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Challenges of Biochar Usages in Arid Soils: A Case Study in the Kingdom of Saudi Arabia

Khalid A. Alaboudi

Abstract

Biochar is a carbon-rich material produced from the pyrolysis of organic biomasses in the absence of oxygen or under low-oxygen conditions. Biochar has received a great interest during the last few decades due to its beneficial roles for carbon dioxide capturing and soil fertility improvement. However, applications of biochar in arid soils are very limited, and there is a lack of knowledge on practical aspects of adding biochar to arid soils. In this chapter, we will focus on biochar applications in the Kingdom of Saudi Arabia soils as an example of arid soils. These soils are characterized by several marks, i.e., high soil pH, sand structures, high CaCO_3 contents, and low soil fertility. In addition, the unsuccessful recycling practices of agricultural and food wastes in the Kingdom of Saudi Arabia are also discussed. This chapter provides an overview of current biochar knowledge pertinent to its application to arid soils, summarizes what is known so far about biochar and its applications in arid regions, and demonstrates the possible strategies that can be used for enhancing the practices of biochar addition to these soils.

Keywords: biochar, carbon sequestration, soil fertility, applications, limitations

1. Introduction

Soil formation is a complex process resulting from long-term interactions among several environmental factors, i.e., climate, soil-forming processes, and land uses [1]. Such processes influence soil's physical, chemical, and biological characteristics and hence affect soil productivity [2]. In arid and semiarid regions, many challenges may face soil productivity; for example, many arid soils are of light texture with low organic matter and nutrient contents [3–5]. These soils exhibit low soil aggregation and can, therefore, be subjected easily to wind erosion [6]. Moreover, secondary minerals may dominate in such soils like calcite and gypsum [1], and these minerals can significantly diminish soil fertility [7, 8]. Another important threat that faces agricultural sustainability in arid sand semiarid soils is soil salinity [9]. Generally, the term arid or semiarid refers to the regions of limited rainfall and high evapotranspiration [10]. Areas with mean annual precipitation (MAP) ranging from 100 to 250 mm yr^{-1} are called arid climatic zones, while areas with MAP ranging between 250 and 600 mm yr^{-1} are called semiarid zones [11]. These two climatic regions cover approximately 30% or more of the total earth's surface [12]. To improve the productivity of low-fertility soils, organic applications should

therefore be incorporated within the top soil [13, 14] to raise soil contents of both C and nutrients [14]. However, the negative implications of using easily decomposed organic amendments on the environment should be taken into account, e.g., emissions of greenhouse that possesses global warming [15]. Accordingly, biochar might be the appropriate organic amendments to improve the characteristics of such soils but decrease the emissions of greenhouse gases on the other hand. In the following section, we will discuss the distribution of arid and semiarid soil and the potentialities of using biochar to improve soil properties and attain sustainability in crop production

2. Distribution pattern of arid and semiarid soils

As shown in **Figure 1**, arid and semiarid soils are located in North and South Africa, the Middle East region, North and South America, and finally in Australia [16]. More than 95% of the total arid soils exist in Africa and Middle East regions. According to the UNEP [16], aridity index (AI) is commonly used to quantify the aridity of a specific region. Briefly, this index is estimated based on climate variability by calculating the ratio of annual average rainfall to potential evapotranspiration (P/PET). For this concern, lands are classified in the following ascending order based on the average precipitation: hyperarid, arid, semiarid, and dry subhumid, and their average precipitation rates are 0, 1–59, 60–119, and 120–179 mm yr⁻¹, respectively [16]. In this chapter we will focus on the Kingdom of Saudi Arabia lands as an example of arid lands and the major problems hindering the application of biochar technology in these soils. In the Kingdom of Saudi Arabia, almost 25% of the total land area is arable lands (52.7 million ha), in which 45% are calcareous, sandy textured soils, with very low contents of organic matter and nutrients [17].

3. Major characteristics of arid soils

Salt content, in many arid soils, is relatively high. These soils accumulate on the soil's surface because of the high evapotranspiration rates. In addition, these regions have dry climate with high temperature and high evaporation rate. The

Figure 1.
Distribution pattern of arid and semiarid regions [16].

deeper soil layers are usually occupied by Ca. The arid soils can be applicable for cultivation in case proper water for irrigation becomes available. Due to high temperature, the degradation rate of soil's organic matter in arid soils is very high; consequently, these soils need further application rates. In the Kingdom of Saudi Arabia, most of agricultural soils are of coarse texture, with high CaCO_3 contents and high pH values. The lack of sufficient water in the Kingdom of Saudi Arabia led to increase the potentiality of soil salinization. Therefore, these soils are of poor fertility, in terms of physical (high infiltration rate, sand texture, and bad hydraulic properties), chemical (low organic matter contents, insufficient nutrients, and high soil pH), and biological (low microbial communities in soils due to the absence of organic residues and soil nutrients) characteristics [18]. Usually the pH value in the Kingdom of Saudi Arabia soils is greater than 8 with high CaCO_3 contents (>30%) [19]. In spite of the Kingdom of Saudi Arabia having the largest land mass among Middle East countries, it has the lowest arable land per capita worldwide [20]. A point to note is that the major water sources in the Kingdom of Saudi Arabia are groundwater and desalination of seawater [21]. Therefore, intensive studies are performed to overcome the infertility problems of arid soils in the Kingdom of Saudi Arabia by using organic and inorganic soil amendments, i.e., compost bio inoculums and mineral polymers [22–24]. However, these amendments need to be applied intensively because of their low nutritive contents and fast degradation rates [25].

4. Agricultural and food wastes in the Kingdom of Saudi Arabia

Due to the arid characteristics of Kingdom of Saudi Arabia lands, agricultural activities are also thought to be very low. According to the World Bank [20], the agricultural lands in the Kingdom of Saudi Arabia cover only 1736.472 km² [20]. On the other hand, the Kingdom of Saudi Arabia is considered the largest food and agricultural importer in the Gulf Cooperation Council with average imported food products of 80% in 2013 [26, 27]. These conditions hinder the development of the agricultural sector in the Kingdom of Saudi Arabia. A positive point to note is that such arid conditions are suitable for cultivation of date palm plant. According to the Food and Agricultural Organization (FAO), the Kingdom of Saudi Arabia has the highest harvested areas of date palm in 2016 with an average area of 145,516 ha. Palm trees generate huge wastes annually [28]; accordingly, proper recycling and management of these wastes can improve soil conditions.

5. Biochar

Biochar is an organic carbon-rich product, produced by burning agricultural and animal wastes in the absence of oxygen [29]. Several studies demonstrated its beneficial role for improving soil fertility and waste management, remediation of contaminated soils and water, and reducing greenhouse gas emissions [25, 30, 31]. In this chapter, we will discuss the potential benefits of biochar as a soil amendment for improving its fertility and productivity.

5.1 Ancient production of biochar

Biochar was initially produced by ancient Egyptians to produce liquid wood tar from charring processes in order to cover and preserve the dead bodies [32]. Thereafter, in South America (terra preta), 2500 years later, biochar is created both

Feedstock	Temperature	pH	%							CEC, cmolc kg ⁻¹	C/N ratio	%		H/C ratio	O/C ratio	SSA, m ² g ⁻¹	Reference
			C	N	P	S	Ca	Mg	K			O.M	Ash				
Sugar cane bagasse	<500	8.63	74.02	1.00	0.24	—	0.17	0.32	2.00	69.62	74.02	87.80	12.21	0.42	0.23	92.30	[31]
Orange peel	<500	8.75	66.36	2.13	0.25	—	1.04	0.28	1.86	68.28	31.15	88.80	11.17	0.65	0.32	0.20	
Oak wood	600.00	6.38	87.50	0.20	—	—	—	—	—	75.70	489.00	—	0.01	0.33	0.07	642.00	[40]
Corn stover	350.00	9.39	60.40	1.20	—	—	—	—	—	419.30	51.00	—	11.40	0.75	0.29	293.00	[41]
	600.00	9.42	70.60	1.07	—	—	—	—	—	252.10	66.00	—	16.70	0.39	0.10	527.00	
Corn stalk	400.00	9.60	51.10	1.34	0.25	—	—	—	1.34	—	38.13	—	—	—	—	—	[42]
	500.00	10.10	48.40	0.55	0.44	—	—	—	2.65	—	88.00	—	—	—	—	—	
Wheat straw	425.00	10.40	46.70	0.59	—	—	1.00	0.60	2.60	—	79.15	—	20.80	—	—	—	[43]
Rice straw	400.00	—	71.30	1.46	—	—	—	—	24.60	—	48.84	—	36.20	—	—	—	[44]
Peanut hull	500.00	8.60	82.00	2.70	0.30	0.10	—	—	—	—	30.37	—	9.30	0.44	0.03	200.00	[45]
Coco peat	500.00	10.30	84.40	1.02	0.03	0.27	0.06	2.30	—	—	82.75	—	15.90	0.41	0.10	13.70	[46]
Coconut charcoal	<500	8.86	76.50	0.20	—	—	—	—	—	—	426.60	—	2.90	0.12	—	—	[47]
Pinewood	<500	8.47	53.20	0.40	—	—	—	—	—	—	143.40	—	65.70	0.35	—	—	
<i>Eucalyptus deglupta</i>	350.00	7.00	82.40	0.57	0.06	0.03	—	—	—	4.69	144.56	—	0.20	—	0.12		[48]
Hardwood sawdust	500.00	—	63.80	0.22	—	0.01	—	—	—		290.00	—	22.80	0.60	0.14	1.00	[49]
Chinese pine	600.00	8.38	66.67	2.21	—	—	—	—	—	31.58	30.17	—	12.50	0.58	0.31	—	[50]

Feedstock	Temperature	pH	%							CEC, cmolc kg ⁻¹	C/N ratio	%		H/C ratio	O/C ratio	SSA, m ² g ⁻¹	Reference
			C	N	P	S	Ca	Mg	K			O.M	Ash				
Cattle waste	380.00	8.20	62.10	0.10	—	—	—	—	—	39.00	621.00	—	25.60	1.90	0.27	—	[51]
Sewage sludge	380.00	8.50	38.30	5.20	—	—	—	—	—	0.50	7.37	—	44.90	0.94	0.25	—	

Data obtained from Abdelhafez et al. [25].

Table 1.
Physicochemical characteristics of different types of biochar.

naturally by forest fires and by humans through burning bits for different practices, i.e., cooking and manufacturing [25]. In terra preta soils, the acidic conditions were the limiting factors affecting negatively crop production wherein these soils suffer severely from Al toxicity. To overcome this problem, the liming effect of biochar was an effective approach to overcome Al toxicity in soil [33].

5.2 Production technologies of biochar

All organic materials (feedstock, crop wastes, animal wastes manure) can be used for biochar production. Simply, biochar is a charcoal-like material that is produced in the absence of oxygen or limited oxygen conditions [25]. In this process organic wastes are burned at relatively low temperature $< 700^{\circ}\text{C}$, and three main components are produced through the pyrolysis process, i.e., solid biochar (carbonized biomass with average C contents of >60), synthetic gas (which can be used as a power source), and bio oil (fuel material) [25]. Farmers in the past used to burn the agricultural wastes under limited oxygen conditions by covering the waste piles with soil dust. In this traditional method, approximately half the amount of organic C was lost into the atmosphere. Therefore, people have tried to develop the production technology through using pit kiln and brick kilns in order to eliminate the losses of C and other gas emission. After biochar technology has risen, non in situ equipment have been designed to maximize the biochar yield, eliminate the C lose and ash content and using syngas and bio oil as secondary products [25]. It is worthy to mention that organic materials start to decompose at low temperature (about 120°C), followed by hemicellulose and lignin compounds, which degrade at $200\text{--}260^{\circ}\text{C}$ and $240\text{--}350^{\circ}\text{C}$, respectively [34].

5.3 Physical and chemical characteristics of biochar

Both pyrolysis conditions and the types of organic wastes identify the major characteristics of the produced biochar [25, 35]. Usually biochar (a carbon-rich product) is characterized by its high surface area and lower concentrations of hydrogen and oxygen [36, 37]. Thus, its application can improve soil characteristics (chemical, physical, and biological). Moreover, this organic product is considered relatively stable in soil because of its low availability of labile organic carbon [38] besides its low content of nutrients [39]. **Table 1** shows the main physiochemical characteristics of different types of biochars. For both physical and chemical characteristics, pyrolysis conditions and type of organic wastes are the main factors identifying them. Clearly, all biochars have the same characteristics, especially the high C contents and low N contents. Nitrogen usually starts to be volatile at 200°C ; therefore, N contents are low in most types of biochars. The high pH of biochar might be attributed to the high content of alkaline metals, i.e., Ca, Mg, and K, which are stable during biochar production. Despite the low nutrient content of biochar, its application to soils improves its fertility because it is usually added at high rates as soil amendments. The pyrolysis conditions play an important role for identifying the physical characteristics of biochar. The higher surface area of biochar is a consequence of high temperature during the pyrolysis reaction [25].

6. Applications of biochar for soil fertility improvement

As mentioned above the porous structure of biochar facilitates its adsorption of water and, therefore, increases soil water holding capacity [52, 53]. This might increase the efficiency of water use in the arid zone soils [54]. The previous studies

also demonstrated that the addition of biochar increases both soil aggregation and saturated hydraulic conductivity but decreases soil bulk density [53, 55, 56]. Therefore, application of biochar is a recommended practice to improve the physical characteristics of light textured soils [3]. For soil chemical characteristics, most studies showed that biochar has a negative effect on the availability of soil nutrients, i.e., its application increases soil pH [57, 58]. The liming effect of biochar can be attributed to the high concentrations of cationic metals, i.e., Ca^{2+} , Mg^{2+} , and K^+ , which are stable and do not volatilize during the pyrolysis process [25]. In most cases, biochar has a relative high pH (within the range of 8–11.5) [57, 59, 60]. Therefore, addition of biochar is more favorable for acidic soils than the alkaline ones. The black earth (terra preta) was an acidic soil in the enteral Amazon basin, and AL toxicity and P deficiency were the main reasons hindering the agricultural activities. Continuous applications of biochar to these soils neutralized soil acidity but increased the available P fraction; consequently, biochar enhanced and sustained soil health of terra preta [25, 32, 59]. Moreover, high doses of biochar can increase soil salinity [61–65]. On the other hand, the addition of biochar can raise soil organic matter contents and elevate soil cation exchange capacity (CEC) [66]. For nutrients contents, it is worth mentioning that most biochar types are typically low in nutrient contents, especially N. As a result, applications of biochar only in agricultural is not adequate to supply the needed macro- and micronutrients [25, 67]. However, biochar plays an important role in mitigating soil nutrient losses by seepage or leaching [66]. Applications of biochar to soils increased its OC contents, which is suitable for soil organisms and provides more favorable habitats to microbes and, therefore, facilitates soil biological activities [68]. In addition, the release of organic molecules suppresses the activities of soil microbes [69].

7. Limitation of biochar application in the Kingdom of Saudi Arabia soils

As mentioned above the high pH of biochar limited its applications in arid soils. For this concern, application of biochar to agricultural soils in the Kingdom of Saudi Arabia is very limited due to many reasons as follows:

1. Low cultivated areas in the Kingdom of Saudi Arabia: as mentioned above, agricultural activities in the Kingdom of Saudi Arabia are very limited due to the arid conditions.
2. The chemical characteristics of soils in the Kingdom of Saudi Arabia; especially soil pH is one of the major factors hindering the application of biochar to agricultural soils. Our demonstration proves that most types of biochar are of alkaline nature and its application to agricultural soil may negatively affect the availability of soil nutrients due to increasing soil pH. The pH of the produced biochar is a function of pyrolysis temperature and time; by elevating the pyrolysis temperature and time, the pH of the produced biochars increased to reach 11.5 in some studies [53].
3. The lack of knowledge regarding biochar technology and its beneficial role for enhancing agricultural activates.

In a bibliometric study conducted by Arfaoui et al. [70], they have shown that Iran, the Kingdom of Saudi Arabia, and Egypt are the highest contributor countries for biochar studies and publications in the Middle East countries. As shown in **Figure 2** (biochar article number and geographic distribution according to the

Figure 2.
Article number and geographic distribution according to the lead author's country of origin [70].

lead author's country of origin), China, the USA, and Iran are the leader countries for biochar studies and publications, followed by Pakistan, Middle East countries (Egypt and the Kingdom of Saudi Arabia), and to a lesser extent in Australia. In the Kingdom of Saudi Arabia, the Saudi Biochar Research Group in the King Saud University (Saudi Arabia) contributed to most publications in the Middle East countries.

We concluded that biochar is a promising soil amendment that can be used effectively for enhancing soil fertility. In arid regions like the Kingdom of Saudi Arabia, additional researches are needed to investigate the potential neutralization of biochar alkalinity; consequently, it can be added safely to agricultural soils. There are different sources of agricultural and food wastes that can be used for biochar production. In the case of date palm wastes, the average annual waste of one tree is about 40 kg; therefore, date palm wastes can be used effectively for biochar production in the Kingdom of Saudi Arabia. Therefore, the government of Kingdom of Saudi Arabia has to encourage the scientists for initiating intensive researches on biochar production and investigate its beneficial roles for improving soil fertility and agricultural production.

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References

- [1] De Queiroz AF, Salviano AM, Da Cunha TJF, Olszewski N, DE Souza Júnior VS, De Oliveira Neto MB. Potentialities and limitations of agricultural use in soils of semi-arid region of the state of Bahia. *Anais da Academia Brasileira de Ciências*. 2018;**90**(4):3373-3387
- [2] Ivanov IV, Prikhod'ko VE, Zamotaev IV, Manakhov DV, Novenko EY, Kalinin PI, et al. Synlithogenic evolution of floodplain soils in valleys of small rivers in the Trans-Ural Steppe. *Eurasian Soil Science*. 2019;**52**:593-609
- [3] Elshony M, Farid I, Alkamar F, Abbas M, Abbas H. Ameliorating a sandy soil using biochar and compost amendments and their implications as slow release fertilizers on plant growth. *Egyptian Journal of Soil Science*. 2019;**59**(4):305-322
- [4] Oliveira Filho JS, Vieira JN, da Silva EMR, de Oliveira JGB, Pereira MG, Brasileiro FG. Assessing the effects of 17 years of grazing exclusion in degraded semi-arid soils: Evaluation of soil fertility, nutrients pools and stoichiometry. *Journal of Arid Environments*. 2019;**166**:1-10
- [5] Hammouda I, Elbaalawy A, Elf-fishy M. Effect of compost additives and application time of phosphorus in different methods on growth, productivity and quality of peanut in sandy soils. *Egyptian Journal of Soil Science*. 2019;**59**(4):339-352
- [6] Sirjani E, Sameni A, Moosavi AA, Mahmoodabadi M, Laurent B. Portable wind tunnel experiments to study soil erosion by wind and its link to soil properties in the Fars province, Iran. *Geoderma*. 2019;**333**:69-80
- [7] Bashir MA, Rehim A, Liu J, Imran M, Liu H, Suleman M, et al. Soil survey techniques determine nutrient status in soil profile and metal retention by calcium carbonate. *Catena*. 2019;**173**:141-149
- [8] Marques MJ, Álvarez AM, Carral P, Esparza I, Sastre B, Bienes R. Estimating soil organic carbon in agricultural gypsiferous soils by diffuse reflectance spectroscopy. *Water*. 2020;**12**(1):261
- [9] Mahdavi SM, Fujimaki H. Soil salinity resistance effect on evaporation. *Eurasian Soil Science*. 2019;**52**:526-534
- [10] Food and Agrocultural Organization (FAO). *Arid Zone Forestry: A Guide for Field Technicians*. 1989. ISBN: 92-5-102809-5
- [11] D'Odorico P, Porporato A, Runyan C. Ecohydrology of arid and semiarid ecosystems: An introduction. In: D'Odorico P, Porporato A, Wilkinson RC, editors. *Dryland Ecohydrology*. Cham: Springer; 2019. pp. 1-27. DOI: 10.1007/978-3-030-23269-6_1
- [12] Shi WY, Zhu XC, Zhang FB, Wang KB, Deng L, Ma MG. Soil carbon biogeochemistry in arid and semiarid forests. In: Mazadiego LF, Garcia EDM, Barrio-Parra F, Izquierdo-Díaz M, editors. *Applied Geochemistry with Case Studies on Geological Formations, Exploration Techniques and Environmental Issues*. IntechOpen; 2019. DOI: 10.5772/intechopen.87951
- [13] Barajas-Aceves M, Dendoovem L. Nitrogen, carbon and phosphorus mineralization in soils from semi-arid highlands of Central Mexico amended with tannery sludge. *Bioresource Technology*. 2001;**77**:121-130
- [14] Farid I, Abbas M, El-Ghozoli A. Implications of humic, fulvic and

K-humate extracted from each of compost and biogas manures as well as their teas on faba bean plants grown on a typic Torripsamment soil and emissions of soil CO₂. *Egyptian Journal of Soil Science*. 2018;**58**(3):275-289

[15] Chang N, Zhai Z, Li H, Wang L, Deng J. Impacts of nitrogen management and organic matter application on nitrous oxide emissions and soil organic carbon from spring maize fields in the North China plain. *Soil and Tillage Research*. 2020;**196**:104441

[16] United Nations Convention to Combat Desertification (UNCCD). *World Atlas of Desertification*. 2nd ed. Nairobi: UNEP; 1997

[17] Mridha MAU, Al-Barakah FN. Green cultivation of moringa on arid agricultural land in Saudi Arabia. *Acta Horticulturae*. 2014:1158. ISHS 2017

[18] Ibrahim A, Usman ARA, Al-Wabel MI, Nadeem M, Ok YS, Al-Omran A. Effects of conocarpus biochar on hydraulic properties of calcareous sandy soil: Influence of particle size and application depth. *Archives of Agronomy and Soil Science*. 2017;**63**(2):185-197

[19] Alotaibi KD, Schoenau JJ. Addition of biochar to a sandy desert soil: Effect on crop growth. *Water Retention and Selected Properties. Agronomy*. 2019;**9**:327

[20] World Bank. Arable Land (hectares per person)-Saudi Arabia. 2017. Available from: <http://data.worldbank.org/indicator/AG.LND.ARBL.HA.PC?end=2014&locations=SA&start=1961&view=chart>

[21] Abdula'aly AI, Chammem AA. Groundwater treatment in the central region of Saudi Arabia. *Desalination*. 1997;**96**:203-214

[22] Mridha AU, Al-Qarawi AA. Bio-organic -an effective fertilizer for arid lands agriculture and date palm plantation in Saudi Arabia. *Biosciences Biotechnology Research Asia*. 2013;**10**(1):247-251

[23] Waqas M, Nizami AS, Aburizaiza AS, Barakat MA, Rashid MI, Ismail IMI. Optimizing the process of food waste compost and valorizing its applications: A case study of Saudi Arabia. *Journal of Cleaner Production*. 2018;**176**(1):426-438

[24] Hozzein WN, Abuelsoud W, Wadaan MAM, Shuikan AM, Selim S, Al Jaouni S, et al. Exploring the potential of actinomycetes in improving soil fertility and grain quality of economically important cereals. *Science of The Total Environment*. 2019;**651**(2):2787-2798

[25] Abdelhafez AA, Abbas MHH, Li J. Biochar: The black diamond for soil sustainability, contamination control and agricultural production. In: Huang W-J, editor. *Engineering Applications of Biochar*. IntechOpen; 2017. DOI: 10.5772/intechopen.68803. Available from: <https://www.intechopen.com/books/engineering-applications-of-biochar/biochar-the-black-diamond-for-soil-sustainability-contamination-control-and-agricultural-production>

[26] USDA Foreign Agricultural Service. Report Number SA1417. *Global Agricultural Information Network*; 2014

[27] Lovelle M. Food and Water Security in the Kingdom of Saudi Arabia. Australia: Future Directions International Pty Ltd.; 2015, 2015. Available from: <http://www.futuredirections.org.au/publication/food-and-water-security-in-the-kingdom-of-saudi-arabia/>

[28] Alananbeh KM, Bouqellah NA, Kaff NS. Cultivation of oyster mushroom *Pleurotus ostreatus* on

- date-palm leaves mixed with other agro-wastes in Saudi Arabia. *Saudi Journal of Biological Sciences*. 2014;**21**(6):616-625
- [29] Lehmann J, Joseph S. Biochar for environmental management: An introduction. In: Lehmann J, Joseph S, editors. *Biochar for Environmental Management: Science and Technology*. London: Earthscan; 2009. pp. 1-12
- [30] Major J, Rondon M, Molina D, Riha SJ, Lehmann J. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. *Plant and Soil*. 2010;**333**:117-128
- [31] Abdelhafez AA, Li J. Removal of Pb(II) from aqueous solution by using biochars derived from sugarcane bagasse and orange peel. *Journal of the Taiwan Institute of Chemical Engineers*. 2016;**61**:367-375
- [32] Emrich W. *Handbook of Charcoal Making. The Traditional and Industrial Methods*. Dordrecht, Holland: D. Reidel Publishing Company; 1985
- [33] Verheijen FGA, Montanarella L, Bastos AC. Sustainability, certification, and regulation of biochar. *Pesquisa Agropecuária Brasileira*. 2012;**47**:649-653
- [34] Sjöström E. *Wood Chemistry: Fundamentals and Applications*. 2nd ed. San Diego, CA: Academic Press; 1993
- [35] Chen B, Yuan M. Enhanced sorption of polycyclic aromatic hydrocarbons by soil amended with biochar. *Journal of Soils and Sediments*. 2011;**11**:62-71
- [36] Bird MI, Ascough PL, Young IM, Wood CV, Scott AC. X-ray microtomographic imaging of charcoal. *Journal of Archaeological Science*. 2008;**35**:2698-2706
- [37] Abdullah H, Wu H. Biochar as a fuel: 1. Properties and grindability of biochars produced from the pyrolysis of mallee wood under slow-heating conditions. *Energy and Fuels*. 2019;**23**:4174-4181
- [38] Farrell M, Kuhn TK, Macdonald LM, Maddern TM, Murphy DV, Hall PA, et al. Microbial utilisation of biochar-derived carbon. *Science of the Total Environment*. 2013, 2013;**465**:288-297
- [39] Agblevor FA, Beis S, Kim SS, Tarrant R, Mante NO. Biocrude oils from the fast pyrolysis of poultry litter and hardwood. *Waste Management*. 2010;**30**:298-307
- [40] Nguyen B, Lehmann J. Black carbon decomposition under varying water regimes. *Organic Geochemistry*. 2009;**40**:846-853
- [41] Nguyen B, Lehmann J, Hockaday WC, Joseph S, Masiello CA. Temperature sensitivity of black carbon decomposition and oxidation. *Environmental Science and Technology*. 2010;**44**:3324-3331
- [42] Feng Y, Xu Y, Yu Y, Xie Z, Lin X. Mechanisms of biochar decreasing methane emission from Chinese paddy soils. *Soil Biology and Biochemistry*. 2012;**46**:80-88
- [43] Zhang A, Cui L, Pan G, Li L, Hussain Q, Zhang X, et al. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agriculture, Ecosystems and Environment*. 2010;**139**:469-475
- [44] Peng X, Ye LL, Wang C, Zhou H, Sun B. Temperature and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an ultisol in southern China. *Soil Tillage Research*. 2011;**112**(2):159-166
- [45] Novak JM, Lima I, Xing B, Gaskin JW, Steiner C, Das KC, et al. Characterization of designer biochar

produced at 18 engineering applications of biochar different temperatures and their effects on a loamy sand. *Annals of Environmental Science*. 2009;**3**(1):195-206

[46] Lee Y, Park J, Ryu C, Gang KS, Yang W, Park Y, et al. Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500°C. *Bioresource Technology*. 2013;**148**:196-201

[47] Erin N, Yargicoglu EN, Sadasivam BY, Reddy KR, Spokas K. Physical and chemical characterization of waste wood derived biochars. *Waste Management*. 2014;**36**:256-268

[48] Rondon MA, Lehmann J, Ramírez J, Hurtado M. Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with biochar additions. *Biology and Fertility of Soils*. 2007;**43**(6):699-708

[49] Fabbri D, Torri C, Spokas KA. Analytical pyrolysis of synthetic chars derived from biomass with potential agronomic application (biochar): Relationships with impacts on microbial carbon dioxide production. *Journal of Analytical and Applied Pyrolysis*. 2012;**93**:77-84

[50] Liu XH, Han FP, Zhang XC. Effect of biochar on soil aggregates in the loess plateau: Results from incubation experiments. *International Journal of Agriculture & Biology*. 2012;**14**:975-979

[51] Shinogi Y, Yoshida H, Koizumi T, Yamaoka M, Saito T. Basic characteristics of low temperature carbon products from waste sludge. *Advances in Environmental Research*. 2003;**7**(3):661-665

[52] Dugan E, Verhoef A, Robinson S, Sohi S. Bio-char from sawdust, maize stover and charcoal: Impact on water holding capacities (WHC) of three soils from Ghana. In 19th World

Congress of Soil Science, Symposium 2010;**4**(2):9-12

[53] Mukherjee A, Lal R. Biochar impacts on soil physical properties and greenhouse gas emissions. *Agronomy*. 2013;**3**:313-339

[54] Bassouny M, Abbas M. Role of biochar in managing the irrigation water requirements of maize plants: The pyramid model signifying the soil hydro-physical and environmental markers. *Egyptian Journal of Soil Science*. 2019;**59**(2):99-115

[55] Asai H, Samson BK, Stephan HM, Songyikhangsuthor K, Homma K, Kiyono Y, et al. Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Research*. 2009;**111**:81-84

[56] Karhu K, Mattila T, Bergström I, Regina K. Biochar addition to agricultural soil increased CH₄ uptake and water holding capacity—Results from a short-term pilot field study. *Agriculture, Ecosystems & Environment*. 2011;**140**:309-313

[57] Yuan JH, Xu RK, Zhang H. The forms of alkalis in the biochar produced from crop residues at different temperatures. *Bioresource Technology*. 2011;**102**(3):3488-3497

[58] Abdelhafez AA, Abbas MHH, Hamed MH. Biochar: A solution for soil Pb pollution. In: *The 8th International Conference for Development and the Environment in the Arab World* Assiut University, Egypt. 2016. pp. 89-103

[59] Guo M, He Z, Uchimiya SM. Introduction to biochar as an agricultural and environmental amendment. In: Guo M, He Z, Uchimiya SM, editors. *Agricultural and Environmental Applications of Biochar: Advances and Barriers*. Madison, WI,

USA: Soil Science Society of America; 2016. pp. 1-14. SSSA Spec. Publ. 63

[60] Guo M, Xiao P, Li H. Valorization of agricultural byproducts through conversion to biochar and bio-oil. In: Simpson BK, Kwofie EM, Aryee AN, editors. *Byproducts from Agriculture and Fisheries: Adding Value for Food, Feed, Pharma and Fuels*. Somerset, NJ, USA: John Wiley & Sons, Inc.; 2020. pp. 501-522

[61] Sigua GC, Novak JM, Watts DW, Johnson MG, Spokas K. Efficacies of designer biochars in improving biomass and nutrient uptake of winter wheat grown in a hard setting subsoil layer. *Chemosphere*. 2016;**142**:176-183

[62] Zhang Y, Idowu OJ, Brewer CE. Using agricultural residue biochar to improve soil quality of desert soils. *Agriculture*. 2016;**6**(1):10

[63] Blok C, van der Salm C, Hofland-Zijlstra J, Streminska M, Eveleens B, Regelink I, et al. Biochar for horticultural rooting media improvement: Evaluation of biochar from gasification and slow pyrolysis. *Agronomie*. 2017;**7**:6

[64] Luo X, Liu G, Xia Y, Chen L, Jiang Z, Zheng H, et al. Use of biochar-compost to improve properties and productivity of the degraded coastal soil in the Yellow River Delta, China. *Journal of Soils and Sediments*. 2017;**17**:780-789

[65] Zheng H, Wang X, Chen L, Wang Z, Xia Y, Zhang Y, et al. Enhanced growth of halophyte plants in biochar-amended coastal soil: Roles of nutrient availability and rhizosphere microbial modulation. *Plant Cell Environment*. 2018;**41**(3):517-523

[66] Igalavithana AD, Ok YS, Usman ARA, Al-Wabel MI, Oleszczuk P, Lee SS. The effects of biochar amendment on soil fertility. In: Guo M, He Z, Uchimiya SM, editors.

Agricultural and Environmental Applications of Biochar: Advances and Barriers. Madison, WI, USA: Soil Science Society of America; 2016. pp. 123-144. SSSA Spec. Publ. 63

[67] Tian J, Miller V, Chiu PC, Maresca JA, Guo M, Imhoff PT. Nutrient release and ammonium sorption of poultry litter and wood biochars in stormwater treatment. *Science of The Total Environment*. 2016;**553**:596-606

[68] Paz-Ferreiro J, Mendez A, Gasco G. Application of biochar for soil biological improvement. In: Guo M, He Z, Uchimiya SM, editors. *Agricultural and Environmental Applications of Biochar: Advances and Barriers*. Madison, WI, USA: Soil Science Society of America; 2016. pp. 145-174. SSSA Spec. Publ. 63

[69] Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota—A review. *Soil Biology and Biochemistry*. 2011;**43**:1812-1836

[70] Arfaoui A, Ibrahimi K, Trabelsi F. Biochar application to soil under arid conditions: A bibliometric study of research status and trends. *Arabian Journal of Geosciences*. 2019;**12**:45