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Evaluation of the Characteristics of Avocado Seed Biochar at Various Pyrolysis Temperatures for Sustainable Waste Management

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Abstract Avocado seeds are produced as a byproduct in households and industrial settings where avocados are used. These seeds become waste without economic or other advantages if not appropriately managed. Moreover, technology is needed to transform avocado seed waste into products with economic or practical benefits. One such technology involves converting avocado seed waste into biochar. Biochar can enhance carbon sequestration, nutrient retention, and water retention in soil. This research examines how different pyrolysis temperatures affect the characteristics of biochar produced from avocado seeds. The results show that pore formation begins at 400 ℃ of pyrolysis, although it is more clearly visible at a temperature of 500 ℃. FTIR analysis revealed that the available functional groups in the biochars were O–H, C-H, C=C, and C=O. The C content and C/N ratio of biochar increased with increasing pyrolysis temperature; however, H, O, N, H/C, and O/C decreased with increasing pyrolysis temperature. The dominant element content of avocado seed biochar is K_2O, P_2O_5, and SO_3, categorized as macronutrients. Through this analysis, the biochar from avocado seeds has the potential to serve as a soil amendment.

Keywords Avocado Seed, Biochar, Characteristics, Waste Management

1. Introduction

The avocado stands out as a highly significant fruit due to its rich nutritional profile and is extensively consumed and cultivated globally [1]. The avocado is found abundantly in tropical and subtropical regions; the avocado has been historically consumed as a food source [2]. The processing of avocados in various industries results in substantial by-products, including avocado seeds. With an annual estimated production of four million metric tonnes of avocado fruit, the seed comprises approximately 13–18% of the overall fruit [3].

Avocado seeds are produced by households and industrial operations that utilize avocados. If not managed properly, avocado seeds become waste without economic or other benefits. Several of these by-products are presently not fully utilized, leading to increased waste disposal expenses through methods such as onsite incineration and landfill disposal. Furthermore, these practices contribute to environmental pollution and pose potential health risks. Avocado organic waste primarily consists of seeds and husks with a small amount of pulp. This waste is often used as fertilizer and a soil improver through landfilling and composting [4]. Avocado industrial processes generate substantial waste from peeling, shelling, cutting, and oil extraction. Avocado seed oil can serve as a feedstock for biodiesel production [5]. Avocado seed waste can be converted into activated carbon, which has been prepared to exhibit relatively good efficacy in reducing ammonium levels in aqueous solutions [6].

As a result, technology is required to convert avocado seed waste into products with economic or other useful benefits. One technology that can be used is converting avocado seed waste into biochar. Biochar is a solid substance generated through the thermochemical conversion of biomass (feedstock) under oxygen-free or limited-oxygen conditions. Avocado seed biochar has the potential to enhance agricultural soils and sequester carbon [7]. The properties of biochar vary depending on the substrate and the production method used, and the most common approach involves biomass pyrolysis. This process requires precise temperature control to ensure the material's desired properties and performance [8]. Adding biochar to soil improves cation exchange capacity and stabilizes organic carbon in soils containing pyrolyzed carbon [9]. Applying avocado seed biochar to soil represents an alternative technique that enhances soil physicochemical characteristics and soil functioning as part of the ecosystem and the broader environment over the long term [7]. Due to its structural and porous properties, biochar proves effective in adsorption [10]. Biochar derived from avocado seeds is produced and utilized primarily as a substitute for soil conditioners [11].

The quality of biochar is influenced by both the type of raw material and the manufacturing process, with one of the key influencing factors being the pyrolysis temperature. Biomass, such as avocado seeds, is processed at temperatures ranging from 400 to 600 ℃ to produce solid (bio-char) and liquid (bio-oil) products, with or without a catalyst. Optimal conditions for bio-oil production (37.5%) were found to be at 600 ℃ with a heating rate of 50 ℃/min in the presence of a KOH catalyst. Avocado seed pyrolysis demonstrates potential as a technology for producing sustainable fuels and valuable compounds [12]. Biochars produced at higher temperatures have a more pronounced impact on soil fertility than those made at lower temperatures [13]. Pyrolysis of avocado seeds at 500 ℃, with a heating rate of 10 ℃/min and a retention period of 20 minutes, in a liquid product (32%), solid product "char" (34%), and gaseous product (34%), with a biomass conversion rate of 67%, and avocado seed pyrolysis shows promise as a method for producing activated carbon, biofuel, and valuable compounds [14].

Pyrolysis biochars (500-600 ℃) have demonstrated the potential for use as soil additives and an efficient technique for carbon sequestration, nutrient retention, and water retention. The porous structure of high temperature biochars can support soil microorganism activity, enhance water absorption, and increase soil density. Additionally, the high alkalinity of biochar can help neutralize acidic soil, thereby improving soil fertility and plant growth [15]. Biochar begins to decompose at pyrolysis temperatures below 400 ℃, particularly between 220 and 350 ℃ [16]. Pyrolysis is a process that involves heating organic materials to temperatures exceeding 400-500 ℃ in the absence of oxygen. This process converts the original biomass into solid biochar, condensable oil, and gaseous fractions due to enhanced cracking and carbonization reactions [17]. The pyrolysis of avocado seeds can cause the thermal degradation of the polymeric components of avocado seeds, primarily starch, but also cellulose, lignin, and hemicellulose, at temperatures ranging from 250 ℃ to 500 ℃ [18]. Torrefaction and pyrolysis were conducted using a rotary furnace at temperatures ranging from 150 ℃ to 900 ℃ to increase the concentration of synthesis gases (H2, CO) and CO_2 [19]. Therefore, this study aims to investigate the impact of different pyrolysis temperatures on the characteristics of biochar derived from avocado seeds, a global problem due to the consumption and use of avocados as raw material in the global food industry.

2. Materials and Methods

2.1. Material Preparation

The samples consisted of avocado seeds (*Persea americana*) obtained from traditional markets. These avocado seeds were washed and cleaned using water to remove dirt, such as soil and husk. Then, they were cut into slices resembling chips and air-dried for 24 hours. Following this initial drying phase, the avocado seeds were further processed by drying them in an oven at 105 ℃ for 24 hours. Avocado seeds that have undergone this oven process are now ready to be used in the production of biochar through a pyrolysis process (Figure 1).

Figure 5. XRD diagram of biochar avocado seed under different pyrolysis temperatures

Figure 5 illustrates the XRD spectra at temperatures of 300 ℃, 400 ℃, 500 ℃, and 600 ℃. The pyrolysis process alters the structure of the biochar from amorphous to crystalline as the temperature increases. The XRD results show that the crystal and amorphous indexes decrease as the pyrolysis temperature rises and undergo significant changes at 300 ℃, 400 ℃, and 500 ℃. However, at a temperature of 600 ℃, the sample appears to have reached a saturation point. The diffraction peak of 2-theta at 300 ℃ is relatively high at 19.4°. After increasing the temperature to 400 ℃, 500 ℃, and 600 ℃, the peak shifted to 23.7°, 23.8°, and 24.1°, respectively. Based on the data, there is no further increase in crystallinity at temperatures of 300 ℃, 400 ℃, 500 ℃, and 600 ℃, indicating that the formation of double bonds (C=C) in biochar is not very significant and pointing to a lack of crystalline order in the structure.

XRD analysis of biochar pyrolyzed at 300 ℃, 400 ℃, 500 ℃, and 600 ℃ shows the presence of relatively wide and less sharp diffraction peaks. These peaks indicate that biochar at these temperatures tends to have an amorphous or semi-amorphous structure [35]. Biochar at these temperatures may possess good adsorption potential for organic and inorganic compounds in waste. Its unique properties can be utilized in environmental restoration, soil quality improvement, and treating waste due to biochar's ability to interact with various components in the environment, such as pollutants or heavy metals [36-38].

3.4. Ultimate Analysis

In the ultimate analyses, as depicted in Table 2, it becomes evident that with an increase in pyrolysis temperature from 300 ℃ to 600 ℃, there is a notable increase in the carbon content of the biochars, ranging from 63.76% to 74.18%. Conversely, the hydrogen content experiences a decrease from 5.05% to 2.77%, while the oxygen content drops from 16.00% to 8.60%. This observation implies that raising the pyrolysis temperature leads to a higher degree of carbonization in the biochars, causing them to become progressively more aromatic, as indicated by Chen et al. [39]. Due to the pyrolysis process, the biochars exhibit an increase in carbon content compared to the original biomass, accompanied by deoxygenation resulting from the loss of functional groups during pyrolysis. The reduction in hydrogen and oxygen levels corresponds to the breakage of weaker bonds within the biochar structure, a change favored by higher temperatures. Furthermore, the decrease in hydrogen content can be attributed to the higher proportion of hydrogen compounds in the volatile matter, as discussed by Sánchez et al. [40]. Additionally, the nitrogen contents in the biochar decrease from 1.79% to 1.61% with increasing pyrolysis temperature.

Table 2. Ultimate analysis of biochar avocado seed under different pyrolysis temperatures

	Pyrolysis temperature			
	300 ℃	**400 ℃**	**500 ℃**	**600 ℃**
C (%)	63.763	69.269	73.394	74.176
H (%)	5.053	3.995	3.359	2.77
N (%)	1.766	1.797	1.751	1.61
O (%)	15.000	16.000	9.100	8.600
H/C	0.079	0.057	0.045	0.037
O/C	0.235	0.230	0.123	0.115

The decrease in H/C ratios and the increase in O/C ratios with rising temperature indicate a growing level of aromaticity in the biochar, as noted in the study by Mui et al. [41]. The O/C ratios of the biochar were at their lowest at 600 ℃, whereas they were highest at 300 ℃. This signifies that biochar produced at higher temperatures has lower oxygen content, as discussed in the research conducted by Fu et al. [42].

3.5. Element Content of Avocado Seed Biochar by X-Ray Fluorescence

The elemental composition of biochar determined through X-Ray Fluorescence (XRF) analysis is presented in Table 3. The results from XRF analysis detected a total of 8 elements: K_2O, P_2O_5, Fe_2O_3, SO_3, MnO, ZnO, CuO, and Rb_2O. It's important to note that the data represents the percentage of each element rather than the actual concentration. The percentages of elements SO_3, MnO, ZnO, CuO, and Rb2O decreased as the pyrolysis temperature increased. However, K_2O, P_2O_5, and Fe_2O_3 did not show a clear pattern in relation to pyrolysis temperature. The presence of these elements in biochar is influenced by the process of partial diffraction or devolatilization occurring at elevated temperatures, as indicated in studies by Hossain et al. [43] and Claoston et al. [44]. According to the XRF analysis, K_2O, P_2O_5, and SO_3 are the dominant elements among these, and all three are classified as macronutrients.

Table 3. Element of biochar avocado seed under different pyrolysis temperatures

Element content (%)	Raw material	Pyrolysis temperature			
		300 ℃	**400 ℃**	**500 ℃**	**600 ℃**
K_2O	83.930	88.407	89.200	89.532	88.405
P_2O_5	7.768	6.747	6.413	6.627	7.533
Fe_2O_3	1.174	0.661	0.594	0.625	0.836
SO_3	5.284	3.467	3.176	2.610	2.731
MnO	0.129	0.079	0.067	0.073	0.059
ZnO	0.348	0.200	0.151	0.148	0.099
CuO	0.223	0.140	0.106	0.105	0.073
Rb_2O	0.518	0.295	0.213	0.216	0.140

3.6. Potential Application of Avocado Seed Biochar as Soil Amendment

Land use for diverse activities and purposes is rising and becoming more intensive, affecting the land component's quality [45]. Furthermore, ongoing agricultural intensification with inorganic fertilizers has reduced soil quality [46]. Soil amendments can be employed to address this problem, and one such material is biochar.

Biochar, an organic material rich in carbon, results from heating organic matter in an oxygen-deprived environment, a process known as pyrolysis. It has been verified that the carbon content in avocado seed biochar falls within the range of 63.76% to 74.18% (as shown in Table 1). Carbon in biochar exhibits remarkable stability, taking more than a century to decompose. Consequently, amending soils with biochar represents an effective means of carbon sequestration. Biochar functions by sequestering carbon, storing it within the soil, and preventing it from undergoing decomposition, as elucidated by Lehmann et al. [47]. Pyrolysis processes, through biochar formation, contribute to reducing the amount of carbon dioxide in the atmosphere [10].

On the other hand, avocado seed biochar also contains essential macronutrients such as Nitrogen, K_2O, P_2O_5, and SO_3. When used as a soil amendment, it enhances various soil attributes, including physical and biochemical properties, soil fertility, and productivity. Over the long term, it contributes to soil improvement by promoting soil aggregation, enhancing water retention, modifying pH levels, and fostering microbial activities. This overall enhancement of soil quality has the potential to reduce the need for chemical fertilizers over time, as discussed in the study by Nepal et al. [48].

4. Conclusions

In this study, we investigated how varying pyrolysis temperatures affect the properties of biochar derived from avocado seed waste (*Persea americana*). The temperature at which pyrolysis occurs plays a crucial role in shaping the characteristics of biochar. At 400 ℃, pores began to form on the biochar's surface, becoming more pronounced at a pyrolysis temperature of 500 ℃. As the pyrolysis temperature increased from 300 ℃ to 600 ℃, we observed an increase in the carbon content and C/N ratio, accompanied by a decrease in H, O, N, H/C, and O/C values. This was expected since higher pyrolysis temperatures lead to greater devolatilization, resulting in biochar that is predominantly composed of carbon. FTIR analysis revealed functional groups in the biochar, including O–H, C-H, C=C, and C=O. The primary elements found in avocado seed biochar are K_2O, P_2O_5, and SO_3, which are categorized as macronutrients. Based on our analysis, biochar produced from avocado seeds shows potential as a soil amendment.

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REFERENCES

[1] Ahmad T., Danish M., “A review of avocado waste-derived adsorbents: Characterizations, adsorption characteristics, and surface mechanism,” Chemosphere vol. 296, pp. 134036, 2022. DOI: 10.1016/j.chemosphere.2022.134036.

[2] Faris A., “Review on avocado value chain in Ethiopia,” Industrial Engineering Letters, vol. 6, no. 3, pp. 33–40, 2016.

[3] Tesfaye T., Ayele., Gibril M., Ferede E., Limeneh D. Y., Kong F., “Beneficiation of avocado processing industry by-product: A review on future prospect,” Current Research in Green and Sustainable Chemistry, vol. 5, pp.100253, 2022. DOI: 10.1016/j.crgsc.2021.100253.

[4] Sánchez F., Araus K., Domínguez M. P., San-Miguel G., “Thermochemical transformation of residual avocado seeds: torrefaction and carbonization,” Waste and Biomass Valorization, vol. 8, no. 7, pp. 2495-2510, 2017. DOI: 10.1007/s12649-016-9699-6.

[5] Valensya D., Rozalia I., Syamsuddin Y., “Utilization of avocado seed waste as raw material for producing biodiesel with cao catalyst from eggshell,” IOP Conference Series: Materials Science and Engineering, vol. 845, no. 1, p. 012020, 2020. DOI: 10.1088/1757-899X/845/1/012020.

[6] Zhu Y., Kolar P., Shah S. B., Cheng J. J., Lim P. K., “Avocado seed-derived activated carbon for mitigation of aqueous ammonium,” Industrial Crops and Products, vol. 92, pp. 34-41, 2016. DOI: 10.1016/j.indcrop.2016.07.016

[7] Demissie H., Gedebo A., Agegnehu G., “Agronomic potential of avocado-seed biochar in comparison with other locally available biochar types: a first-hand report from Ethiopia,” Applied and Environmental Soil Science, vol. 2023, pp. 1-15, 2023. DOI: 10.1155/2023/7531228.

[8] Van Y., Jaromír J., Tin C., “Environmental performance and techno-economic feasibility of different biochar applications: An overview,” Chemical Engineering Transactions”, vol. 83, pp. 469–474, 2021. DOI: 10.3303/CET2183079.

[9] Crowley D., “Biochar as a soil amendment for avocado production,” California Avocado Society 2012 Yearbook, 2012.

[10] Chaiwong K., Kiatsiriroat T., Vorayos N., Thararax C., “Study of bio-oil and bio-char production from algae by slow pyrolysis,” Biomass and Bioenergy, vol. 56, pp. 600-606, 2013. DOI: 10.1016/j.biombioe.2013.05.035.

[11] Hafiza S., Riaz A., Arshad Z., Zahra S. T., Akhtar J., Kanwal S., Zeb H., Kim J., “Effect of pyrolysis temperature on the physiochemical properties of biochars produced from raw and fermented rice husks,” Korean Journal of Chemical Engineering, vol. 40, pp. 1986–1992, 2023, DOI: 10.1007/s11814-023-1465-4.

[12] Durak H., Aysu T., “Effect of pyrolysis temperature and catalyst on production of bio-oil and bio-char from avocado seeds,” Research on Chemical Intermediates, vol. 41, pp. 8067-8097, 2015. DOI: 10.1007/s11164-014-1878-0.

[13] Antal MJ., Grønli M., “The art, science, and technology of charcoal production,” Industrial & Engineering Chemistry Research, vol. 42, no. 8, pp. 1619–1640, 2003. DOI: 10.1021/ie0207919.

[14] Yarbay-Şahin RZ., Örenay O., Dolaş Y., Yargıç AŞ., Özbay N., “Experimental study of thermal pyrolysis of avocado seed for liquid fuel production,” International Journal of Innovative Approaches in Agricultural Research, vol. 4, no. 4, pp. 447-452, 2020. DOI: 10.29329/ijiaar.2020.320.6.

[15] Dhar S. A., Sakib T. U., Hilary L. N., “Effects of pyrolysis temperature on production and physicochemical characterization of biochar derived from coconut fiber biomass through slow pyrolysis process,” Biomass Conversion and Biorefinery, vol. 12, no. 7, pp. 2631-2647, 2022. DOI: 10.1007/s13399-020-01116-y.

[16] Tsai C. H., Tsai W. T., Liu S. C., Lin, Y. Q., “Thermochemical characterization of biochar from cocoa pod husk prepared at low pyrolysis temperature,” Biomass Conversion and Biorefinery, vol. 8, pp. 237-243, 2018. DOI: 10.1007/s13399-017-0259-5.

[17] Mohan D., Sarswat A., Ok Y. S., “Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - A critical review,” Bioresource Technology, vol. 160, pp. 191-202, 2014. DOI: 10.1016/j.biortech.2014.01.120.

[18] Elizalde-González M. P., Mattusch J., Peláez-Cid A. A., Wennrich R., “Characterization of adsorbent materials prepared from avocado kernel seeds: Natural, activated and carbonized forms,” Journal of Analytical and Applied Pyrolysis, vol. 78, no. 1, pp. 185-193, 2007. DOI: 10.1016/j.jaap.2006.06.008.

[19] García-Vargas M. C., Contreras M. D. M., Castro E., “Avocado-derived biomass as a source of bioenergy and bioproducts,” Applied Sciences, vol. 10, no. 22, pp. 8195, 2020. DOI: 10.3390/app10228195.

[20] Ma X., Zhou, B., Budai A., Jeng A., Hao X., Wei D., Zhang Y., Rasse D., “Study of biochar properties by scanning electron microscope—energy dispersive X-ray spec-troscopy (SEM-EDX),” Communications in Soil Science and Plant Analysis, vol. 47, no. 5, pp. 593-601, 2016. DOI: 10.1080/00103624.2016.1146742.

[21] Mutolib A., Rahmat A., Triwisesa E., Hidayat H., Hariadi H., Kurniawan K., Sutiharni S., Sukamto S., “Biochar from agricultural waste for soil amendment candidate under different pyrolysis temperatures,” Indonesian Journal of Science and Technology, vol. 8, no. 2, pp. 243-258, 2023. DOI: 10.17509/ijost.v8i2.55193.

[22] Rahmat A., Sutiharni S., Elfina Y., Yusnaini Y., Latuponu H, Minah F. N., Sulistyowati Y., Mutolib A., “Characteristics of Tamarind Seed Biochar at Different Pyrolysis Temperatures as Waste Management Strategy: Experiments and Bibliometric Analysis,” Indonesian Journal of Science and Technology, vol. 8, no. 3, pp. 517-538, 2023. DOI: 10.17509/ijost.v8i3.63500.

[23] Pariyar P., Kumari K., Jain M. K., Jadhao P. S., "Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application," Science of The Total Environment, vol. 713, p. 136433, 2020. DOI: 10.1016/j.scitotenv.2019.136433.

[24] Muzyka R., Misztal E., Hrabak J., Banks S. W., Sajdak M., "Various biomass pyrolysis conditions influence the porosity and pore size distribution of biochar," Energy, vol. 263, p. 126128, 2023. DOI: 10.1016/j.energy.2022.126128.

[25] Fuertes A. B., Arbestain M. C., Sevilla M., Maciá-Agulló J. A., Fiol S., López R., Smernik R. J., Aitkenhead W. P., Arce F., Macìas F., "Chemical and structural properties of carbonaceous products obtained by pyrolysis and hydrothermal carbonisation of corn stover," Soil Research, vol. 48, no. 7, pp. 618-626, 2010. DOI: 10.1071/SR10010.

[26] Mohanty P., Nanda S., Pant K. K., Naik S., Kozinski J. A., Dalai A. K., "Evaluation of the physiochemical development of biochars obtained from pyrolysis of wheat straw, timothy grass and pinewood: effects of heating rate," Journal of Analytical and Applied Pyrolysis, vol. 104, pp. 485-493, 2013. DOI: 10.1016/j.jaap.2013.05.022.

[27] Kim K. H., Kim J. Y. Y., Cho T. S. S., Choi J. W., "Influence of pyrol-ysis temperature on physicochemical properties of biochar obtained from the fast pyrolysis of pitch pine (Pinus rigida)," Bioresource Technology, vol. 118, pp. 158–162, 2012. DOI: 10.1016/j.biortech.2012.04.094.

[28] Mukherjee S., Sarkar B., Aralappanavar V. K., Mukhopadhyay R., Basak B. B., Srivastava P., Marchut-Mikolajczyk O., Bhatnagar A., Semple K. T., Bolan N., "Biochar-microorganism interactions for organic pollutant remediation: Challenges and perspectives," Environmental Pollution, vol. 308, p. 119609, 2022. DOI: 10.1016/j.envpol.2022.11960

[29] Bolan S., Hou D., Wang L., Hale L., Egamberdieva D., Tammeorg P., Li R., Wang B., Xu J., Wang T., Sun H., Padhye L. P., Wang H., Shiddique K. H. M., Rinklebe J., Kirkham M. B., Bolan N., "The potential of biochar as a microbial carrier for agricultural and environmental applications," Science of the Total Environment, vol. 86, p. 163968, 2023. DOI: 10.1016/j.scitotenv.2023.163968

[30] Mullen C. A., Boateng A. A., Goldberg N. M., Lima I. M., Laird D. A., Hicks K. B., "Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis," Biomass and Bioenergy, vol. 34, no. 1, pp. 67–74, 2010. DOI: 10.1016/j.biombioe.2009.09.012.

[31] Angın D., Sensöz S., "Effect of pyrolysis temperature on chemical and surface properties of biochar of rapeseed (Brassica napus L.)," International Journal of Phytoremediation, vol. 16, pp. 684–693, 2014. DOI: 10.1080/15226514.2013.856842

[32] Li S., Chen G., "Thermogravimetric, thermochemical, and infrared spectral characterization of feedstocks and biochar derived at different pyrolysis temperatures," Waste Management, vol. 78, pp. 198–207, 2018. DOI: 10.1016/j.wasman.2018.05.048.

[33] Jindo K., Mizumoto H., Sawada Y., Sanchez-Monedero M. A., Sonoki T., "Physical and chemical characterization of biochars derived from different agricultural residues," Biogeosciences, vol. 11, pp. 6613–6621, 2014. DOI: 10.5194/bg-11-6613-2014.

[34] Reza M. S., Islam S. N., Afroze S., Abu Bakar M. S., Sukri R. S., Rahman S., Azad A. K., "Evaluation of the bioenergy potential of invasive Pennisetum purpureum through pyrolysis and thermogravimetric analysis," Energy, Ecology and Environment, vol. 5, pp. 118-133, 2020. DOI: 10.1007/s40974-019-00139-0.

[35] Bardalai M., Mahanta D. K., "Characterisation of biochar produced by pyrolysis from areca catechu dust," Materials Today: Proceedings, vol. 5, no. 1, pp. 2089-2097, 2018. DOI: 10.1016/j.matpr.2017.09.205.

[36] Mohan D., Pittman J. C. U., Steele P. H., "Pyrolysis of wood/biomass for bio-oil: a critical review," Energy & fuels, vol. 20, no. 3, pp. 848-889, 2006. DOI: 10.1021/ef0502397.

[37] Uchimiya M., Wartelle L. H., Klasson K. T., Fortier C. A., Lima I. M., "Influence of pyrolysis temperature on biochar property and function as a heavy metal sorbent in soil," Journal of Agricultural and Food Chemistry, vol. 58, no. 9, pp. 5538-5547, 2010. DOI: 10.1021/jf104206c.

[38] Ahmad M., Lee S. S., Dou X., Mohan D., Sung J. K., Yang J. E., Ok Y. S., "Effects of pyrolysis temperature on soybean stover-and peanut shell-derived biochar properties and TCE adsorption in water," Bioresource Technology, vol. 118, pp. 536-544, 2012. DOI: 10.1016/j.biortech.2012.05.042.

[39] Chen Y., Yang H., Wang X., Zhang S., Chen H., "Biomass-based pyrolytic polygeneration system on cotton stalk pyrolysis: Influence of temperature," Bioresour Technol, vol. 107, pp. 411–418, 2012. DOI: 10.1016/j.biortech.2011.10.074.

[40] Sánchez M. E., Lindao E., Margaleff D., Martínez O., Morán A., "Pyrolysis of agricultural residues from rape and sunflowers: Production and characterization of bio-fuels and biochar soil management," Journal of Analytical and Applied pyrolysis, vol. 85, no. 1-2, pp. 142-144, 2009. DOI: 10.1016/j.jaap.2008.11.001.

[41] Mui E. L. K., Cheung W. H., Valix M., McKay G., "Dye adsorption onto char from bamboo," Journal of Hazardous Materials, vol. 177, pp. 1001–1005, 2010. DOI: 10.1016/j.jhazmat.2010.01.018.

[42] Fu P., Yi W., Bai X., Li Z., Hu S., Xiang J., "Effect of temperature on gas composition and char structural features of pyrolyzed agricultural residues," Bioresource Technology, vol. 102, no. 17, pp. 8211–8219, 2011. DOI: 10.1016/j.biortech.2011.05.083.

[43] Hossain M. K., Strezov V., Chan K. Y., Ziolkowski A., Nelson P. F., "Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar," Journal of Environmental Management, vol. 92, no. 1, pp. 223-228, 2011. DOI: 10.1016/j.jenvman.2010.09.008.

[44] Claoston N., Samsuri A. W., Ahmad-Husni M. H., Mohd-Amran M. S., "Effects of pyrolysis temperature on the physicochemical properties of empty fruit bunch and rice husk biochars," Waste Management & Research, vol. 32, no. 4, pp. 331-339, 2014. DOI: 10.1177/0734242X14525822.

[45] Darma S., Fahrunsyah F., "Effect of soil damage on carrying capacity of biomass production: A lesson from

Tanjung Selor District – Tanjung Redeb, Indonesia," Universal Journal of Agricultural Research, vol. 10, no. 6, pp. 682-690, 2022. DOI: 10.13189/ujar.2022.100609.

[46] Triharyanto E., Setyaningrum D., Muhammad D. M., "Potential of liquid organic fertilizer on flowering, yield of shallots (Allium cepa L. Aggregatum) and soil quality, Universal Journal of Agricultural Research, vol. 10, no. 5, pp. 526-533, 2022. DOI: 10.13189/ujar.2022.100507.

[47] Lehmann J., Gaunt J., Rondon M., "Biochar sequestration in terrestrial ecosystems-A review," Mitigation and Adaptation Strategies for Global Change, vol. 11, pp. 403–427, 2006. DOI: 10.1007/s11027-005-9006-5.

[48] Nepal J., Ahmad W., Munsif F., Khan A., Zou Z., "Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications," Frontiers in Environmental Science, Vol. 11:1114752. 2023. DOI: 10.3389/fenvs.2023.1114752.