Article

Impacts on biochar aging mechanism by eco-environmental factors

Ghulam Murtaza[1], **Zeeshan Ahmed**[2,3,4], **Muhammad Usman**[5], **Ahsan Areeb**[6], **Allah Ditta**[7], **Zia Ullah**[1], **Faisal Mahmood**[8]

[1]Faculty of Environmental Science and Engineering, Kunming University of Science and Technology, Kunming 650500, China

[2]Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, Xinjiang 830011, China

[3]Xinjiang Desert Plant Roots Ecology and Vegetation Restoration Laboratory, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, Xinjiang 830011, China

[4]Cele National Station of Observation and Research for Desert-Grassland Ecosystems, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Xinjiang 848300, China

[5]Department of Botany, Government College University Lahore, Lahore 54000, Pakistan

[6]Department of Agronomy, Faculty of Agricultural Science and Technology, Bahauddin Zakariya University, Multan 66000, Pakistan

[7]Department of Environmental Sciences, Shaheed Benazir Bhutto University Sheringal, Dir (U), 18000, Khyber Pakhtunkhwa, Pakistan

[8]Faculty of Life Science and Technology, Kunming University of Science and Technology, Kunming 650500, China

E-mail: zeeshanagronomist@yahoo.com

Received 20 April 2020; *Accepted 30 May 2020*; *Published 1 September 2020*

Abstract

Biochar is a type of pyrogenic carbon that can potentially contribute to agricultural productivity and environment sustainability by increasing remediation of contaminated soil and its reactivity. However, occurrence of biochar aging process disturbs its remediation role, because various surface attributes of biochar happened to be altered through different biotic and abiotic factors. In current review, several important factors critically affecting the aging process are discussed that includes soil physical, chemical, biological components along with soil temperature. It was noted that aging process in biochar might be accelerated by elevated temperature; soil components protected it mainly by soil organic matter through its interaction with soil microbes. To promote prolong biochar application in nature; aging of biochar can be better managed through its influencing factors.

Keywords agricultural productivity; biochar aging; environment sustainability; pyrogenic; soil microbes.

Proceedings of the International Academy of Ecology and Environmental Sciences
ISSN 2220-8860
URL: http://www.iaees.org/publications/journals/piaees/online-version.asp
RSS: http://www.iaees.org/publications/journals/piaees/rss.xml
E-mail: piaees@iaees.org
Editor-in-Chief: WenJun Zhang
Publisher: International Academy of Ecology and Environmental Sciences

1 Introduction

Biochar is a carbon rich solid produce of organic residue generated through pyrolysis process and its production highly depends on pyrolysis conditions and feedstock types (Oni et al., 2020). Being a commercial bio-product, it can be used in different sectors mainly energy, agriculture and other industries. However, production of biochar can increase the property of soil and deliver the chances for extra income (Oni et al., 2020). Feedstock such as animal manures, paper mill products and agricultural wastes is generally used for biochar production (Brewer et al., 2014). Biochar production ranges from small scale cooking stove to large level expending pyrolysis process. Pyrolysis is a thermochemical method used for transforming biomass into biochar at a temperature ranging from 350°C and 700°C in absence of air. Pyrolysis and gasification are mostly adopted thermochemical methods for biochar production in solid shape (Bhutto et al., 2016). Biochar application as soil amender has substantial effects on soil fertility through modification of soil physio-chemical and biological properties (Awad et al., 2018).

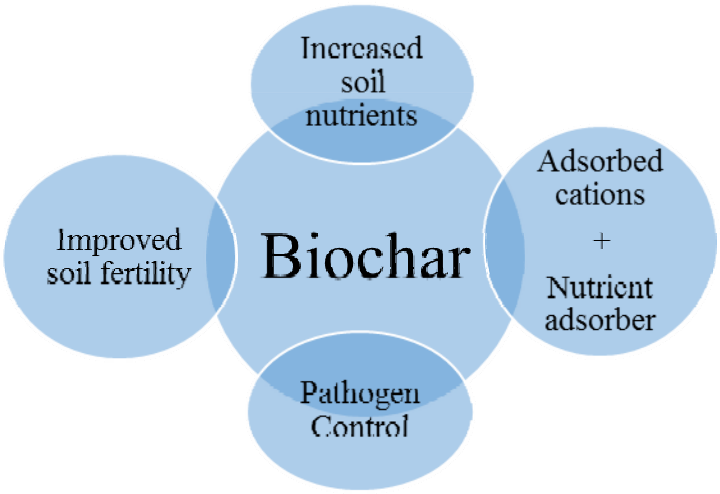

Fig. 1 Benefits of biochar amendments to environment.

Increasing human population and their activities are also deteriorating the quality of environment through rapid depletion of natural resources (Zhang, 2007; Verma et al., 2020). Moreover, large scale use of pesticides in agriculture and accumulation of toxic metals in the soil are major environmental concerns seriously affecting the humans, animals and plants (Kumar et al., 2013; Sayadi and Rezaei, 2014). So, biochars are applied because they act as a potential sorbent in contaminated soils, enable carbon sequestration and improve soil fertility (Jaffery et al., 2013). Biochar addition not only increases the soil quality but it also improves plant growth and ultimately crop yield. Biochar also serves as a source of carbon sequestration and nutrients in soil (El-Naggar et al., 2019). Biochar substantially affect many soil characteristics like change in water holding capacity, pH and nutrient acquisition mainly by altering the soil physiochemical properties. It can accelerate different responses in many species of soil microbes hence causing structural changes in microbial community Moreover fluctuations in nutrient cycling also takes place mainly due to biochar addition (Lauber et al., 2009; Rousk et al., 2010). Biochar comprise of many components including free radicle, minerals and volatile organic compounds (Spokas et al., 2011). It reshapes the soil microbial community and influences their enzymatic activity as they catalyze several biogeochemical processes like element cycles and soil organic matter turnover (Paz-Ferreiro et al., 2013). Contaminant degradation through microbe inoculation (myco-remediation) together with biochar can be used to increase the biological degradation of pollutants (Chen et al., 2012; Garcia-Delgado et al., 2015), providing a promising method for remediation of contaminated soil. The adsorption of toxic heavy metals, organic contaminants and hazardous anions by biochar immobilizes them and prevents leaching of toxic heavy metals into water table (Chen et al., 2012; Yang et al., 2016). Changes in a substantial quantity of biochar or some of its constituents may change with the passage of time this process is generally called aging (Mia et al., 2017). Biochar aging is comparatively slow and a fraction of biochar derived organic matter such as fulvic and humic acid, dissolved organic carbon can be smoothly lost from the soil by leaching (Mia et al., 2017; Wang et al., 2015). To fully analyze the long term effects of biochar, a complete understanding of the aging process in biochar is pre-requisite and should be proceeded in a scientific manner.

Table 1 Summary of pyrolysis mechanism in biochar production.

Pyrolysis type	Temperature (^{o}C)	Residence time	Yield of biochar (%)	References
Slow	300 -700^{o}C	different hours to days	37%	Gai et al., 2014
Fast	400-600^{o}C	< 1 s	12%	Tomczyk et al., 2020
Gasification	750 - 1000^{o}C	15 to 25 s	10%	Leng et al., 2012
Fast	500 - 1000^{o}C	< 1 s	15%	Gurwick et al., 2013
Gasification	700-1000^{o}C	Sec-min	10%	Tomczyk et al., 2020
Slow (bio-carbonization)	300-800^{o}C	Sec-h	35%	Tomczyk et al., 2020
Slow	300-600^{o}C	h-days	25-35%	Novotny et al., 2015

2 Eco-environmental Factors

2.1 Soil influenced aging process of biochar

This kind of aging is quite slow and normally follows a steady path to achieve a stable condition after many decades. It could be the result of gradual removal of easily degradable constituents of biochar, ultimately leaving aromatic carbon that decomposes or oxidizes at slower pace (Hale et al., 2011; Liu et al., 2013; Mukherjee et al., 2014). Furthermore, synergistic effects between biochar and soil probably modifies surface chemistry due to the microbial sorption and soil organic matter, ensuing in an raised negative charge on surface in result of presence of an various functional groups such as carboxylic acid and others (Mukherjee et al., 2014). Moreover, slow progression of aging process may occur due to physical barrier of soil interacting with mineral surfaces (Paetsch et al., 2018). Liang et al. (2006) reported that anthrosols-rich biochar contains 72-90% higher carbon content present in the form of organao-mineral fraction as compared to biochar poor soils (2-70%). However, environmental conditions influence the consistency of biochar in the soils. For instance, high soil moisture and temperature conditions have been involved to facilitate speedy biotic and abiotic aging of biochar in soils (Fuertes et al., 2010). Generally, association of biochar with clay mineral in soil and its resistance within newly organized aggregates may enhance the longevity and stability of biochar in soil (Fang et al., 2013; Keith et al., 2011). Nguyen and Lehmann (2009) reported a quick loss of carbon from biochar which was incubated in a sandy medium. They further inferred that in the absence of proper biochar protecting system, use of sand instead of soil as medium was the main reason of this loss. Biochar was knowingly merged in clay minerals and micro aggregates for protection against aging process (Nguyen et al., 2010). Generally, biochar mineralization may be improved by labile organic-matter. Clarity about the effect of biochar addition with external nitrogen on soil carbon mineralization is not only crucial to understand soil organic carbon kinetics and soil improvement but it is also vital to know its role in affecting the carbon sequestration (Sarkhot et al., 2012). Hamer et al. (2004) reported that 0.2 to 0.7% C mineralization for oak tree and biochar of crop residue (produced at 800^{o}C) in absence of labile organic matter, and it was improved from 0.6 to 1.2% after glucose addition. This had been ascribed to metabolic mineralization of biochar carbon via microbial enzymes that were produced to use glucose.

2.2 Temperature influenced aging process of biochar

Temperature is one of the most dominant factors critically the most affecting the process of biochar aging (Cheng et al., 2006; Cheng and Lehmann, 2009). It has been found that rising temperature particularly above 70^{o}C (Cheng et al., 2006; Cheng and Lehmann, 2009), significantly speeds up the process of biochar aging process, although chemisorption between biochar surface and O_2 was endothermic (Boguta et al., 2019). Elemental composition and surface oxidation of functional groups (phenols and carboxylic acids) are two important indicators of biochar oxidation (Joseph et al., 2010; Liang et al., 2008). Biochar oxidation initiates from the surface and depending on protection provided to the core, it proliferates further (Liang et al., 2006; Kimetu and Lehmann, 2010) (Liang et al., 2006). Nonetheless in many old aged biochars likely 600-8700 years old, the core regions have close similarity with spectral features of fresh biochar (Joseph et al., 2010). Nevertheless, inner portion of new biochar can be oxidized at 70^{o}C temperature as indicated by analyses conducted through FTIR (Fourier transform infrared spectroscopy) and XPS (X-ray photoelectron spectroscopy) techniques (Cheng et al., 2006). In addition under the natural conditions (Quan et al., 2020) or particularly at low temperature like -22^{o}C (Fan et al., 2018), aging of biochar continues to occur on, but comparatively at slower rate. An important positive correlation among MAT (mean annual temperature) and oxidation of aged biochar for 130 years was observed and it was confirmed that aging process in biochar can occur in any terrestrial system (Iagalavithana et al., 2017; Kim et al., 2019).

2.3 Soil microbes influenced aging process of biochar

Biochar is sufficiently sterilized during pyrolysis process, hence any direct, contribution to microorganism community in their evacuation (Thies et al., 2015). Zimmerman et al. (2010) stated that biochar degradation may take place through both processes either biotic (oxidative respiration of C or microbes incorporation) or abiotic (solublization, oxidation by chemicals and photo-oxidation).Various studies have emphasized that abiotic degradation can play a vital role, or even a dominant role in biochar transformation (Cheng et al., 2006; Cohen-Ofri et al., 2007). Biological aging of identical refractory sources of carbon such as charred coal and wood or even also graphite (black lead) incubated in soil has remained under observation for long time (Alzarhani et al., 2019; Cheng et al., 2006; Hilscher et al., 2009; Zimmerman et al., 2010). Cao et al. (2017) analyzed the carbon release and reported that the biotic mechanisms were the actual cause of almost half of the biochar aging during one year incubation. After applications of fresh biochar mainly obtained from cow manure and dairy muck, rise in metabolic quotient and total respiration were noted (Kolb et al., 2009; Yavari et al., 2016). The higher biochar oxidation or mineralization may occur and form large microbial populations (Gell et al., 2011; Yargicoglu et al., 2017). Biochar formed at low temperature or produced through natural fires contains large amount of volatile carbon that would be used as N or C source by microbes (Logan et al. 2019; Zimmerman et al., 2010). After the addition of biochar in soil, living conditions become improved for microbes, because water holding capacity increases and pore size has been changed (Meynet et al., 2012; Zhu, 2015). Additionally, pores of biochar may serve as protective habitats and facilitate microbe's growth because they provide protection from competitors and grazers (Cheng et al., 2006; Liao et al., 2019). Up till now, little knowledge is present about the role and extent of biotic processes affecting the microbial oxidation of biochar over a wide range of environments. Hence in future, much more effort and research is needed on these aspects.

3 Conclusions

In this paper, potential impact of different eco-environmental factors including temperature, soil microbes and different soil properties on biochar aging has been described. After application of biochar these factors influence to change the physical and surface properties like surface functional groups, specific surface area and pore volume etc. Consequently, physico-chemical characteristics as well as chemical reactivity of biochar will change and ultimately biochar-soil interaction will be altered. Hence future studies should focus on long term characterization of biochar aging process under specific conditions, to get environmentally safe different types of biochars.

Acknowledgement

Authors delightfully acknowledge the Kunming University of Science and Technology, Kunming, China for supporting this study. Authors also acknowledge the sincere efforts of Dr. Abid Ali (University of Agriculture, Faisalabad) in improving the final draft of this review paper.

References

Alzarhani AK, Clark DR, Underwood GJC, Ford H, Cotton TEA, Dumbrell AJ. 2019. Are drivers of root-associated fungal community structure context specific? The ISME Journal, 13: 1330-1344

Awad Y, Lee M, Kim SS, OK YS, Kuzyakov Y. 2018. Carbon and nitrogen mineralization and enzyme activities in soil aggregate-size classes: Effects of biochar, oyster shells, and polymers. Chemosphere, 198: 40-48

Bhutto AW, Qureshi K, Abro R, Harijan K, Zhao Z, Bazmi AA, Yu G. 2016. Progress in the production of biomass-to-liquid biofuels to decarbonize the transport sector- prospects and challenges. RSC Advances, 6(38), 32140-32170

Boguta P, Sokołowska Z, Skic K, Tomczyk A. 2019. Chemically engineered biochar effect of concentration and type of modifer on sorption and structural properties of biochar from wood waste. Fuel, 256: 115893

Brewer CE, Chuang VJ, Masiello CA, Gonnermann H, Gao X, Dugan B, Davies CA. 2014. New approaches to measuring biochar density and porosity. Biomass and Bioenergy, 66: 176-185

Cao T, Chen W, Yang T, He T, Liu Z, Meng J. 2017. Surface Characterization of Aged Biochar Incubated in Different Types of Soil. Bio Resources, 12(3): 6366-6377

Chen B, Yuan M, Qian L. 2012. Enhanced bioremediation of PAH-contaminated soil by immobilized bacteria with plant residue and biochar as carriers. Journal of Soils and Sediments, 12 (9): 1350-1359

Cheng CH, Lehmann J, Thies JE, Burton SD, Engelhard MH. 2006. Oxidation of black carbon by biotic and abiotic processes. Organic Geochemistry, 37(11): 1477–1488

Cheng CH, Lehmann J. 2009. Ageing of black carbon along a temperature gradient. Chemosphere, 75(8): 1021-1027

Cohen-Ofri I, Popovitz-Biro R, Weiner S. 2007. Structural characterization of modern and fossilized charcoal produced in natural fires as determined by using electron energy loss spectroscopy. A European Journal, 13(8): 2306-2310

El-Naggar A, El-Naggar AH, Shaheen SM, Sarkar B, Chang SX, Tsang DCW, Ok YS. 2019. Biochar composition-dependent impacts on soil nutrient release, carbon mineralization, and potential environmental risk: A review. Journal of Environmental Management, 241: 458-467

Fan Q, Sun J, Chu L, Cui L, Quan G, Yan J, Hussain Q, Iqbal M. 2018. Effects of chemical oxidation on surface oxygen-containing functional groups and adsorption behavior of biochar. Chemosphere, 207: 33-40

Fang Y, Singh B, Singh BP, Krul E. 2013. Biochar carbon stability in four contrasting soils. European Journal of Soil Science, 65(1): 60-71

Fuertes AB, Arbestain MC, Sevilla M, Macia-Agullo JA, Fiol S, Lopez R. 2010. Chemical and structural properties of carbonaceous products obtained by pyrolysis and hydrothermal carbonisation of corn Stover. Australian Journal of Soil Research, 48: 618-626

Gai XP, Wang HY, Liu J, Zhai LM, Liu S, Ren TZ, Liu HB. 2014. Effects of feedstock and pyrolysis temperature on biochar adsorption of ammonium and nitrate. PLoS One, 9 (12): 113888

Garcia-Delgado C, Alfaro-Barta I, Eymar E. 2015. Combination of biochar amendment and mycoremediation for polycyclic aromatic hydrocarbons immobilization and biodegradation in creosote-contaminated soil. Journal Hazardous Material, 285: 259-266

Gell K, van Groenigen J, Cayuela ML. 2011. Residues of bioenergy production chains as soil amendments: Immediate and temporal phytotoxicity. Journal of Hazardous Materials, 186(2-3): 2017-2025

Hale S, Hanley K, Lehmann J, Zimmerman A, Cornelissen G. 2011. Effects of chemical, biological, and physical aging as well as soil addition on the sorption of pyrene to activated carbon and biochar. Environmental Science & Technology, 45(24): 10445-10453

Hamer U, Marschner B, Brodowski S, Amelung W. 2004. Interactive priming of black carbon and glucose mineralization. Organic Geochemistry, 35(7): 823-830

Hilscher A, Heister K, Siewert C, Knicker H. 2009. Mineralisation and structural changes during the initial phase of microbial degradation of pyrogenic plant residues in soil. Organic Geochemistry, 40(3): 332-342

Igalavithana AD, Mandal S, Niazi NK, Vithanage M, Parikh SJ, Mukome FND, Rizwan M, Oleszczuk P, Al-Wabel M, Bolan N, Tsang DCW, Kim KH, Ok YS. 2018. Advances and future directions of biochar characterization methods and applications. Critical Reviews in Environmental Science and Technology, 47(23): 2275-2330

Jeffery S, Bezemer TM, Cornelissen G, Kuyper TW, Lehmann J, Mommer L, Sohi SP, van de Voorde TFJ, Wardle DA, van Groenigen JW. 2013. The way forward in biochar research: targeting trade-offs between the potential wins. GCB Bioenergy, 7(1): 1-13

Joseph SD, Camps-Arbestain M, Lin Y, Munroe P, Chia CH, Hook J, Amonette JE. 2010. An investigation into the reactions of biochar in soil. Australian Journal of Soil Research, 48(7): 501-515

Keith A, Singh B, Singh BP. 2011. Interactive priming of Biochar and labile organic matter mineralization in a smectite-rich soil. Environmental Science and Technology, 45(22): 9611-9618

Kim HB, Kim JG, Kim SH, Kwon EE, Baek K. 2019. Consecutive reduction of Cr (VI) by Fe (II) formed through photo-reaction of iron-dissolved organic matter originated from biochar. Environmental Pollution, 253: 231–238

Kimetu JM, Lehmann J. 2010. Stability and stabilisation of biochar and green manure in soil with different organic carbon contents. Australian Journal of Soil Research, 48(7): 577-585

Kolb SE, Fermanich KJ, Dornbush ME. 2009. Effect of Charcoal Quantity on Microbial Biomass and Activity in Temperate Soils. Soil Science Society of America Journal, 73(4): 1173-1181

Kumar N, Amb KM, Kumar NR, Bora A, Khan RS.2103. Studies on biodegradation and molecular characterization of 2, 4-D Ethyl Ester and Pencycuron induced Cyanobacteria by using GC-MS and 16S rDNA sequencing. Proceedings of the International Academy of Ecology and Environmental Sciences, 3(1): 1-24

Lauber CL, Hamady M, Knight R, Fierer N. 2009. Pyrosequencing-Based Assessment of Soil pH as a Predictor of Soil Bacterial Community Structure at the Continental Scale. Applied and Environmental Microbiology, 75(15): 5111-5120

Leng RA, Inthapanya S, Preston TR. 2012. Biochar lowers net methane production from rumen fluid in vitro. Livestock Research for Rural Development, 24(6): 103

Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad JO, Thies J, Luizão FJ, Petersen J, Neves EG. 2006. Black carbon increases cation exchange capacity in soils. Soil Science Society of America Journal, 70(5): 1719-1730

Liang B, Lehmann J, Solomon D, Sohi S, Thies JE, Skjemstad JO, Wirick S. 2008. Stability of biomass-derived black carbon in soils. Geochimica et Cosmochimica Acta, 72(24): 6069-6078

Liao H, Li Y, Yao H. 2019. Biochar Amendment Stimulates Utilization of Plant-Derived Carbon by Soil Bacteria in an Intercropping System. Frontiers in Microbiology, 10: 1361

Liu Z, Demisie W, Zhang M. 2013. Simulated degradation of biochar and its potential environmental implications. Environmental Pollution, 179: 146-152

Logan M, Visvanathan C. 2019. Management strategies for anaerobic digestate of organic fraction of municipal solid waste: Current status and future prospects. Waste Management and Research, 37(1): 27-39

Meynet P, Hale SE, Davenport RJ, Cornelissen G, Breedveld GD, Werner D. 2012. Effect of Activated Carbon Amendment on Bacterial Community Structure and Functions in a PAH Impacted Urban Soil. Environmental Science and Technology, 46(9): 5057-5066

Mia S, Dijkstra FA, Singh B. 2017. Aging Induced Changes in Biochar's Functionality and Adsorption Behavior for Phosphate and Ammonium. Environmental Science and Technology, 51(15): 8359-8367

Mukherjee A, Zimmerman AR, Hamdan R, Cooper WT. 2014. Physicochemical changes in pyrogenic organic matter (biochar) after 15 months of field aging. Solid Earth, 5(2): 693-704

Nguyen BT, Lehmann J, Hockaday WC, Joseph S, Masiello CA. 2010. Temperature sensitivity of black carbon decomposition and oxidation. Environmental Science and Technology, 44(9): 3324-3331

Nguyen BT, Lehmann J. 2009. Black carbon decomposition under varying water regimes. Organic Geochemistry, 40(8): 846-853

Novotny EH, Maia CMB, de F Carvalho MT, de M Madari BE. 2015. Biochar: pyrogenic carbon for agricultural use - A critical review. Revista Brasileira de Ciência Do Solo, 39(2): 321-344

Oni BA, Oziegbe O, Olawole OO. 2020. Significance of biochar application to the environment and economy. Annals of Agricultural Sciences

Paetsch L, Mueller CW, Kögel-Knabner I, von Lützow M, Girardin C, Rumpel, C. 2018. Effect of in-situ aged and fresh biochar on soil hydraulic conditions and microbial C use under drought conditions. Scientific Reports, 8(1): 6852

Paz-Ferreiro J, Fu SL, Mendez A, Gasco G. 2013. Interactive effects of biochar and the earthworm pontoscolex corethrurus on plant productivity and soil enzyme activities. Journal of Soils and Sediments, 14(3): 483-494

Quan G, Fan Q, Cui L, Zimmerman AR, Wang H, Zhu Z, Gao B, Wu L, Yan J. 2020. Simulated photocatalytic aging of biochar in soil ecosystem: Insight into organic carbon release, surface physicochemical properties and cadmium sorption. Environmental Research, 183: 109241

Rousk J, Baath E, Brookes PC, Lauber CL, Lozupone C, Caporaso JG, Knight R, Fierer N. 2010. Soil bacterial and fungal communities across a pH gradient in an arable soil. The ISME Journal, 4(10): 1340-1351

Sarkhot DV, Berhe AA, Ghezzehei TA. 2012. Impact of biochar enriched with dairy manure effluent on carbon and nitrogen dynamics. Journal of Environmental Quality, 41(4): 1107-1114

Sayadi MH, Rezaei MR. 2014. Impact of land use on the distribution of toxic metals in surface soils in Birjand city, Iran. Proceedings of the International Academy of Ecology and Environmental Sciences, 4(1): 18-29

Spokas KA, Novak JM, Stewart CE, Cantrell KB, Uchimiya M, DuSaire MG, RO KS. 2011. Qualitative analysis of volatile organic compounds on biochar. Chemosphere, 85(5): 869-882

Thies JE, Rillig MC, Graber ER. 2015. Biochar effects on the abundance, activity and diversity of the soil biota. In: J. Lehmann, S. Joseph (eds.). Biochar for Environmental Management: Science Technology and Implementation (2nd ed). 327, 390, Routledge, Abingdon, UK

Tomczyk A, Sokołowska Z, Boguta P. 2020. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Reviews in Environmental Science and Bio/Technology, 19: 191-215

Verma SR, Naresh R, Agarwal M, Sundar S. 2020. Role of environmental factors on the spread of bacterial diseases: A modeling study. Computational Ecology and Software, 10(2): 59-73

Wang J, Xiong Z, Kuzyakov Y. 2015. Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy, 8 (3): 1-12

Yang J, Pan B, Li H, Liao S, Zhang D, Wu M, Xing B. 2016. Degradation of p-Nitrophenol on biochars: role of persistent free radicals. Environmental Science and Technology, 50(2): 694-700

Yargicoglu EN, Reddy KR. 2017. Microbial abundance and activity in biochar-Amended landfill cover soils: Evidence from large-scale column and field experiments. Journal of Environmental Engineering, 143(9): 04017058

Yavari S, Malakahmad A, Sapari NB, Yavari S. 2016. Sorption-desorption mechanisms of imazapic and imazapyr herbicides on biochars produced from agricultural wastes. Journal of Environmental Chemical Engineering, 4(4): 3981-3989

Zhang WJ. 2007. Overview and forecast on forestry productions worldwide. Environmental Monitoring and Assessment, 125: 301-312

Zhu L. 2015. Microalgal culture strategies for biofuel production: a review. Biofuels, Bioproducts and Biorefining, 9(6): 801-814

Zimmerman AR. 2010. Abiotic and microbial oxidation of laboratory produced black carbon (Biochar). Environmental Science and Technology, 44(4): 1295-1301