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Impacts on biochar aging mechanism by eco-environmental factors

Ghulam Murtaza1, Zeeshan Ahmed2,3,4, Muhammad Usman5, Ahsan Areeb6, Allah Ditta7, Zia Ullah1, Faisal Mahmood8

1Faculty of Environmental Science and Engineering, Kunming University of Science and Technology, Kunming 650500, China
2Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, Xinjiang 830011, China
3Xinjiang Desert Plant Roots Ecology and Vegetation Restoration Laboratory, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, Xinjiang 830011, China
4Cele National Station of Observation and Research for Desert-Grassland Ecosystems, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Xinjiang 848300, China
5Department of Botany, Government College University Lahore, Lahore 54000, Pakistan
6Department of Agronomy, Faculty of Agricultural Science and Technology, Bahauddin Zakariya University, Multan 66000, Pakistan
7Department of Environmental Sciences, Shaheed Benazir Bhutto University Sheringal, Dir (U), 18000, Khyber Pakhtunkhwa, Pakistan
8Faculty of Life Science and Technology, Kunming University of Science and Technology, Kunming 650500, China
E-mail: zeeshanagronomist@yahoo.com

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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.

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).

![Benefits of biochar amendments to environment.](image)

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 (mycoremediation) 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.

<table>
<thead>
<tr>
<th>Pyrolysis type</th>
<th>Temperature (°C)</th>
<th>Residence time</th>
<th>Yield of biochar (%)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td>300 -700°C</td>
<td>different hours to days</td>
<td>37%</td>
<td>Gai et al., 2014</td>
</tr>
<tr>
<td>Fast</td>
<td>400-600°C</td>
<td>&lt; 1 s</td>
<td>12%</td>
<td>Tomczyk et al., 2020</td>
</tr>
<tr>
<td>Gasification</td>
<td>750 - 1000°C</td>
<td>15 to 25 s</td>
<td>10%</td>
<td>Leng et al., 2012</td>
</tr>
<tr>
<td>Fast</td>
<td>500 - 1000°C</td>
<td>&lt; 1 s</td>
<td>15%</td>
<td>Gurwick et al., 2013</td>
</tr>
<tr>
<td>Gasification</td>
<td>700-1000°C</td>
<td>Sec-min</td>
<td>10%</td>
<td>Tomczyk et al., 2020</td>
</tr>
<tr>
<td>Slow (bio-carbonization)</td>
<td>300-800°C</td>
<td>Sec-h</td>
<td>35%</td>
<td>Tomczyk et al., 2020</td>
</tr>
<tr>
<td>Slow</td>
<td>300-600°C</td>
<td>h-days</td>
<td>25-35%</td>
<td>Novotny et al., 2015</td>
</tr>
</tbody>
</table>

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 organo-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°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°C (Cheng et al., 2006; Cheng and Lehmann, 2009), significantly speeds up the process of biochar aging process, although chemisorption between biochar surface and O₂ 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°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°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.

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