Barontini, F., Nicolella, C., & Tognotti, L. (2012). Gasification of pelletized biomass in a pilot scale downdraft gasifier. *Bioresource Technology*, *116*, 403–412. https://doi.org/10.1016/j.biortech.2012.03.119

Stapf, D., Ceceri, G., Johansson, I., & Whitty, K. (2019). *Biomass pre-treatment for bioenergy*.

Susastriawan, A. A. ., Saptoadi, H., & Purnomo. (2019). Comparison of the gasification performance in the downdraft fixed-bed gasifier fed by different feedstocks: Rice husk, sawdust, and their mixture. *Sustainable Energy Technologies Assessments*, *34*(April), 27–34. https://doi.org/10.1016/j.seta.2019.04.008

Tumuluru, J. S., Hess, J. R., Boardman, R. D., Wright, C. T., & Westover, T. L. (2012). Formulation, Pretreatment, and Densification Options to Improve Biomass Specifications for Co-Firing High Percentages with Coal. *Industrial Biotechnology*, *8*(3), 113–132. https://doi.org/10.1089/ind.2012.0004

Vélez, J. F., Chejne, F., Valdés, C. F., Emery, E. J., & Londoño, C. A. (2009). Co-gasification of Colombian coal and biomass in fluidized bed: An experimental study. *Fuel*, *88*(3), 424–430. https://doi.org/10.1016/j.fuel.2008.10.018

Wasinarom, K., & Charoensuk, J. (2019). Experiment and Numerical Modeling of Stratified Downdraft Gasification Using Rice Husk and Wood Pellet. *BioResources*, *14*(3), 5235–5253.

Yang, Z., & Kumar, A. (2018). The Impacts of Thermal Pretreatments on Biomass Gasification and Pyrolysis Processes. In J. S. Tumuluru (Ed.), *Biomass Preprocessing and Pretreatments for Production of Biofuels: Mechanical , Chemical and Thermal Methods* (pp. 292–324). CRC Press Taylor & Francis Group.

Yoon, S. J., Son, Y. Il, Kim, Y. K., & Lee, J. G. (2012). Gasification and power generation characteristics of rice husk and rice husk pellet using a downdraft fixed-bed gasifier. *Renewable Energy*, *42*, 163–167. https://doi.org/10.1016/j.renene.2011.08.028