CHEMICAL ENGINEERING TRANSACTIONS
VOL. 81, 2020

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081072

Lignocellulosic Biomass and Food Waste for Biochar Production and Application: A Review

Cassendra P.C. Bong[a], Li Yee Lim[a], Chew Tin Lee[a,*], Pei Ying Ong[b], Jiří Jaromír Klemeš[c], Chunjie Li[d], Yueshu Gao[d]

[a]School of Chemical and Energy Engineering, Universiti Teknologi Malaysia (UTM), 81310, Johor, Malaysia.
[b]Innovation Centre in Agritechnology for Advanced Bioprocessing, Universiti Teknologi Malaysia, 84600, Pagoh, Johor, Malaysia.
[c]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 00 Brno, Czech Republic
[d]School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
ctlee@utm.my

The production of biochar from waste materials by pyrolysis can play a significant role in materialising the circular economy. The application of biochar with positive impacts are attributed by the unique properties of biochar, including its surface area, porous structure, functionality and adsorption capacity. The application of biochar with higher stability and resistance due to higher fixed C content contributes to a better C sequestration in the soil. The application of biochar with higher surface area and electrical conductivity is better for adsorption whereas biochar rich with nutrient element is suitable for plant uptake and agricultural purposes. The properties enabling such applications are found to have a varying degree of dependence on the feedstock composition and pyrolysis temperature. The biochar has been conventionally produced from lignocellulosic-rich biomass. There is increasing interest in the use of manure and food waste to produce biochar via pyrolysis. These wastes differ significantly on their lignocellulosic content and mineral content, ash content and elemental content. This difference could give rise to different biochar yield and providing varying properties. Different structural and degradability of the organic pools could lead to different optimum processing condition and the properties of biochar. In this review, the feedstock of interest is lignocellulosic biomass, food waste and manure where the variation in their compositions may contribute to specific properties of the biochar, such as stability, polarity, pH, cation exchange capacity, heating value, surface area and minerals content. The desired applications of biochars include C sequestration, fuel, soil amendment, enhanced crop nutrient and adsorption for pollutant remediation. This paper provides an overview for an optimal selection of the feedstock composition and the properties of the biochar produced via pyrolysis, and their subsequent applications. Overall, it was found that the applications as a soil amendment and adsorption material are the most commonly suited applications for biochar derived from the three reviewed feedstock. Lignocellulosic biomass-derived biochar showed a more significant advantage for C sequestration and as fuel, while manure- and food waste-derived biochar showed a greater functionality in retaining soil nutrients and absorbing pollutants.

1. Introduction

Pyrolysis is a thermal conversion process under zero or limited supply oxygen at a temperature of 300-700 ºC, which transforms organic materials into various products including carbonaceous solid biochar, liquid bio-oil and non-condensable gas. Biochar is of high interest as it can be used for C sequestration and for soil application which leads to a circular economy as biomass is recycled for use. The release of the moisture, decomposition of the volatile matter and changes of the C structure during pyrolysis produces biochar with the unique physicochemical properties and functionality (Tan et al., 2017). These properties give rise to the capability of biochar to be utilised for different applications, such as adsorption of heavy metals (Tang et al., 2020) and herbicides (Yavari et al., 2017), crop improvement by pH buffering (Zhao et al., 2013) and nutrient retention

Paper Received: 01/05/2020; Revised: 30/05/2020; Accepted: 08/06/2020
Please cite this article as: Bong C.P., Lim L.Y., Lee C.T., Ong P.Y., Klemeš J.J., Li C., Gao Y., 2020, Lignocellulosic Biomass and Food Waste for Biochar Production and Application: A Review, Chemical Engineering Transactions, 81, 427-432 DOI:10.3303/CET2081072

(Parivar et al., 2020), refused derived fuel (RDF) (Lee et al., 2017a) and C sequestration in soil (Liew et al., 2018). There are more than 55 potential uses of biochar in which the selection of the suitable final application is dependent on the biochar properties such as its chemical composition, surface functional groups and textural properties (Guizani et al., 2019).

The quality (properties) and quantity (yield) of the biochar are affected by the feedstock and the operating parameters such as residence time, particle size, heating rate, temperature and more (Tripathi et al., 2016). Different feedstocks produce biochar with different qualities and properties that are more suitable for certain applications. The biochar derived from manure showed higher P and K content than straw-based biochar, thus is preferable for supplying crops nutrients (Zhao et al., 2013). Yavari et al. (2017) showed that biochar derived from empty fruit bunch (EFB) showed better adsorption for herbicides compared to straw-based biochar due to its higher polarity and cation exchange capacity (CEC). The high lignin content favours char formation, and cellulose favours tar formation (Tripathi et al., 2016) whereas high O favours liquid yield (Elkhalifa et al., 2019). Food waste has a relatively lower lignocellulosic content (7.4 wt.%) as compared to the lignocellulosic biomass like straw (73.8 wt.%) (Yong et al., 2015) and EFB (> 90 wt.%) (Lee et al., 2017b). In terms of volatile solids (VS), food waste consists of 36 % VS of carbohydrates, 26 % VS of protein and 15 % VS of fats (Fisgativa et al., 2016). The C in the lignocellulosic components are carbonised and transformed into aromatic and highly polymerised structures which are relatively stable (Zhao et al., 2013). The thermal degradation of carbohydrates, proteins and lipids can exhibit a different effect on the biochar properties than the lignocellulosic components due to the stability, biodegradability and thermadegradability of different C pools and polymer structures.

In terms of process parameters, the pyrolysis temperature and residence time have been regarded as the most critical parameters. Slow pyrolysis with a slower heating rate (0.1 - 10 °C/s) (Foong et al., 2020), lower temperature (300 - 500 ºC) and longer residence time (5 - 30 min) favours biochar yield (Elkhalifa et al., 2019) due to the sufficient recondensation and repolymerisation of the released volatiles into biochar. The biochar yield was 25 - 50 wt.%, 15 - 25 wt.% and 5 - 15 wt.% for slow pyrolysis, fast pyrolysis and flash pyrolysis based on their process temperature, heating rate and residence time (Foong et al., 2020). The heating rate was reported to have no clear significance on the composition of the produced biochar (Guizani et al., 2019). Liew et al. (2018) observed that pyrolysis of oil palm biomass at higher microwave power (700 W) had lower char yield (33 wt.%). Still, a higher heating value (26 MJ/kg) than at 500 W. Higher pyrolysis temperature gave rise to a lower char yield but produce biochar with higher stability and resistance due to higher fixed C content (Zhao et al., 2013). The higher C content in biochar (high-temperature pyrolysis) is related to applications such as tar removal by adsorption on biochar, the stability of biochar on soil amendment and C sequestration for global warming mitigation (Crombie et al., 2013).

The desired properties of the biochar that represents different functionalities can be more feedstock-dependent or temperature-dependent. Most studies focus on the biochar properties under different process parameters and single feedstock stream, such as lignocellulosic biomass (Tripathi et al., 2016), food waste (Elkhalifa et al., 2019) and agricultural waste, including crops and animal manure (Wang and Wang, 2019). Tripathi et al. (2016) focus on the biochar yield on different pyrolysis technologies and the effect of operating parameters. Elkhalifa et al. (2019) reviewed on the pyrolysis of food waste to biochar and observed the effect of type of food waste and process parameters on the yield and properties of the biochars produced. Wang and Wang (2018) reviewed on the approaches to modify the biochar according to the environmental applications such as soil amendment, composting and C sequestration. There is still limited studies on comparing the biochar properties prepared from the three interested feedstocks (lignocellulosic biomass, food waste and manure) and their subsequent suitability for different applications. More insight on the physiochemical variations in biochar is important to maximise the specific function of the biochar (Zhao et al., 2013). This paper aims to review the properties of biochar derived from lignocellulosic biomass, manure and food waste, with different composition and process temperature, towards their optimal utilisation for the desired final applications. A matching diagram was consolidated from the review on these feedstocks to the corresponding properties of the biochars and their final applications.

2. Selection of feedstocks for the desired applications of biochar

The feedstocks of interest are lignocellulosic biomass, manure and food waste. Lignocellulosic feedstock, including woody biomass and agricultural biomass, consists mainly 40 - 60 wt.% cellulose, 15 - 30 wt.% hemicellulose and 10 - 25 wt.% lignin (Foong et al., 2020). Different proportions of these three components determined the various elements, mainly C, H, O and N, which can affect the biochar properties (Zhu et al., 2019). The main compositions of food waste are carbohydrates, proteins and lipid, which varies depending on the type of food waste, such as bread, rice, fish waste, vegetable waste and mixed food waste.

Lee et al. (2017b) compared the pyrolysis of three types of oil palm biomass, namely palm kernel shell (PKS), empty fruit bunch (EFB) and palm oil sludge (POS) at 500 °C. The solid residues (PKS and EFB) produced biochar with lower ash content (< 20 wt.%) and high heating value of 27.50 and 26.18 MJ/kg, which is doubled of the sludge-derived biochar. The PKS- and EFB-derived biochar are suitable to be used as RDF due to a heating value comparable to coal. The difference is attributed to the higher content of lignin, volatile matter, C content and lower ash content of the solid residues than sludge. Fu et al. (2019) showed that food waste-derived biochar exhibited relatively lower ash content of 1.98 - 55.05 wt.%, where carbohydrate- or protein-rich feedstock such as cooked rice, bread crumbs and fish residue had an ash content lower than 10 wt.%.

The feedstock composition also influences the adsorption capacities of the produced biochar. Xue et al. (2019) compared the efficiency for the adsorption of ammonia N from 7 types of food waste. Those with higher lignocellulosic content and less ash content such as tea leaves, nut husks and fruit pericarp, showed a higher surface area and a higher number of pores with a better adsorption capacity of ammonia N as compared to starchy staples, meat and bone. Yavari et al. (2017) found that the adsorption of herbicides is more effective for EFB-biochar than rice husk-biochar due to its higher polarity index of 0.42 and higher CEC of 83.9 $cmol_c$/kg, as indicated by the presence of more oxygenated functional groups such as the hydroxyl and carbonyl groups. Fu et al. (2019) investigated the properties of biochar derived from food waste, including eggshell, fish residue, breadcrumb, cooked rice and mixed food waste. The C content of biochar varied from 13 - 80 wt.% depending on the type of food waste. One distinct characteristic is that all the biochar had a relatively lower surface area of less than 2 m^2/g, except for mixed food waste (17.7 m^2/g) with the presence of lipid materials. Biochar from pig manure had a surface area of 8.28 m^2/g (Shen et al., 2020) where lignocellulosic biomass-derived biochar had a range of larger surface area of 10 - 300 m^2/g (Foong et al., 2020). The biochar of larger surface area and pore volume of 25.17 m^3/kg at 700 ºC, along with higher pH, contribute to the immobilisation of heavy metal of manure-based biochar (Shen et al., 2020).

Zhao et al. (2013) studied on 12 different feedstocks, including woody biomass, food waste, animal manure and agricultural biomass, with a pyrolysis temperature of 200 - 650 ºC. The biochar produced showed different properties that are suitable for different final applications. Biochar derived from pig manure and wastewater sludge are rich in P, K and minerals, with P ranging from 1.7 - 4.7 g/kg, K of 0.5 - 3.8 g/kg and an ash content of greater than 50 wt.%, showing high agronomic value. Other feedstocks had P content of less than 2 g/kg but grass- and wheat-based biochar had relatively higher K of 5.1 g/kg. The biochar derived from P and K rich feedstock might also be suitable for C sequestration as soluble P resulted in crosslinking of C bonds during pyrolysis (Zhao et al., 2014).

Parivar et al. (2020) compared the properties of biochar from sawdust, rice husk, food waste, poultry litter, and paper sludge to be used for environmental and agricultural activities. The manure-biochar had the highest CEC of 67.23 $cmol_c$/kg, and food waste-biochar had the lowest with 6.69 $cmol_c$/kg. Zhao et al. (2013) observed great variation in the CEC, 41.7 - 562 $cmol_c$/kg, following different feedstocks, with sawdust-biochar with the lowest and peanut shell-biochar as the highest. Higher CEC indicates higher ability to adsorb nutrients and be able to retain nutrient like K^+ and NH_4^+, preventing nutrient leaching (Bera et al., 2017) and is suitable for soil and crop amendment for agricultural applications. Tang et al. (2020) observed higher efficiency of biochar than compost in reducing the availability of heavy metals but also reducing soil enzymatic activities. The immobilisation of the heavy metals is attributed by the higher pH and CEC, larger surface area and porous structure of the biochar (Jia et al., 2017).

Biochar is well-known for its C sequestration and its beneficial effect for improving soil productivity. The suitability for the use of biochar for this application is based on its fixed C content, molar H/C and O/C ratios that reflect on its resistance and stability (Manya et al., 2018), and the C species retained in the biochar (Zhao et al., 2013). During pyrolysis, 50 % of C is retained in biochar, whereas 10 % is mineralised when biochar is applied to soil (Nan et al., 2020). The recalcitrance and stability of the biochar can be determined by its disintegration by chemical oxidation and biological mineralisation (Nan et al., 2020). A higher temperature of greater than 300 ºC was observed to produce biochar with lower H/C ratio and lower O/C ratio due to the release of O and H and the cracking of the residual biochar (Guizani et al., 2019). A lower H/C ratio indicates higher aromaticity for higher resistance whereas lower O/C indicating lower polarity with lower adsorption (Xue et al., 2019) and lower reactivity (Guizani et al., 2019). Liew et al. (2018) investigated the biochar from oil palm biomass using microwave pyrolysis. At increasing microwave power, the C and fixed C of the biochar increased which gives rise to its aromaticity, associated with low O content, contributes to a higher resistivity to chemical and microbial action, thus suitable for C sequestration. Manyà et al. (2018) investigated the C sequential of biochar from three feedstocks, the corn stover, vine shoots and two-phase olive mill waste. The study observed that an increasing peak temperature from 400 to 600 ºC improved such potential. The improvement follows an increase in the recalcitrance index with a decrease in H:C and O:C, and the stability is feedstock dependent. Biochar produced at a higher temperature generally had higher pH for buffering capacity (Xue et al., 2019), higher surface area and the number of pores and with higher aromaticity but lower polarity due to possible thermal disruption on the surface functional group. Based on machine learning, the C char and the carbonisation degree increased with pyrolysis temperature and is dependent on the C in the feedstock (Zhu et al., 2019). Figure 1 presented the observed properties of the biochar produced from different feedstocks for certain applications.

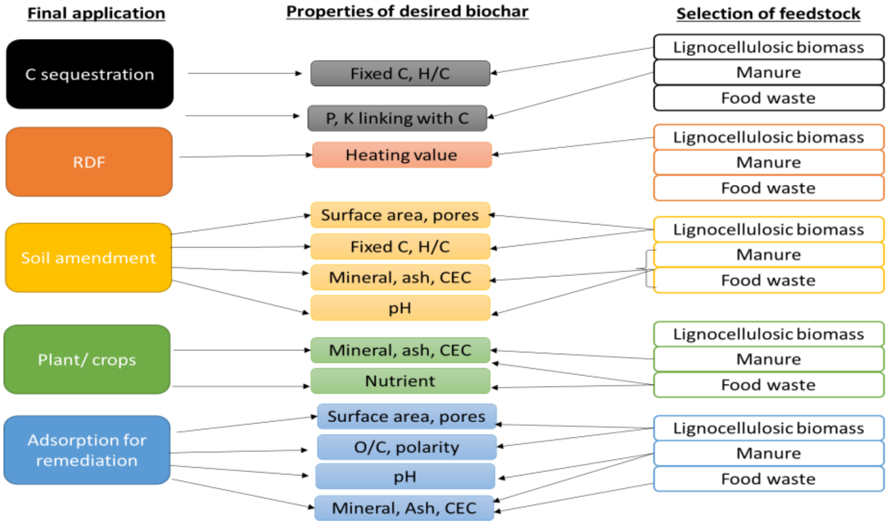

Figure 1: Biochar properties from the pyrolysis of feedstocks for different applications

Soil amendment and adsorption materials are more widely suited for biochar produced from the various feedstock. The beneficial effect of soil amendment can be in the form of structural support in terms of C supply and porosity, whereas adsorption can be of nutrient retention and pollutant removal. These are contributed by the physical properties such as larger surface area and pore size, and the chemical properties such as CEC and functional groups of the biochar. The textural parameters such as pore size, pore volume and surface area increase with increasing processing temperature. Higher temperature improves the physical properties; however, the functional group for adsorption capacity could be significantly disrupted at a temperature greater than 400 ºC (Fu et al., 2019). The effect of temperature might be more significant when food waste is used as feedstock where lignocellulosic based biochar had shown higher surface area for adsorption capacity at a processing temperature of 700 ºC (Shen et al., 2020) or at a microwave power of 700 W (Liew et al., 2018). This is due to the different type of C and their structural linkages between the lignocellulosic biomass and food waste. However, Yavari et al. (2018) had pointed out that the adsorption capacity of herbicides was affected by the functionality of the biochar produced at a lower temperature (300 ºC) than the expanded surface area contributed by higher temperature. Fu et al. (2019) suggested that high temperature is preferable to increase the fixed C in food waste-derived biochar for higher stability, as food waste is rich in carbohydrate that is more biodegradable in nature than lignocellulosic waste.

There is high interest to upgrade conventional biochar to value-added engineered activated biochar by either using gasifying or chemical agents to intensify its porosity and adsorption capacity towards targeted substances (Foong et al., 2020). Alkaline minerals have been used to improve C sequestration along with biochar production. Nan et al. (2020) reported that Mg-doping for the pyrolysis of cow manure at 500 ºC for 2 h exhibited C stability with bulk C of 60 wt.% and surface C of 5.0 g CO_2/ t soil, in addition to the formation of a physical barrier against oxidation and mineralisation on the biochar surface. Biochar from pyrolysis has also been increasingly used in coupling with other waste treatment technologies like anaerobic digestion and composting. Biochar has been observed to increase CH_4 production (Zhang et al., 2020) during the anaerobic digestion of food waste. Biochar was observed to significantly reduce the bioavailability of heavy metals, up to 90.3 % for Cu, during chicken manure composting (Hao et al., 2019). Oldfield et al. (2019) compared the nutrient recovery and C sequestration among compost, biochar and compost-biochar blend. The studies showed that compost had higher nutrient retention, biochar with the lowest global warming potential impact and C recycling, whereas compost-biochar blend showed high recycling for both nutrients and C. Further study is needed in determining the optimal set of operating conditions for a given purpose and a given biomass feedstock (Manyà et al., 2018), with the association of the feedstock logistic and economic consideration (Oldfield et al., 2019). The environmental performance of biochar also differs under different circumstances based on the countries GHG intensity and GHG price (Fan et al., 2019).

The application of biochar to the soil is complicated. The biochar recalcitrance was determined by the processing temperature, whereas the potential of total C sequestration is dependent on the feedstock (Zhao et al., 2013).

The recalcitrance presents the stability of the biochar to contain the sequestrated C against microbial mineralisation. Fan et al. (2020) investigated the effect of soil organic C changes and biochar application for a comprehensive assessment framework of bioenergy C emission footprint. The C footprint is considerably related to the value of the designated value of the global warming potential and the assumption of C neutrality of bioenergy. Biochar can be engineered for GHG mitigation by adsorption of H_2S, NO_x and SO_x (Foong et al., 2020) but there are contradictory findings on such application when only biochar is used and when biochar is applied on different soils (Meschewski et al., 2019). Meschewski et al. (2019) also pointed that the dissolved organic C from biochar, rather than the fixed C, is a more influencing factor to GHG mitigation and the soil microbial community as it can be mineralised by microbes. The high specific surface area, porous structure and the adsorption capacity of biochar can exert a negative impact on soil enzymatic activities, including dehydrogenase and catalyse, by limiting the substrate-enzyme interaction (Tang et al., 2020).

3. Conclusions

The properties of the biochar for certain application are determined by the feedstock composition and process conditions. The application as a soil amendment and adsorption material is the most commonly suited applications for biochar derived from any feedstock. Lignocellulosic biomass-derived biochar showed a greater advantage for C sequestration and as RDF, whilst manure- and food waste-derived biochar showed greater flexibility in retaining nutrients and absorbing targeted substances. The suitability of food waste-based biochar is greatly dependent on the type of food waste used, and most are based on a single type of food waste. There are fewer studies on the use of mixed food waste as a feedstock due to the heterogeneity and the wider range of process temperature for efficient thermal degradation on the varying composition. The application of biochar for GHG mitigation and soil improvement will require more insight into the interaction of biochar with different soil types and soil microbial, and with the different C pools from the soil. A better understanding on the underlying mechanisms can contribute to a better selection of feedstock and design of operating conditions to produce the corresponding biochar with the desired properties for better utilisation and on the environmental impact associated with the biochar application.

Acknowledgements

The authors also acknowledged the funding and support by the EU project Sustainable Process Integration Laboratory – SPIL, funded as project No. CZ.02.1.01/0.0/0.0/15_003/0000456, by Czech Republic Operational Programme Research and Development, Education, Priority 1: Strengthening capacity for quality research under the collaboration agreement with UTM, Malaysia.

References

Bera T., Purakayastha T.J., Patra A.K., Datta S.C., 2017, Comparative analysis of physicochemical, nutrient and spectral properties of agricultural residue biochars as influenced by pyrolysis temperatures, Journal of Material Cycles and Waste Management, 20, 1115-1127,

Crombie K., Mašek O., Sohi S.P., Brownsort, P., Cross, A., 2013, The effect of pyrolysis conditions on biochar stability as determined by three methods, Global Change Biology Bioenergy, 5, 122-131.

Elkhalifa S., Al-Ansari T., Mackey H.R., McKay G., 2019, Food waste to biochars through pyrolysis: a review, Resources, Conservation & Recycling, 144, 310-320.

Fan Y.V., Klemeš J.J., Ko C.H., 2020, Bioenergy carbon emissions footprint considering the biogenic carbon and secondary effects, International Journal of Energy Research, Doi: 10.1002/er.5409

Fan Y.V., Klemeš J.J., Tan R.R., Varbanov P.S., 2019, Graphical break-even based decision-making tool (BBM) to minimise GHG footprint of biomass utilisation: Biochar by Pyrolysis, Chemical Engineering Transactions, 76, 19-25.

Fisgativa H., Tremier A., Dabert P., 2016, Characterising the variability of food waste quality: a need for efficient valorisation through anaerobic digestion, Waste Management, 50, 264-274.

Foong S.Y., Liew R.K., Yang Y., Cheng Y.W., Yek P.N.Y., Wan Mahari W.A., Lee X.Y., Han C.S., Vo D.V.N., Le Q.V., Aghbashlo M., Tabatabaei M., Sonne C., Peng W., Lam S.S., 2020, Valorisation of biomass waste to engineered activated biochar by microwave pyrolysis: Progress, challenges and future directions, Chemical Engineering Journal, 389, 124401.

Fu M.M., Mo C.H., Li H., Zhang Y.N., Huang W.X., Wong M.H., 2019, Comparison of physicochemical properties of biochars and hydrochars produced from food wastes, Journal of Cleaner Production, 236, 117637.

Guizani C., Jeguirim M., Valin S., Peyrot M., Salvador S., 2019, The heat treatment severity index: A new metric correlated to the properties of biochars obtained from entrained flow pyrolysis of biomass, Fuel, 244, 61-68.

Hao J., Wei Z., Wei D., Mohamed T.A., Yu H., Xie X., Zhu L., Zhao Y., 2019, Roles of adding biochar and montmorillonite alone on reducing the bioavailability of heavy metals during chicken manure composting, Bioresource Technology, 294, 122199.

Jia W., Wang B., Wang C., Sun H., 2017, Tourmaline and biochar for the remediation of acid soil polluted with heavy metals, Journal of Environmental Engineering, 5, 2107-2114.

Lee Y.E., Jo J.H., Kim S.M., Yoo Y.S., 2017a, Recycling possibility of the salty food waste by pyrolysis and water scrubbing, Energies, 10, 210.

Lee X.J., Lee L.Y., Gan S., Thangalazhy-Gopakumar S., Ng H.K., 2017b, Biochar potential evaluation of palm oil wastes through slow pyrolysis: Thermochemical characterisation and pyrolytic kinetic studies, Bioresource Technology, 236, 155-163.

Liew R.K., Nam W.L., Chong M.Y., Phang X.Y., Su M.H., Yek P.N.Y., Ma N.L., Cheng C.K., Chong C.T., Lam S.S., 2018, Oil palm waste: An abundant and promising feedstock for microwave pyrolysis conversion into good quality biochar with potential multi-application, Process Safety and Environmental Protection, 115, 57-69.

Manyà J.J., Azuara M., Manso J.A., 2018, Biochar production through slow pyrolysis of different biomass materials: Seeking the best operating conditions, Biomass and Bioenergy, 117, 115-123.

Meschewski E., Holm N., Sharma B.K., Spokas K., Minalt N., Kelly J.J., 2019, Pyrolysis biochar has negligible effects on soil greenhouse gas production, microbial communities, plant germination and initial seedling growth, Chemosphere, 228, 565-576.

Nan H., Zhao L., Yang F., Liu Y., Xiao Z, Cao X., Qiu H., 2020, Different alkaline minerals interacted with biomass carbon during pyrolysis: Which one improved biochar carbon sequestration? Journal of Cleaner Production, 255, 120162.

Oldfield T.L., Sikirica N., Mondini C., López G., Kuikman P.J., Holden N.M., 2018, Biochar, compost and biochar-compost blend as options to recover nutrients and sequester carbon, Journal of Environmental Management, 218, 465-476.

Pariyar P., Kumari K., Jain M.K., Jadhao P.S., 2020, Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application, Science of the Total Environment, 713, 136433.

Shen X., Zeng J., Zhang D., Wang F., Li Y., Yi W., 2020, Effect of pyrolysis temperature on characteristics, chemical speciation and environmental risk of Cr, Mn, Cu and Zn in biochars derived from pig manure, Science of the Total Environment, 704, 135283.

Tan X.F., Liu S.B., Liu Y.G., Gu Y.L., Zeng G.M., Hu X.J., Wang X., Liu S.H., Jiang L.H., 2017, Biochar as potential sustainable precursors for activated carbon production: Multiple applications in environmental protection and energy storage, Bioresource Technology, 227, 359-372.

Tang J., Zhang L., Zhang J., Ren L., Zhou Y., Zheng Y., Luo L., Yang Y., Huang H., Chen A., 2020, Physicochemical features, metal availability and enzyme activity in heavy metal-polluted soil remediated by biochar and compost, Science of the Total Environment, 701, 134751.

Tripathi M., Sahu J.N., Ganesan P., Jewaratnam J., 2016, Thermophysical characterisation of oil palm shell (OPS) char synthesised by the microwave pyrolysis of OPS, Applied Thermal Engineering, 105, 605-612.

Wang J., Wang S., 2019, Preparation, modification and environmental application of biocar: A review, Journal of Cleaner Production, 227, 1002-1022.

Xue S., Zhang X., Ngo H.H., Guo W., Wen H., Li C., Zhang Y., Ma C., 2019, Food waste based biochars for ammonia nitrogen removal from aqueous solutions, Bioresource Technology, 292, 121927.

Yavari S., Malakahmad A., Sapari N.B., Yavari S., 2017, Synthesis optimisation of oil palm empty fruit bunch and rice husk biochars for removal of imazapic and imazapyr herbicides, Journal of Environmental Management, 193, 201-210.

Yong Z., Dong Y., Zhang X., Tan T., 2015, Anaerobic co-digestion of food waste and straw for biogas production, Renewable Energy, 78, 527-530.

Zhang L., Lim E.Y., Loh K.C., Ok Y.S., Lee J.T.E., Shen Y., Wang C.H., Dai Y., Tong Y.W., 2020, Biochar enhanced thermophilic anaerobic digestion of food waste: Focusing on biochar particle size, microbial community analysis and pilot-scale application, Energy Conversion and Management, 209, 112654.

Zhao L., Cao X., Mašek O., Zimmerman A., 2013, Heterogeneity of biochar properties as a function of feedstock sources and production temperatures, Journal of Hazardous Materials, 256-257, 1-9.

Zhao L., Cao X., Zheng W., Kan Y., 2014, Phosphorus-assisted biomass thermal conversion: reducing carbon loss and improving biochar stability, PLoS One, 9, 115373.

Zhu X., Li Y., Wang X., 2019, Machine learning prediction of biochar yield and carbon contens in biochar based on biomass characteristics and pyrolysis conditions, Bioresource Technology, 288, 121527.

Zhu Y., Yi B.J., Yuan Q.X., Wu Y.L., Wang M., Yan S.P., 2018, Removal of methylene blue from aqueous solution by cattle-manure derived low temperature biochar, Royal Society of Chmeistry, 8, 19917-19929.