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Feasibility of biomass waste as feedstock for a small-scale biomass power plant in a rural area

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ABSTRACT

Biomass, one of many renewable energy sources, has received increasing attention in recent years, not only for heating applications but also for generating electricity. A biomass-based gasification power plant is a promising energy conversion system for rural energy sustainability. The present work aims to design and develop, and to perform an evaluation of a small-scale biomass gasification power plant with a capacity of 5000 watts. The plant consists of a downdraft gasifier, an impinging scrubber, a biofilter, a 5000-Watt generator set, and a suction blower. In the present work, the plant is tested using rice husk, wood scrap, and a rice husk-wood scrap blend as feedstocks. The gasifier temperature and tar removal by the impinging scrubber are observed and analysed. The results show that rice husk biomass, wood scrap, and their blend have good potential as feedstocks for a biomass power plant. The biomass gasification power plant can generate electricity without any problem on the generator set. The water-impinging scrubber can be used to reduce tar in the producer gas prior to its supply to the generator set.

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1. Introduction

Energy sustainability cannot be achieved if global energy demand is met solely by fossil fuels. Fossil fuels have been depleted and have become a hot issue to be encountered in order to obtain energy sustainability. Many sources of renewable energy have been explored for their potential for fossil fuel substitution. Biomass, one of many renewable energy sources, has received increasing attention in recent years, not only for heating applications but also for generating electricity. Nearly 1/7 world's energy demand were supplied by biomass energy [1]. Indonesia has a biomass energy potential about 33 GW. Unfortunately, only about 1.6 GW of Indonesia's biomass potential has been used as a useful energy source [2]. In order to expand the utilization, biomass could be used as feedstock of gasification-based power plant. Combustion of producer gas from biomass gasification is cleaner than direct combustion of the biomass [3].

Gasification is a thermochemical process of converting solid biomass into combustible gas "producer gas" in the reactor called a gasifier. Sequence processes, starting from the top to the bottom of the downdraft gasifier, are drying, pyrolysis, oxidation, and reduction. Reduction process which involves Bouduard (R1), Water-Gas (R2), Water-Gas Shift (R3), and Methane formation (R4) reactions forms combustible gas CO, H_2, and CH_4 [4].

$$C + CO_2 \rightarrow 2CO + 172\ kJ/mol \quad \text{(R1)}$$
$$C + H_2O \rightarrow CO + H_2 + 131\ kJ/mol \quad \text{(R2)}$$
$$CO + H_2O \rightarrow CO_2 + H_2 - 41.2\ kJ/mol \quad \text{(R3)}$$
$$C + 2H_2 \rightarrow CH_4 - 74.8\ kJ/mol \quad \text{(R4)}$$

Besides producing producer gas, gasification also produces a contaminant called tar. Tar in the producer gas must be removed when it is used as fuel for internal combustion engines [5-7]. Tar is a blend of condensable HC, counting aromatic compounds with up to 5 rings as well as PAHs [8, 9]. Milne [10] stated that tar content of the producer gas for IC engine application should not exceed 100 mg/Nm^3. There are primary and secondary methods for tar removal from producer gas. When tar removal takes place in the gasifier, the method is called the primary method. In contrast, tar removal occurs outside the gasifier in the secondary method [11, 12]. Since the secondary method is easier to perform than the primary method, the secondary method is preferred in gasification systems. The most popular secondary method is scrubbing method, either wet scrubber or dry scrubber. Wet scrubber uses liquid adsorbent, such as water [13, 14], waste palm oil [15], and engine oil [16]. Meanwhile, dry scrubber uses solid adsorbent, such as zeolite [17].

Many biomass power plants have been developed and reported so far. However, typically those plants have a huge capacity that is not suitable for rural and remote areas. Thus, the small scale of 5000 Watt of biomass gasification power plant is designed and developed in the present work. The plant is tested its performance using rice husk feedstock. The 5000-Watt plant can provide electricity to up to 10 households in a rural area for 8 hours at night. This biomass power plant also provides a benefit of biomass utilisation in waste management.

2. Materials and methods

As shown in Fig. 1, the present work starts with the design of the plant, followed by fabrication and installation. Once the experiment is set up, the test of the plant is performed using 5 kg of the feedstock, i.e. rice husk (RH), wood scrap (WS), and rice husk-wood scrap blend (RH-WS). Data taken during the test include the gasifier temperature (TR), producer gas temperature (TG), adsorbent temperature (TA), and exhaust gas temperature of the generator set (TEx). Other data taken include the temperature of the water adsorbent (TA) in the impinging scrubber and the temperatures of the producer gas entering (TG1) and leaving (TG2) the scrubber. The producer gas sample is analysed using a gas chromatograph to determine the percentages of CO, H_2, and CH_4. The results are then analyzed to figure out performance of the plant.

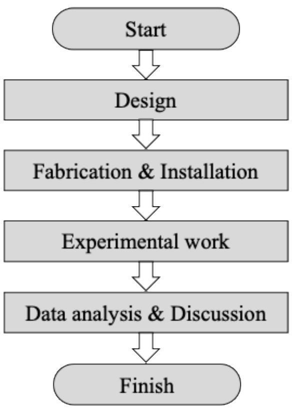


Fig. 1. Flow diagram of the work

Meanwhile, Fig. 2 displays the experimental setup of the 5000-Watt biomass power plant. The plant has the main components of a downdraft gasifier, an impinging scrubber, a bio-filter, a suction fan, and a 5000-Watt generator set.

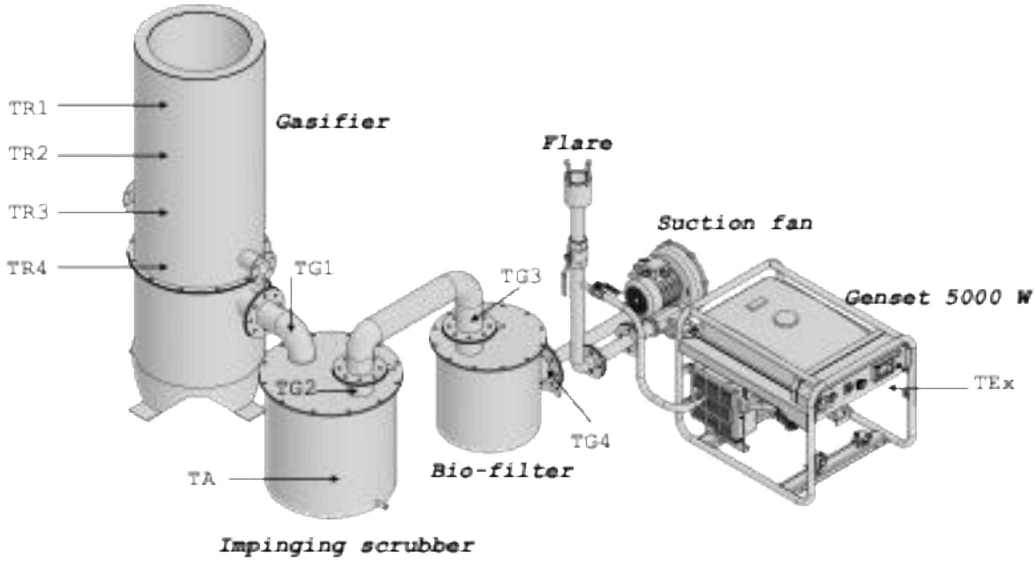


Fig. 2. Schematic diagram and photograph of the 5000-Watt biomass power plant

HHV of the producer gas is calculated using Eq. (1), tar content in the producer gas before and after the impinging scrubber is gravimetrically analysed to obtain tar removal efficiency (η) of the scrubber, which is calculated using Eq. (2), and heat absorption rate (Q) by the water adsorbent is calculated using Eq. (3)

$$HHV = \frac{[(x_1.HHV)_{CO}+(x_2.HHV)_{H2}+(x_3.HHV)_{CH4}]}{100} \quad (1)$$

where, x_1 denotes CO volume fraction, x_2 denotes H_2 volume fraction, x_3 represents CH_4 volume fraction [18]. Following Prasad *et al*. [19], gross heating values of CO = 12.71 MJ/Nm^3, H_2 = 12.78 MJ/Nm^3, and CH_4 = 39.76 MJ/Nm^3.

$$\eta = \frac{Tar1-Tar2}{Tar1} \times 100\% \quad (2)$$

where Tar 1 and Tar 2 are the gravimetric tar in the producer gas at the inlet and outlet of the impinging scrubber

$$Q = \frac{m \times c_p \times (TA_1 - TA_2)}{t} \quad (3)$$

where m is the mass of the water (50 kg), TA_1 and TA_2 are the initial and final temperatures of the water (°C), and t is the running time (minute).

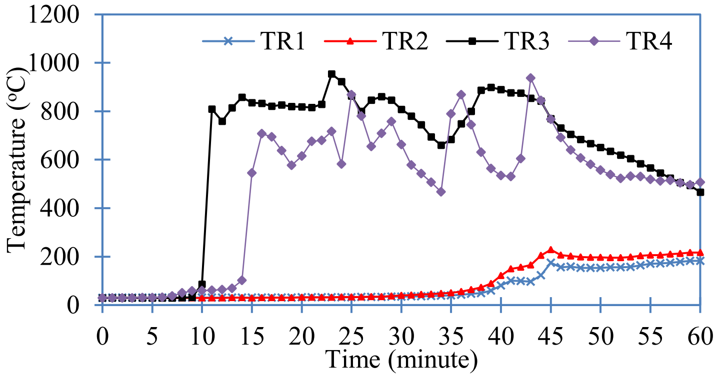
3. Results and Discussion

The following section discusses the performance of main component of the power plant, i.e. a gasifier and an impinging scrubber.

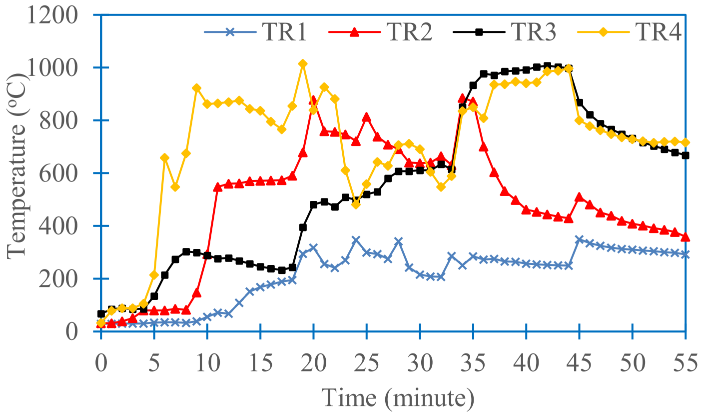
3.1. Performance of a Gasifier

Fig. 3 shows the temperature profile of the gasifier for feedstocks of rice husk, wood scrap, and a rice husk-wood scrap blend. The graph indicates that the oxidation zone is TR3, which has the highest temperature, while the reduction zone is at TR4. The reduction zone is the location where combustible gases (CO, H2, and CH4) are formed. Basically, the reduction process is the gasification process itself.

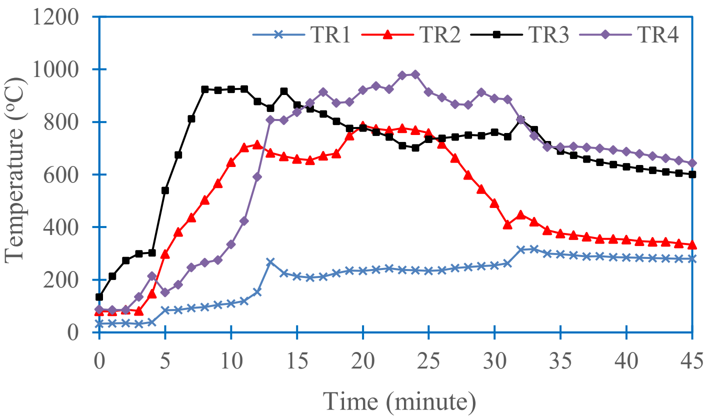
In the present work, gasification of rice husk occurs at a gasification temperature of about 800-900 °C, whereas TR1 and TR2 indicate the drying temperature and pyrolysis temperature, respectively. The trend of the temperature profile is in good agreement with the theoretical temperature profile of biomass gasification in a downdraft gasifier.



(a) Rice husk (RH) feedstock



(b) Wood scrap (WS feedstock



(c) Rice husk-wood scrap blend (RH-WS) feedstock

Fig. 3. Temperature profile of the gasifier

Fig. 4 compares gasification temperature, i.e. reduction temperature (TR4) for using feedstocks of rice husk (RH), wood scrap (WS), and rice husk-wood scrap blend (RH-WS). The graph shows that the gasification temperatures for RH, WS, and RH-WS are 800-900 °C, 700-850 °C, and 600-700 °C, respectively. The graph also shows that the reduction temperature of RH gasification is the least fluctuating among other feedstocks. This indicates stable gasification occurs when using RH feedstock. The chemical energy of the syngas is formed in this situation by converting the sensible heat of the gases and charcoal [20]. Numerous reduction processes occur in the temperature range of 800–1000 °C in the absence of, or in the sub-stoichiometric presence of, oxygen [21].

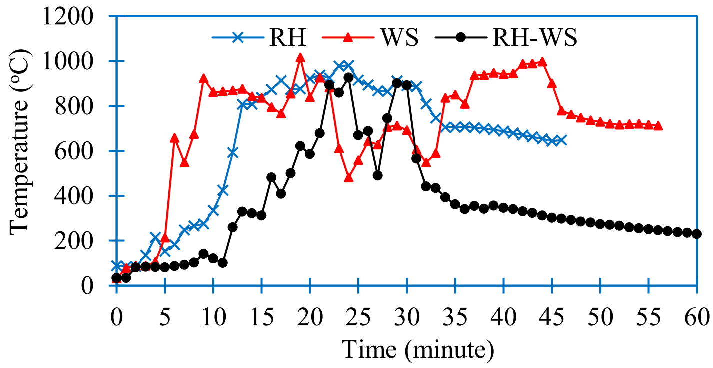


Fig. 4. Temperature of gasification

Fig. 5 presents tar content of the producer gas obtained from rice husk, wood scrap, and their blend at the exit of the gasifier. The graph shows tar content of the producer gas at the exit of the gasifier. Tar content of RH producer gas, WS producer gas, and RH-WS producer gas are 101.33 g/Nm^3, 188.04 g/Nm^3, and 228.71 g/Nm^3, respectively. The higher and more unform reduction temperature, the more tar is converted into producer gas [22] hence less tar content in the producer gas.

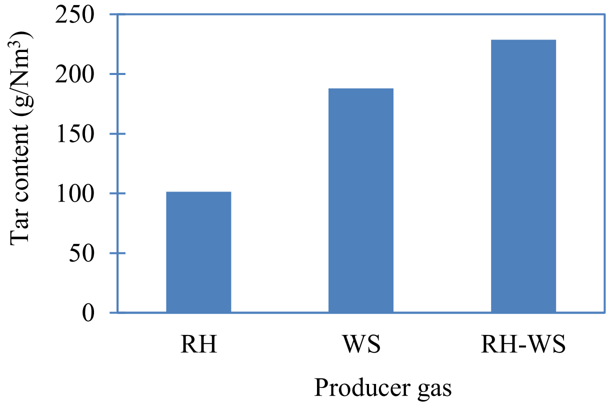


Fig. 5. Tar content of the producer gas

In addition, Fig. 6 presents combustible gas (CO, H_2, CH_4) composition and higher heating value (HHV) of the producer gas from rice husk (RH), wood scrap (WS), and blend of rice husk-wood scrap (RH-WS). CO percentage is the highest in the producer gas of RH-WS, and the lowest is in the RH producer gas. CO percentage of RH and RH-WS producer gas are 9.37% and 13.92%, respectively. In contrast, H_2 percentage is the highest in the RH producer gas (i.e. 3,02%) and the lowest in the RH-WS producer gas (i.e. 0.82%). Meanwhile, percentage of CH_4 is almost similar for the three producer gases, i.e. about 0.5%-0,8%). The highest HHV of the producer gas is obtained with the blend feedstock, i.e. 2.19 MJ/Nm^3. Whereas, HHV of RH and WS producer gas are 1.62 MJ/Nm^3 and 1.98 MJ/Nm^3, accordingly. The highest HHV of RH-WS producer gas is due to the highest composition of CO is obtained in RH-WS producer gas. More amount of CO generated during blend gasification mean that higher char and water consumption rate occur in the reduction zone which increases CO [23].

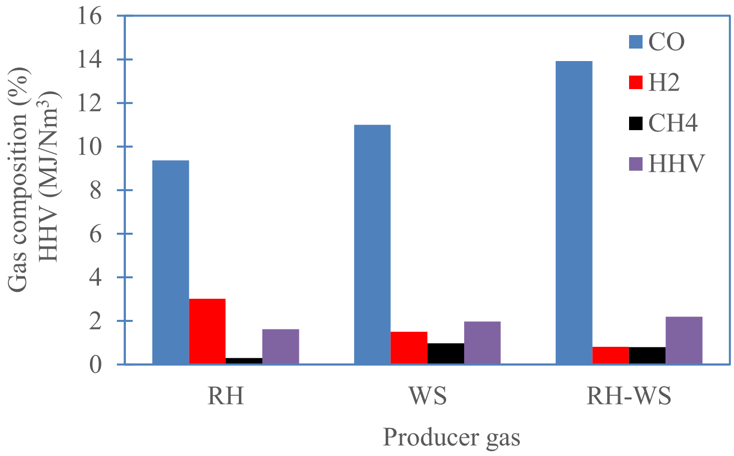


Fig. 6. Gas composition and HHV of the producer gas

3.2. Performance of an Impinging Scrubber

The water scrubber is able to reduce the tar content of the producer gas, as indicated by the decrease in tar content after the scrubber, as shown in Fig. 7. The tar content after the scrubber (TC2) has a lower value than the tar content before the scrubber (TC1). Tar removal efficiency of the scrubber is calculated using Eq. (2) and the result is shown in Figure 7. The result shows the water impinging scrubber has tar removal efficiency of about 40-50%. Cold water in the scrubber absorbs heat from the producer gas, the producer gas temperature reduces to the condensation temperature of the tar. Tar condenses into liquid tar and disperses into the water adsorbent. Since tar is removed in the scrubber, the producer gas leaving the scrubber contains less tar than the gas entering it.

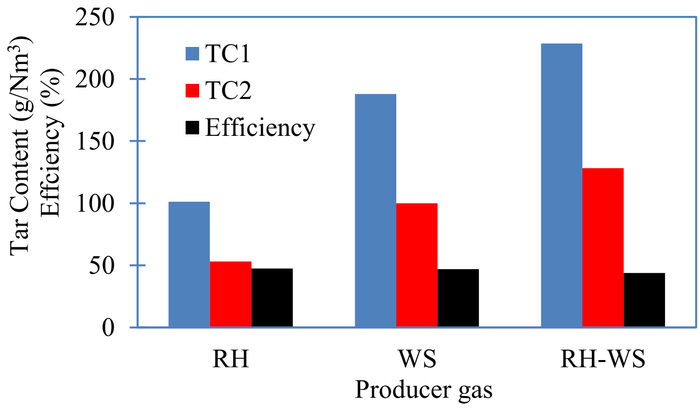


Fig. 7. Tar removal efficiency of the water impinging scrubber

Besides quantitative tar gravimetric analysis, tar removal ability of the scrubber can also be performed with a visual method by comparing the visual appearance of the isopropanol in the impinging bottle before and after the scrubber. Fig. 8 displays the photograph of Isopropanol in the impinging bottles before and after the scrubber. Isopropanol before impinging scrubber has a black color which indicates high tar content of the producer gas since condensate tar has a black color. Isopropanol in the after scrubbing bottle has yellowish color. This indicates less tar content in the impinging bottle after the impinging scrubber. By comparing those colors, it indicates that tar absorption occurs in the impinging scrubber. Thus, it can be stated that the impinging scrubber using water adsorbent is able to work properly.

Fig. 8. Photograph of Isopropanol before and after the impinging scrubber

Meanwhile, Fig. 9 presents water adsorbent temperature (TA), producer gas temperature entering (TG1) and leaving (TG2) the impinging scrubber during rice husk gasification. The data of TA, TG1, and TG2 are used to analyzed heat transfer characteristic from the producer gas and the water adsorbent in the impinging scrubber. Water temperature increases significantly after 15 minutes. This is due to gas temperature entering the scrubber start rises at that time. From Fig. 8, it can be stated that the impinging scrubber works properly since the gas exit temperature is lower than gas inlet temperature. This means heat of the gas is absorbed by the water in the scrubber. By using Eq. (3) and temperature of the water at initial and final state, the heat absorption rate by the water is found to be 74.9 kJ/minute which is displayed in Fig. 10.

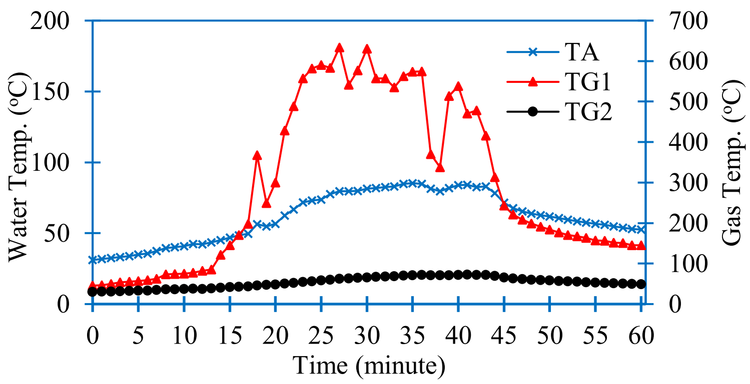


Fig. 9. Water and producer gas temperature of the impinging scrubber

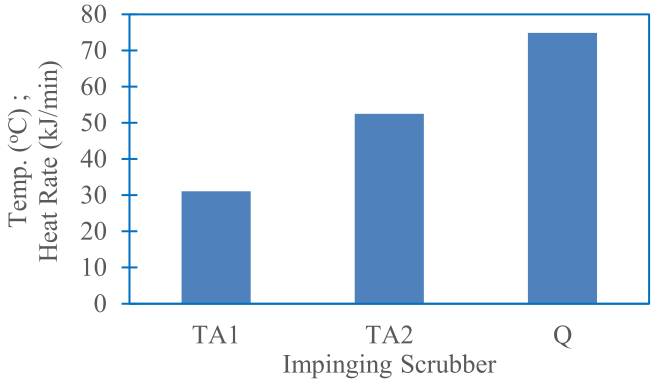


Fig. 10. Heat absorption rate

4. Conclusion

The small-scale 5,000-watt biomass gasification power plant is designed and fabricated at a local workshop in Yogyakarta. The plant is tested using a feedstock of rice husk, wood scrap, and their blend. It can be concluded that the plant can generate electricity without any problem on the generator set. Biomass waste of rice husk, wood scrap, and their blend has a good potential as feedstock for a biomass power plant. The water impinging scrubber can be used for tar reduction of the producer gas prior to being supplied to the generator set. In addition, the small-scale 5000 Watt biomass gasification power plant provides benefits not only by electrifying up to 10 households but also by supporting government programs for renewable energy utilisation and energy sustainability.

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References

[1] Jain, T., Sheth, P.N. “Design of energy utilization test for a biomass cook stove: Formulation of an optimum air flow recipe.” *Energy* 166 (2019): 1097–1105.

[2] Anis, S., Zainal, Z.A. “Tar reduction in biomass syngas via mechanical, catalytic and thermal methods: A review.” *Renew. Sustain. Energy Rev.* 15, no. 5 (2011): 2355-2377. https://doi.org/10.1016/j.rser.2011.02.018

[3] Hernández, J.J., Aranda-Almansa, G., Bula, A. “Gasification of biomass wastes in an entrained flow gasifier: Effect of the particle size and the residence time.” *Fuel Process. Technol.* 91, no. 6 (2010): 681–692.

[4] Susastriawan, A.A.P., Purwanto, Y., Purnomo, Warisman, A. “Development of An Air-Stage Downdraft Gasifier and Performance Evaluation on Feedstock of Rice Husk. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 84, no. 1 (2021): 20-32. https://doi.org/10.37934/arfmts.84.1.2032

[5] Du, X., Li, Y. “Experimental comparison and optimization on granular bed filters with three types of filling schemes.” *Applied Energy* 253 (2019): 113563. https://doi.org/10.1016/j.apenergy.2019.113563

[6] Tuomi, S., Kurkela, E., Simell, P., Reinikainen, M. "Behaviour of tars on the filter in high temperature filtration of biomass-based gasification gas." *Fuel* 139 (2015): 220-231. https://doi.org/10.1016/j.fuel.2014.08.051

[7] Nakamura, S., Kitano, S., Yoshikawa, K. "Biomass gasification process with the tar removal technologies utilizing bio-oil scrubber and char bed." *Applied Energy* 170 (2016): 186-192.

[8] Anis, S., Zainal, Z.A. "Tar reduction in biomass producer gas via mechanical, catalytic and thermal methods: A review." *Renewable and Sustainable Energy Reviews* 15, no. 5 (2011): 2355-2377. https://doi.org/10.1016/j.rser.2011.02.018

[9] Woolcock, P.J., Brown, R.C. "A review of cleaning technologies for biomass-derived syngas." Biomass and Bioenergy 52 (2013): 54-84. https://doi.org/10.1016/j.biombioe.2013.02.036

[10] Milne, T.A., Evans, R.J., Abatzaglou, N. "Biomass gasifier "tars": Their nature, formation, and conversion." *National Renewable Energy Laboratory. Report* NREL/TP-570-23357 (1998)

[11] Anis, S., Zainal, Z.A. "Tar reduction in biomass syngas via mechanical, catalytic and thermal methods: A review." *Renew. Sustain. Energy Rev.* 15, no. 5 (2011): 2355-2377. https://doi.org/10.1016/j.rser.2011.02.018

[12] Paethanom, A., Bartocci, P., Alessandro, B.D., Amico, M.D., Testarmata, F., Moriconi, N., Yoshikawa, K., Fantozzi, F. "A low-cost pyrogas cleaning system for power generation: Scaling up from lab to pilot." *Applied Energy* 111 (2013): 1080-1088. http://dx.doi.org/10.1016/j.apenergy.2013.06.044

[13] Phuphuakrat, T., Namioka, T., Yoshikawa, K. "Absorptive removal of biomass tar using water and oily materials." *Bioresource Technology* 102, no. 2 (2011): 543-549 http://doi.org/10.1016/j.biortech.2010.07.073

[14] Bhave, A.G.A., Vyas, D.K., Patel, J.B. "A wet packed bed scrubber-based syngas cooling–cleaning system." *Renewable Energy* 33, no. 7 (2008): 1716-1720. http://doi.org/10.1016/j.renene.2007.08.014

[15] Ahmad, N.A. & Zainal, Z.A "Performance and chemical composition of waste palm cooking oil as scrubbing medium for tar removal from biomass syngas." *Journal of Natural Gas Science and Engineering* 32 (2016): 256-261. http://dx.doi.org/10.1016/j.jngse.2016.03.015

[16] Unyaphan, S., Tarnpradab, T., Takahashi, F., Yoshikawa, K. "Improvement of tar removal performance of oil scrubber by producing syngas microbubbles." *Applied Energy* 205 (2017): 802-812. http://dx.doi.org/10.1016/j.apenergy.2017.08.071

[17] Sudarsono, Susastriawan, A.A.P., Purwanto, Y, La Astamu. "An Effect of Zeolite Size on Performance of Dry Scrubber in Tar Removal of Biomass Derived Syngas." *International Journal of Heat and Technology* 40 no. 2 (2022): 599-603 https://doi.org/10.18280/ijht.400229

[18] Saptoadi, H., Susastriawan, A.A.P., Subbarao P.M.V. "Performance of Spray Scrubber for Tar Removal and Energy Density of CPG from Rice Husk Gasification." *International Journal of Heat and Technology* 42, no. 4 (2024): 1193-1199. https://iieta.org/journals/ijht/paper/10.18280/ijht.420409

[19] Prasad, L., Subbarao, P.M.V., Subrahmanyam, J.P. "Experimental investigation on gasification characteristic of high lignin biomass (Pongamia shells)." Renewable *Energy* 80 (2015): 415-423. https://doi.org/10.1016/j.renene.2015.02.024

[20] Chawdhury, M.A. & Mahkamov, K. "Development of a small downdraft biomass gasifier for developing countries." *J. Sci. Res*. 3, no. 1 (2011). https://doi.org/ 10.3329/jsr.v3i1.5613.

[21] Buragohain B, Mahanta, P., V.S. Moholkar, V.S. "Biomass gasification for decentralized power generation: the Indian perspective." *Renew. Sustain. Energy Rev.* 14, no. 1 (2010): 73–92. https://doi.org/10.1016/j.rser.2009.07.034.

[22] Mishra, S. & R.K. Upadhyay R.K. "Review on biomass gasification: gasifiers, gasifying mediums, and operational parameters." Mater. Sci. Energy Technol. 4 (2021): 329–340, https://doi.org/10.1016/j.mset.2021.08.009.

[23] Ali, B.I. & Gunjo, D.G. "Performance evaluation of throated downdraft gasifier using peanut shell and mango seed hull as a feedstock." *Results in Engineering* 20 (2023): 101642 https://doi.org/10.1016/j.rineng.2023.101642