Simulation of Temperature Distribution in Biochar Kiln with Different Feedstock Types

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Abstract. *Biochar has been used as a soil fertility improvement. It is a stable carbon-rich solid product obtained from the thermal pyrolysis of organic matter. This work aims to evaluate the temperature distribution in biochar kiln characterized by the pyrolysis feedstocks. The biochar yield was used to identify the potential of the pyrolysis feedstocks for biochar production. The different pyrolysis feedstock types (i.e., corncob, rice husk, and dry longan leaf) were investigated in this study. The biochar kiln with a dimension of 500 mm × 380 mm (height × diameter) consisting of the core with diameter of 115 mm and puncture diameter of 6.35 mm was developed. The computer simulation was applied and the simulation results were compared with the experimental results in order to validate the model. The simulation results illustrated that the highest temperature was found at the core and transversely decreased in radial direction to the kiln wall. The temperature averagely over the radial and longitudinal positions inside the kiln was found to be equal to 293.3 ± 176.7 °C, 363.4 ± 270.9 °C, and 369.6 ± 277.1 °C and biochar yield was found to be equal to 15.7 wt.%, 24.3 wt.%, and 11.4 wt.% for corncob, rice husk, and dry longan leaf, respectively. These findings indicated that the kiln parameters could be properly developed to satisfy the feedstock types since their temperature distribution could affect the biochar yield.*

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Keywords:

Biochar; Feedstock; Pyrolysis; Simulation; Thermal characteristics

1. Introduction

Biomass has been known as a renewable source. The carbonization along with the thermal stabilization of biomass can produce an organic matter called biochar. It is a stable carbon-rich product and has been used as a soil fertility improvement. The biomass is heated to temperature varying between 400 to 1,250 °C under limited or no oxygen with time duration varying between 1 s to 3 h, depending on the conversion process [1]. The slow pyrolysis can produce more biochar than the intermediate pyrolysis and fast pyrolysis, respectively [2].

In this study, the temperature distributions were investigated under the slow pyrolysis process condition. As such, the biomass is expectedly heated under the low to moderate temperature ranging from 400 to 500 °C for a long time span varying between 30 min to 3 h. The pyrolysis temperature, heating time, heat rate, and particle size have been reported to influence the yield and properties of biochar, including the alkalinity and surface area of biochar [3-9]. The alkalinity of biochar is useful to acidic sandy soil, which helps to neutralize the soil acidity, increase the soil pH and improve the nitrification [7, 10]. The pores of biochar help to improve the soil structure. The high surface area contributed by the pores can increase the water holding capacity of soil and sustain the soil nutrients, which is favorable to the microorganism habitation and activity [7]. The other biochar properties, i.e., total organic carbon, fixed carbon, and mineral elements of biochar, were found to be most affected by the feedstock properties [8]. The design information and the discussion of the effect of process parameters on the temperature distribution, productivity, and quality obtained from the small-scale biochar production were provided in the previous studies [11]. In the present study, the temperature distribution inside the biochar kiln was estimated and biochar kiln was modeled using the simplified equations of heat transfer, i.e., conduction, convection, and radiation. The computer simulation was applied to assess the temperature distribution inside the kiln with different feedstock types (i.e., corncob, rice husk, and dry longan leaf). The effect of the feedstock types on the temperature distribution along with the weight percent of yields for each feedstock type was also investigated.

2. Materials and Method

The biochar kiln was made of carbon steel with a dimension of 500 mm × 380 mm (height × diameter) and had a unit capacity of 50 L. The lid and the bottom of the kiln were cut at its center with the diameter of 115 mm (Fig. 1).

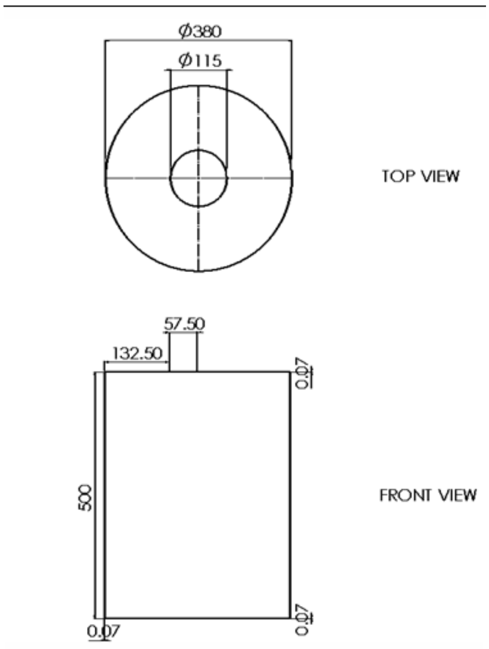

Fig. 1: Biochar kiln (dimension displayed in millimeters)

The core of the biochar kiln was located at the center of the kiln. The core was made of carbon steel pipe with thickness of 2.5 mm, inner diameter of 115 mm, height of 470 mm, and core puncture diameter of 6.35 mm. The dimension of the core and the locations of the core puncture were detailed in Fig. 2.

Seven K-type thermocouple probes with the temperature range of 0 to 1,000 °C were set up inside the kiln in radial and longitudinal positions (radial positions at 49 mm, 123 mm, and 182 mm from the kiln center and longitudinal positions at 80 mm, 261 mm, and 385 mm from the bottom of the kiln) (Fig. 3). Three probes at longitudinal positions of 261 mm were set up at radial positions of 49 mm, 123 mm, and 182 mm. The longitudinal positions of 80 mm and 385 mm were attached by two probes each at radial positions of 49 mm and 182 mm.

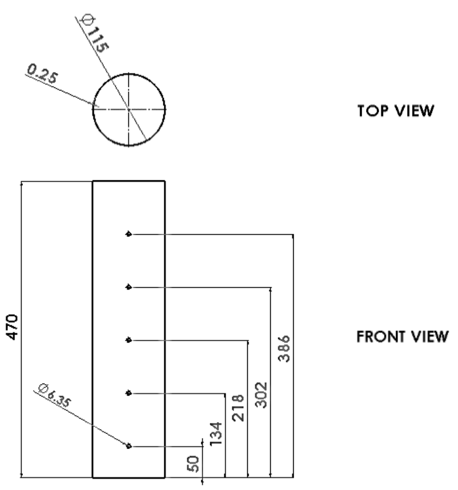

Fig. 2: Core of the biochar kiln (dimension displayed in millimeters)

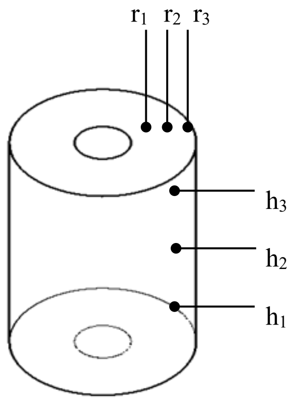

Fig. 3. Thermocouple attachment at different longitudinal and radial positions (h1 = 80 mm, h2 = 261 mm, h3 = 385 mm, r1 = 49 mm, r2 = 123 mm, and r3 = 182 mm)

The temperatures were acquired in real time and were stored in a computer using data logger (Wisco Online Datalogger OD04). The desired pyrolysis temperature was controlled by fuel filling rate. The different feedstock types (i.e., corncob, rice husk, and dry longan leaf) were applied to characterize the temperature distribution.

2.1 Experimental Procedure

The experimental procedure is as follows:

- The moisture content of feedstocks used was less than or equal to 10% wb.
- Seven kilograms of feedstock were loaded in the biochar kiln around the core for each experiment.
- The lid was tightly closed and the thermocouples were set. The biochar kiln was placed on the sieve platform before fuel was loaded in the core.
- The three kilograms of fuel were used. Fuel was divided into three equal portions and was slowly filled for each hour.
- The fuel was ignited from the top of the core. The combustion of fuel continued for 3 h.
- Following the process of slow pyrolysis, the feedstock was thermo-chemically decomposed and transformed into biochar.
- After the process finished, the outputs (i.e., biochar, nonbiochar, and ash) were sorted out and weighed using digital weighing scale with accuracy ±0.1 g, while gas quantity was calculated using mass balance.

2.2 Simulation Analysis

In this study, the temperature distributions in the biochar kiln with different feedstock types (i.e., corncob, rice husk, and dry longan leaf) were simulated using computer software program in order to reveal the thermal characteristics inside the biochar kiln. The governing, initial and boundary equations under specified conditions were numerically solved using finite element method. The heat transfer formulations were applied [12]. The axisymmetric heat transfer was determined in order to simplify the problem. The three-dimensional temperature distribution in biochar kiln was therefore illustrated in two dimensions. Furthermore, the assumptions of simulation were detailed as follows. The model was considered in steady-state heat transfer at specified time. The heat transfer of core from inner core surface to outer core surface was conduction. The heat transfers inside the kiln from outer core surface to inner kiln wall were conduction, convection, and radiation. The heat transfer of the kiln from outer kiln wall to surroundings was free convection.

The effect of feedstock types on the temperature distribution was investigated on the present specific-designed biochar kiln. The simulation results for each feedstock type were compared with the experimental results in order to verify the accuracy of the model.

3. Results and Discussion

3.1 The comparison of temperature distribution of simulation results with the experimental results

The simulation results were validated with the experimental results in order to verify the accuracy of the model. The comparison of the temperature distribution of simulation results with the experimental results along radial distance of biochar kiln at various longitudinal positions (i.e., base (h_1 = 80 mm), middle (h_2 = 261 mm), and top (h_3 = 385 mm) of the kiln) and feedstock types (i.e., corncob, rice husk, and dry longan leaf) are displayed in Figs. 4-6.

Percent error between simulation and experimental results of temperature at any radial location of biochar kiln with different feedstock types are shown in Table. 1.

It can be noted that the simulation results of the rice husk were in most agreement with the experimental results since the thermal conductivity of rice husk was consistent with the heat transfer parameters of the model. The average error of temperature for each feedstock type was found to be equal to 10.8 ± 16.8%, 7.0 ± 9.1%, and 11.7 ± 18.0% for corncob, rice husk, and dry longan leaf, respectively. The considerably inconsistent numbers between the simulation and experimental results were the result of the model assumptions and numerical scheme used. The temperature distributions were most accurately predicted at the height of 80 mm (base) of the kiln for all feedstock types. The minimum errors of the temperature averagely over three radial locations were found to be equal to 0.4 ± 0.1%, 0.9 ± 0.6%, and 1.2 ± 0.4% for corncob, rice husk, and dry longan leaf, respectively.

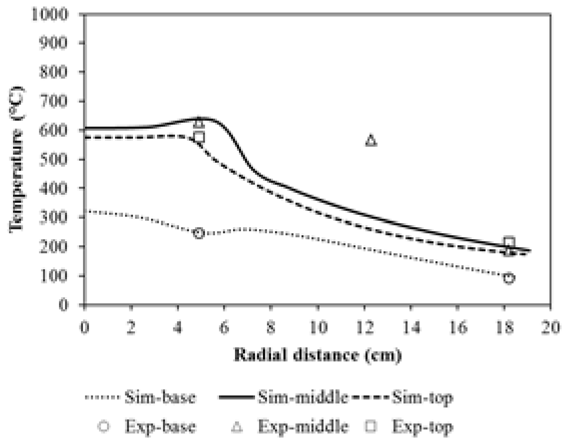

Fig. 4: Temperature simulation compared with experiment along radial direction in biochar kiln at base (h_1 = 80 mm), middle (h_2 = 261 mm), and top (h_3 = 385 mm) of the kiln with corncob as feedstock

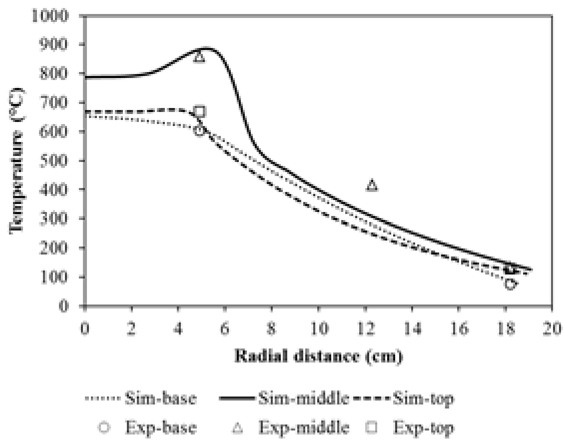

Fig. 5: Temperature simulation compared with experiment along radial direction in biochar kiln at base (h_1 = 80 mm), middle (h_2 = 261 mm), and top (h_3 = 385 mm) of the kiln with rice husk as feedstock

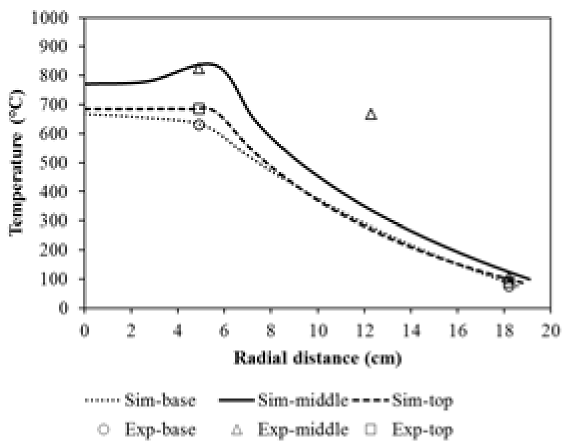

Fig. 6: Temperature simulation compared with experiment along radial direction in biochar kiln at base (h_1 = 80 mm), middle (h_2 = 261 mm), and top (h_3 = 385 mm) of the kiln with dry longan leaf as feedstock

Location	Radial distance (cm)	Error (%)		
		Corncob	Rice husk	Longan leaf
Base	4.9	0.5	1.3	1.4
(h_1 = 80 mm)	12.3	-	-	-
	18.2	0.3	0.4	0.9
Middle	4.9	0.1	0.1	0.1
(h_2 = 261 mm)	12.3	46.6	25.8	49.5
	18.2	6.5	10.1	17.7
Top	4.9	5.6	6.6	0.5
(h_3 = 385 mm)	12.3	-	-	-
	18.2	16.3	4.5	11.8

Table. 1: Percent error between simulation and experimental results of temperature at any radial location of biochar kiln with different feedstock types

3.2 The effect of feedstock types on the temperature distribution

The temperature distributions for any feedstock type were simulated corresponding to the variations of temperature and radial distance as shown in Figs. 4-6. It can be observed that:

- The temperature distributions inside the biochar kiln with different feedstock types had similar trend.
- When the fuel was ignited, the heat was transferred through the core wall by conduction and continued inside the kiln by conduction, convection, and radiation.
- The highest temperature was therefore found at the core and transversely decreased in radial direction to the kiln wall.
- The highest temperature in longitudinal position was found at the height of 264 mm (middle), 385 mm (top), and 80 mm (base) from the bottom of the kiln, respectively.

The temperature averagely over the radial and longitudinal positions inside the kiln for each feedstock type was found to be equal to 293.3 ± 176.7 °C, 363.4 ± 270.9 °C, and 369.6 ± 277.1 °C for corncob, rice husk, and dry longan leaf, respectively. The kiln with the corncob as feedstock was more uniform in temperature distribution than that with rice husk and dry longan leaf as feedstock, respectively. Even though, the temperature distributions were different from the previous report [11], they were in the range values obtained from the slow pyrolysis process aforementioned earlier.

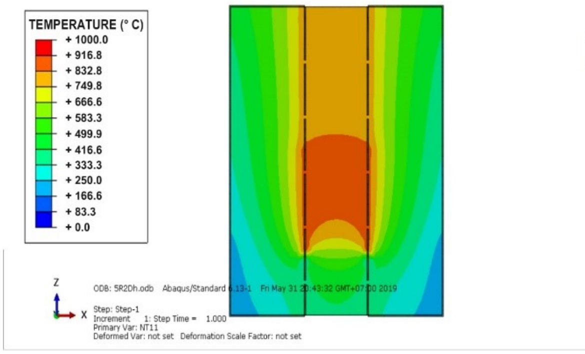

Fig. 7: Temperature distribution in biochar kiln with corncob as feedstock

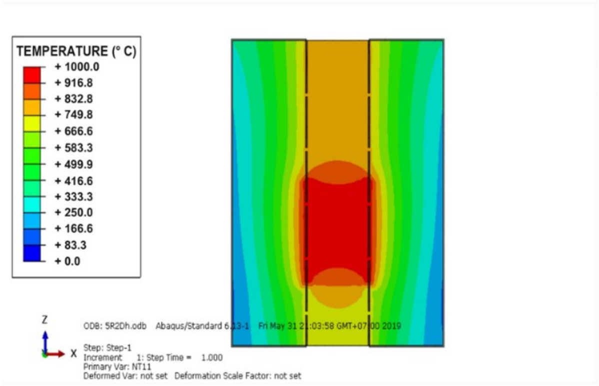

Fig. 8: Temperature distribution in biochar kiln with rice husk as feedstock

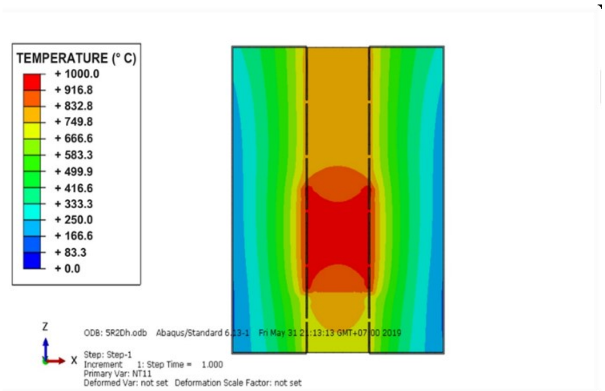

Fig. 9: Temperature distribution in biochar kiln with dry longan leaf as feedstock

3.3 The effect of feedstock types on the biochar yield

Fig. 10 summarized the weight percent of yields for each feedstock type. Rice husk was greater in biochar yield than corncob and dry longan leaf, i.e., 24.3 wt.%, 15.7 wt.%, and 11.4 wt.% for rice husk, corncob, and dry longan leaf, respectively. The order of the biochar yield was in agreement with the previous report [13]. The increase in the biochar yield was attributed to the decrease in the heating rate and temperature. However, the equal portions of fuel were slowly filled for each hour. The heating rate was therefore not considered in this study. It can be noted that the temperature inside the biochar kiln significantly affected the yields. Additionally, since lignin and cellulose mainly caused the biochar production [14, 15], the high percentage of biochar yield of rice husk was probably due to the high lignin and cellulose contents compare with corncob and dry longan leaf.

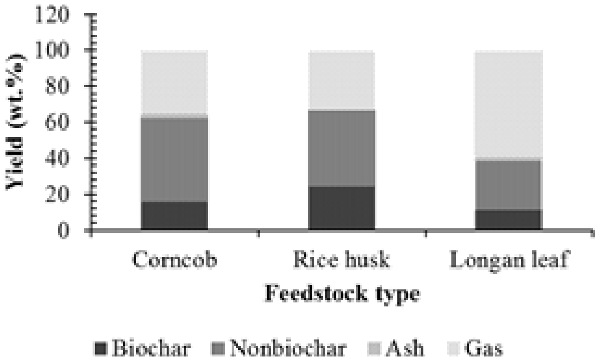

Fig. 10: The weight percent of yields for each feedstock type

The pyrolysis temperature has been reported to be a key factor in controlling thermal stability of biochar. The feedstocks were rapidly thermo-chemically decomposed in the present temperature range of slow pyrolysis and transformed into vapor with complex organic compounds and gases. Furthermore, above temperature of 250 °C, carbon presumably converted to CO_2, CO, and CH_4, resulting in weight loss during the process [16]. Fig. 10 distinctly shows that the percentage of gas yield was inversely relative with the biochar yield (i.e., 58.9 wt.%, 35.1 wt.%, and 32.9 wt.% for dry longan leaf, corncob, and rice husk, respectively). Since, the calorific value of dry longan leaf was respectively higher than that of corncob and rice husk [13, 17], the nonbiochar amount obtained from the biochar production of dry longan leaf was small compare with the other feedstocks. By comparing the biochar yield of three feedstock types, it could be suggested that all feedstocks were suitable to be converted via the slow pyrolysis process, following the decreasing order: rice husk > corncob > dry longan leaf.

4. Conclusions

The temperature distributions in biochar kiln with different feedstock types were successfully simulated in this study. The simplified equations of heat transfer were used to model the thermal characteristics inside the biochar kiln. The simulation results of three feedstock types were in agreement with the experimental results, following the order: rice husk > corncob > dry longan leaf. The feedstock type affected the temperature distribution and the biochar yield. The biochar yield of the feedstocks followed the order: rice husk > corncob > dry longan leaf.

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References

[1] Tripathi, M., Sahu, J.N. and Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review, *Renewable and Sustainable Energy Reviews*, vol. 55, March 2016, pp. 467-481.

[2] Sohi, S.P., Krull, E., Lopez-Capel, E. and Bol, R. (2010). A review of biochar and its use and function in soil, in *Advances in Agronomy*, D.L. Sparks, Ed. Burlington: Academic Press, pp. 47-82.

[3] Chen, D., Yu, X., Song, C., Pang, X., Huang, J. and Li, Y. (2016). Effect of pyrolysis temperature on the chemical oxidation stability of bamboo biochar, *Bioresource Technology*, vol. 218, October 2016, pp. 1303-1306.

[4] Demirbas, A. (2004). Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues, *Journal of Analytical and Applied Pyrolysis*, vol. 72, November 2004, pp. 243-248.

[5] Liu, X., Zhang, Y., Li, Z., Feng, R. and Zhang, Y. (2014). Characterization of corncob-derived biochar and pyrolysis kinetics in comparison with corn stalk and sawdust, *Bioresource Technology*, vol. 170, October 2014, pp. 76-82.

[6] Budai, A., Wang, L., Gronli, M., Strand, L.T., Antal, Jr., M.J., Abiven, S., Dieguez-Alongso, A., Anca-Couce, A. and Rasse, D.P. (2014). Surface properties and chemical composition of corncob and miscanthus biochars: Effects of production temperature and method, *Journal of Agricultural and Food Chemistry*, vol. 62, April 2014, pp. 3791-3799.

[7] Shaaban, A., Se, S.M., Dimin, M.F., Juoi, J.M., Husin, M.H.M. and Mitan, N.M.M. (2014). Influence of heating temperture and holding time on biochars derived from rubber wood sawdust via slow pyrolysis, *Journal of Analytical and Applied Pyrolysis*, vol. 107, May 2014, pp. 31-39.

[8] Suliman, W., Harsh, J.B., Abu-Lail, N.I., Fortuna, A.M., Dallmeyer, I. and Garcia-Perez, M. (2016). Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties, *Biomass and Bioenergy*, vol. 84, January 2016, pp. 37-48.

[9] Zhang, J., Liu, J. and Liu, R. (2015). Effects of pyrolysis temperature and heating time on biochar obtained from the pyrolysis of straw and lignosulfonate, *Bioresource Technology*, vol. 176, January 2015, pp. 288-291.

[10] Yuan, J.H., Xu, R.K. and Zhang, H. (2011). The forms of alkalis in the biochar produced from crop residues at different temperatures, *Bioresource Technology*, vol. 102, February 2011, pp. 3488-3497.

[11] Panyoyai, N., Wongsirsamuay, T. and Khamdaeng, T. (2018). Temperature distribution inside biochar kiln for biochar production, paper presented in *the 10th International Conference on Sciences, Technology and Innovation for Sustainable Well-Being (STISWB 2018)*, Vientiane, Lao PDR.

[12] Logan, D.L. (2007). *A First Course in the Finite Element Method*, 4th edition, ISBN: 0-534-55298-6, Nelson, Ontario.

[13] Biswas, B., Pandey, N., Bisht, Y., Singh, R., Kumar, J. and Bhaskar, T. (2017). Pyrolysis of agricultural biomass residues: Comparative study of corncob, wheat straw, rice straw and rice husk, *Bioresource Technology*, vol. 237, August 2017, pp. 57-63.

[14] Mary, G.S., Sugumaran, P., Niveditha, S., Ramalakshmi, B., Ravichandran, P. and Seshadri, S. (2016). Production, characterization and evaluation of biochar from pod (*Pisum sativum*), leaf (*Brassica oleracea*) and peel (*Citrus sinensis*) wastes, *International Journal of Recycling of Organic Waste Agriculture*, vol. 5, March 2016, pp. 43-53.

[15] Shariff, A., Noor, N.M., Lau, A. and Ali, M.A.M. (2016). A comparative study on biochar from slow pyrolysis of corn cob and cassava wastes, *International Journal of Biotechnology and Bioengineering*, vol. 10, December 2016, pp. 767-771.

[16] Sun, Y., Gao, B., Yao, Y., Fang, J., Zhang, M., Zhou, Y., Chen, H. and Yang, L. (2014). Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties, *Chemical Engineering Journal*, vol. 240, March 2014, pp. 574-578.

[17] Saqib, N.U., Oh, M., Jo, W., Park, S.K. and Lee, J.Y. (2017). Conversion of dry leaves into hydrochar through hydrothermal carbonization (HTC), *International Journal of Recycling of Organic Waste Agriculture*, vol. 19, January 2017, pp. 111-117.

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