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Biochar as a Soil Ameliorant: How Biochar Properties Benefit Soil Fertility—A Review

Christine Beusch

Institute of Ecology, Chair of Soil Science, Technische Universität Berlin, Berlin, Germany
Email: christine.beusch@email.de

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Abstract

In recent years, biochar has received great attention among researchers worldwide. This carbon-rich material, mainly produced from residues from agriculture and forestry, holds a wide range of properties, e.g. large specific surface area, high cation exchange capacity, and substantial nutrient contents, that can have beneficial effects when added to soils. This review is giving a brief introduction to biochar properties and how feedstock, pyrolysis temperature, and time influence these properties. As the majority of studies concentrate on the soil amending effects of biochar, this review also provides an overview of how biochar affects the chemical, physical, hydrological, and biological properties of soils. For example, biochar addition to soils can raise the pH, increase the organic carbon content, enhance nutrient retention, foster porosity, augment the water-holding capacity, and increase microbial biomass. Consequently, biochar can contribute to soil fertility, increase yields, help closing nutrient cycles, and thus help secure food safety in a region. However, the knowledge about the long-term effects is still limited and should be broadened by a more systematic testing of biochar effects in the future to help bring the benefits of biochar into practice.

Keywords

Biochar, Soil Amendment, Feedstock, Pyrolysis Temperature, Soil Fertility

1. Introduction

Biochar is a solid and carbon-rich material produced by pyrolysis of biomass in a low oxygen (O) environment (Joseph et al., 2010; Lehmann & Joseph, 2015; Solaiman & Anawar, 2015; Wang et al., 2016). The term "biochar" was introduced in 2006 by Lehmann et al., specifying charcoal used for environmental purposes and in particular to maintain or improve soil fertility.

Since the mid-1990s, Anthropogenic Dark Earths or *terra preta de Índio* soils located in the Central Amazon received growing attention in soil research (Lehmann et al., 2003; Neves et al., 2004). These relict Anthrosols have been heavily modified by pre-Columbian settlers by the addition of several inorganic and organic materials, e.g. charcoal, ash, bones, biomass waste, manure, faeces, and urine (Glaser & Birk, 2012). Radiocarbon data revealed ages of the analysed soil samples ranging from 350 to 2310 years BP (Neves et al., 2004). Other than the relatively poor soils in their direct vicinity, *terra preta* soils exhibit large stocks of stable organic matter and high nutrient levels that facilitate agricultural use (Glaser et al., 2001; Glaser & Birk, 2012). These favourable soil properties still persist despite challenging conditions of the humid tropics (Lehmann et al., 2003). Inspired by these findings, the interest in charcoal application to improve soils is growing worldwide. Since 2008, the number of scientific articles about biochar application started to increase (Lehmann et al., 2015), reaching a total of 6934 scientific publications in late 2018 (Wu et al., 2019).

The objectives of this review are 1) to provide a condensed overview of the state-of-the-art knowledge of the factors that control biochar properties, 2) to summarise the effects of biochar addition on soil properties and soil fertility, and 3) to suggest future directions to help bring the benefits of biochar into practice.

2. Methods

This review is based on an extensive literature research via Science Direct and Google Scholar. The author searched for the key words “biochar and soil and amendment” and selected the literature relevant for this review.

3. Biochar Properties

3.1. General Properties

Biochars are usually produced from agricultural and forestry residues, or municipal, green, and food waste (Ippolito et al., 2020). The pyrolysis of the original feedstock transforms carbon into a recalcitrant form with a high degree of aromatisation that may persist in soils hundreds to thousands of years (Wang et al., 2016). In general, biochars are of alkaline pH due to high inorganic carbonate and ash content (Yuan et al., 2011) with a large specific surface area (SSA) and high pore volume (Cheng et al., 2018; Laird et al., 2010; Suliman et al., 2016; Zhao et al., 2013). They also have a high cation exchange capacity (CEC) (Liang et al., 2006) and can develop positive and negative surface charges (Cheng et al., 2008; Liang et al., 2006) that may attenuate leaching of cationic and anionic nutrients when applied to soils (e.g. Agegnehu et al., 2015; Beusch et al., 2019; Knowles et al., 2011; Sika & Hardie, 2014; Zheng et al., 2013). Biochars may also exhibit substantial amounts of a variety of nutrients, however, this and numerous other physicochemical biochar properties largely depend on feedstock and pyrolysis conditions (Ippolito et al., 2020; Zhao et al., 2013).

3.2. Influence of Feedstock Type on Biochar Properties

Feedstock plays a crucial role for biochar properties and composition. Original feedstock properties like structure and nutrient content are reflected in the pyrolysed end product and determine the characteristics of biochars (Zhao et al., 2013). Wood biochar for example inherits the xylem structure of the parent material, whereas chicken manure biochar has a more heterogeneous structure based on the the components of the manure, like straw, digested food, and feathers (Downie et al., 2009; Ippolito et al., 2020; Joseph et al., 2010).

Lignocellulosic feedstocks, like wood, crop, and herbaceous material, consist of varying ratios of lignin, hemicellulose, and cellulose (Fawzy et al., 2021). Biochars produced from lignin-rich feedstock tend to have higher C contents with a more aromatic C structure, leading to higher long-term stability, higher SSA and porosity, lower pH, lower CEC, and lower nutrient content and availability than biochars produced of herbaceous material and non-lignocellulosic feedstock like manure or biosolids (Das et al., 2021; Ippolito et al., 2020; Fawzy et al., 2021; Gul et al., 2015; Li et al., 2020; Zhao et al., 2013). In a meta-data analysis review comprising approx. 5400 peer-reviewed scientific articles, Ippolito et al. (2020) found that wood-based biochars have the greatest SSA while crop- and grass-based biochars exhibit the greatest CEC. An overview of the biochar properties that are influenced by the lignin content of the original feedstock is given in **Figure 1**.

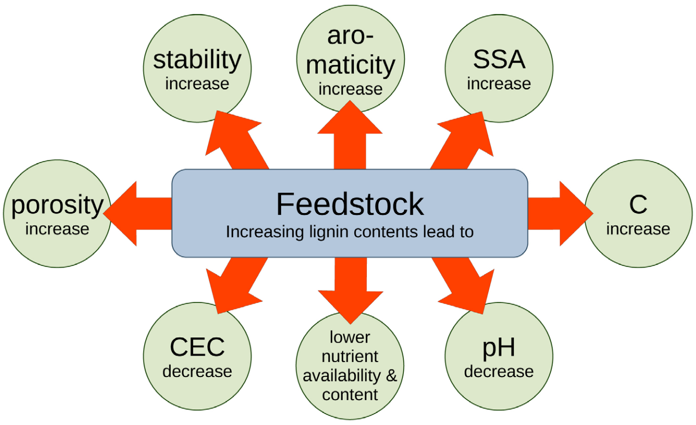

Figure 1. Influence of the lignin content of the feedstock on biochar properties.

Mineral element contents also depend of the type of feedstock (Zhao et al., 2013). During the pyrolysis process, volatile compounds of the biomass like O, hydrogen (H), and sulphur (S) are lost, leading to an accumulation of the non-volatile elements such as C, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), and copper (Cu) (Al-Wabel et al., 2013; Ippolito et al., 2020; Zhao et al., 2013).

3.3. Influence of Pyrolysis Temperature on Biochar Properties

In their meta-study, Ippolito et al. (2020) identified that pyrolysis type, whether fast or slow, only had a marginal influence on biochar properties. Thus, besides feedstock, the pyrolysis temperature plays a decisive role for the physicochemical properties of biochars (Al-Wabel et al., 2013; Das et al., 2021; Ippolito et al., 2020; Zhao et al., 2013). Pyrolysis temperature predominantly controls numerous biochar properties. An overview of the biochar properties that are influenced by the pyrolysis temperature is given in **Figure 2**.

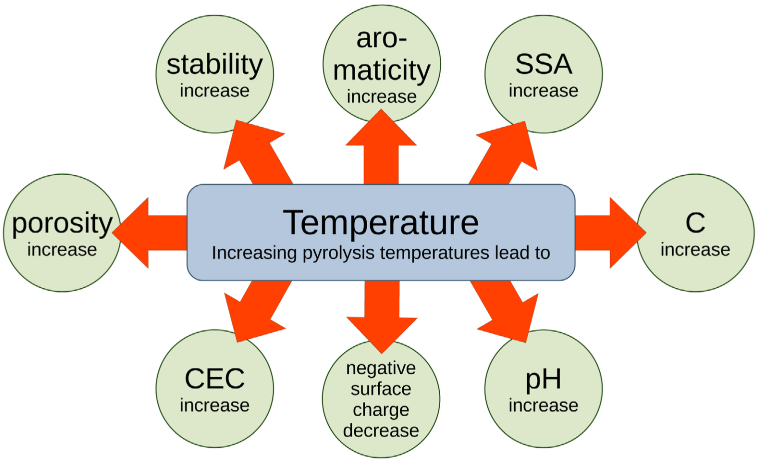

Figure 2. Influence of the pyrolysis temperature on biochar properties.

Greater pyrolysis temperatures lead to an increase of C content, SSA, porosity, pH, alkalinity, inorganic element concentrations, ash content, CEC, and aromaticity (e.g. Al-Wabel et al., 2013; Chen et al., 2019; Downie et al., 2009; Ezepue et al., 2019; Ippolito et al., 2020; Joseph et al., 2010; Yuan et al., 2011; Zhao et al., 2013). The latter accounts for higher recalcitrance and long-term stability of high-temperature biochars with half-lives that exceed 1000 years (Ippolito et al., 2020). With increasing temperature, more volatile components are lost and the biochar yield decreases (Al-Wabel et al., 2013; Yuan et al., 2011). Moreover, higher temperatures foster decomposition of acidic functional groups like phenolic hydroxyl and carboxyl groups, while carbonyl groups form (Chen et al., 2019; Chun et al., 2004; Yuan et al., 2011). Yuan et al. (2011) also reported decreasing zeta potential with increasing pyrolysis temperatures, indicating less negative surface charges for high-temperature biochars than for low-temperature biochars.

3.4. Influence of Time on Biochar Properties

Most scientific publications refer to the initial properties of fresh biochars. However, these properties are changing over time when biochars have been exposed to a moisture-containing environment, as it is the case after application to soil. This process is referred to as “ageing”. The changes are induced by abiotic and biotic reactions, solubilisation processes, and interactions with organic materials, microbes, minerals, and aqueous phases of the soil (Mia et al., 2017; Mukherjee et al., 2014). In general, ageing processes are enhanced with increasing temperatures and duration of exposure (Cheng & Lehmann, 2009) and in particular affect the biochar surface (Cheng & Lehmann, 2009; Heitkötter & Marschner, 2015; Liu et al., 2013b; Sorrenti et al., 2016).

After some residence time in soils, the biochar surface is coated and the pores are clogged with organic and mineral components of soils (Joseph et al., 2010; Mukherjee et al., 2014; Ren et al., 2016; de la Rosa et al., 2018; Sorrenti et al., 2016), leading to a decrease of SSA (Ghaffar et al., 2015; Liu et al., 2013b; Mia et al., 2017; Ren et al., 2016) and a reduction of the inner reactive surface (Pignatello et al., 2006). Also biochar pH is decreasing over time (Cheng & Lehmann, 2009; Mukherjee et al., 2014; de la Rosa et al., 2018; Sorrenti et al., 2016). While ageing stimulates the development of acidic functional groups (Heitkötter & Marschner, 2015; Rechberger et al., 2017; de la Rosa et al., 2018; Sorrenti et al., 2016), the concentration of base functional groups on the biochar surface decreases over time (Cheng et al., 2008; Cheng & Lehmann, 2009). Furthermore, the negative surface charge is increasing with ageing, leading to a high surface charge density and enhanced CEC (Cheng et al., 2008; Heitkötter & Marschner, 2015; Liang et al., 2006; Mia et al., 2017; Mukherjee et al., 2014), but declining anion exchange capacity (AEC) (Cheng et al., 2008; Lawrinenko et al., 2016). This increase of surface acidity over time indicates that the liming effect of biochars may only persist for a short period of time (de la Rosa et al., 2018). An overview of the biochar properties that are influenced by the pyrolysis temperature is given in **Figure 3**.

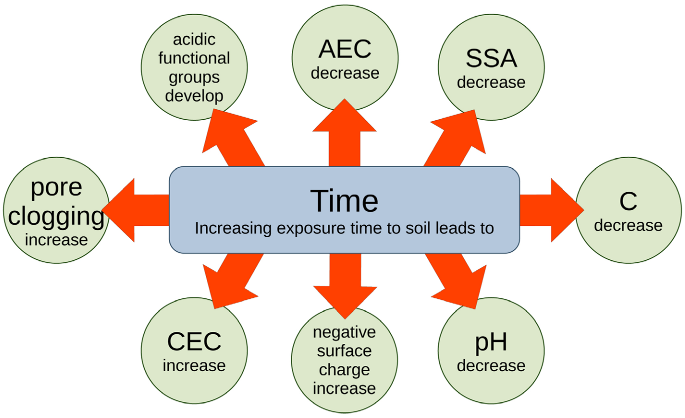

Figure 3. Influence of the exposure time to soil on biochar properties.

In addition, the elemental composition is effected by ageing. Total concentrations of N and O increase as well as the atomic concentrations of O, S, N, sodium (Na), aluminium (Al), Ca, manganese (Mn), and Fe detected at the biochar surface, while C and K contents decrease (Cheng et al., 2008; Cheng & Lehmann, 2009; Ghaffar et al., 2015; Mia et al., 2017; de la Rosa et al., 2018; Sorrenti et al., 2016). In particular, the changes in the surface chemistry may alter the adsorption properties of aged biochars (Cheng & Lehmann, 2009; Ghaffar et al., 2015; Liu et al., 2013b; Ren et al., 2016; Singh et al., 2010). Several studies reported a decrease of nitrate (NO_3^-) retention over time, indicating that the effectiveness of nutrient retention may be an artefact of fresh biochars that may not continue over a longer period of time (Beusch et al., 2019; Eykelbosh et al., 2015; Gronwald et al., 2015; Kanthle et al., 2016). However, due to increase of CEC, aged biochars may provide a higher potential to retain cations (Mia et al., 2017).

4. Biochar as a Soil Ameliorant

The majority of studies concentrates on the soil amending effects of biochar that benefit soil fertility (Solaiman & Anawar, 2015; Wu et al., 2019). **Table 1** gives an overview soil properties that are positively affected by biochar addition.

Table 1. Overview of chemical, physical, hydrological, and biological soil properties that are positively affected by biochar addition.

	References
Chemical properties	
Increase of pH	E.g. Cheng et al. (2018); Gopal et al. (2020); Gul et al. (2015); Herath et al. (2013); Hossain et al. (2020); Laird et al. (2010); Liang et al. (2006); Martinsen et al. (2014); Mukherjee et al. (2011); Novak et al. (2009); Palanivell et al. (2020); Silber et al. (2010); Ulyett et al. (2014); Xu et al. (2016)
Liming effect	E.g. Jeffery et al. (2011); Jindo et al. (2020); Liu et al. (2013a); Shen et al. (2016); Sika and Hardie (2014); Verheijen et al. (2010)
Increase of SOC	E.g. Arthur et al. (2015); Gopal et al. (2020); Hailegnaw et al. (2019); Han et al. (2016); de Jesus Duarte et al. (2019); Laird et al. (2010); Lehmann et al. (2006); Liu et al. (2015); Novak et al. (2009); Prommer et al. (2014); Weng et al. (2017)
Increase of CEC	E.g. Gul et al. (2015); Herath et al. (2013); Jindo et al. (2020); Laird et al. (2010); Liang et al. (2006); Martinsen et al. (2014); Mukherjee et al. (2011); Silber et al. (2010)
Addition of nutrients	E.g. Cheng et al. (2018); Gopal et al. (2020); Han et al. (2016); Hien et al. (2021); Hossain et al. (2020); Ilyas et al. (2021); Jindo et al. (2020); Laird et al. (2010); Martinsen et al. (2014); Novak et al. (2009); Piash et al. (2021)
Increase of nutrient retention	E.g. Agegnehu et al. (2015); Beusch et al. (2019); Cheng et al. (2018); Hossain et al. (2020); Lima et al. (2018); Limwikran et al. (2019); Singh et al. (2010); Steiner et al. (2008); Ulyett et al. (2014)
Reduction of nutrient leaching	E.g. Agegnehu et al. (2015); Beusch et al. (2019); Blanco-Canqui (2021); Cheng et al. (2018); Hossain et al. (2020); Kanthle et al. (2016); Novak et al. (2009); Sika and Hardie (2014); Singh et al. (2010); Steiner et al. (2008); Xu et al. (2016)
Physical properties	
Reduction of bulk density	E.g. Abel et al. (2013); Basso et al. (2013); Burrell et al. (2016); Hardie et al. (2014); Herath et al. (2013); Hossain et al. (2020); de Jesus Duarte et al. (2019); Jiang et al. (2019); Obia et al. (2016); Omondi et al. (2016); Qian et al. (2020)
Enhanced aggregate stability	E.g. Burrell et al. (2016); Gul et al. (2015); Han et al. (2021); Herath et al. (2013); Hossain et al. (2020); Obia et al. (2016); Omondi et al. (2016); Ouyang et al. (2013); Soinne et al. (2014)
Increase of SSA	E.g. Arthur et al. (2015); Cheng et al. (2018); Ippolito et al. (2020); Laird et al. (2010); Liang et al. (2006); Lima et al. (2018)

Continued

Increase of porosity	E.g. Abel et al. (2013); Głab et al. (2016); Hossain et al. (2020); de Jesus Duarte et al. (2019); de Melo Carvalho et al. (2014); Obia et al. (2016); Omondi et al. (2016); Qian et al. (2020)
Hydrological properties	
Increased water-holding capacity	E.g. Agegnehu et al. (2015); Basso et al. (2013); Castellini et al. (2015); Herath et al. (2013); Hien et al. (2021); Hossain et al. (2020); Jeffery et al. (2011); Lima et al. (2018); Obia et al. (2016); Omondi et al. (2016); Ouyang et al. (2013); Ulyett et al. (2014); Xu et al. (2016)
Increase of soil water content	E.g. Abel et al. (2013); Basso et al. (2013); Głab et al. (2016); Hardie et al. (2014); Qian et al. (2020)
Increase of plant available water	E.g. Abel et al. (2013); Blanco-Canqui (2021); Burrell et al. (2016); de Jesus Duarte et al. (2019); Martinsen et al. (2014); de Melo Carvalho et al. (2014); Omondi et al. (2016); Qian et al. (2020)
Biological properties	
Increase of microbial biomass, activity, or diversity	E.g. Blanco-Canqui (2021); Gao et al. (2019); Gopal et al. (2020); Gul et al. (2015); Gwenzi et al. (2015); Han et al. (2021); Heitkötter and Marschner (2015); Hossain et al. (2020); Jaafar et al. (2015); Liu et al. (2015); Madiba et al. (2016); Nelissen et al. (2014a); Prommer et al. (2014); Sánchez-García et al. (2015); Xu et al. (2016); Van Zwieten et al. (2010a)
Habitat for microorganisms	E.g. Gul et al. (2015); Kim et al. (2013); Lehmann et al. (2011); Molnár et al. (2016)
Increase of arbuscular mycorrhizal colonisation	E.g. Blackwell et al. (2010); Gopal et al. (2020); LeCroy et al. (2013); Lehmann et al. (2011); Madiba et al. (2016); Shen et al. (2016); Solaiman et al. (2010); Warnock et al. (2007)
Increase of earthworm abundance and activity	E.g. Kamau et al. (2019); Topoliantz et al. (2005); Van Zwieten et al. (2010b)

Biochar application to soils can also mitigate climate change by sequestration of carbon (e.g. Lehmann et al., 2006; Lorenz & Lal, 2014; Mao et al., 2012; Wang et al., 2016) and reduce greenhouse gas (GHG) emissions (e.g. Gurwick et al., 2013; Mukherjee & Lal, 2013; Nelissen et al., 2014b; Singh et al., 2010; Woolf et al., 2010). Biochar can also be a management option for degraded soils and support immobilisation of heavy metals (e.g. Beesley et al., 2011; Schweiker et al., 2014; Uchimiya et al., 2010; Wagner and Kaupenjohann, 2014), remediate organic contaminants (e.g. Ahmad et al., 2014; Beesley et al., 2011; Chen et al., 2008; Hale et al., 2016), mitigate salt stress to plants in saline soils (e.g. Lashari et al., 2013; Saifullah et al., 2018; dos Santos et al., 2021; Sun et al., 2017; Thomas et al., 2013), and improve soil nutrient availability in acidic soils (e.g. Bornø et al., 2018; Hass et al., 2012; Hong & Lu, 2018; Molnár et al., 2016; Novak et al., 2009; Xu et al., 2014). Besides improving crop yields (e.g. Agegnehu et al., 2015; Blanco-Canqui, 2021; Gopal et al., 2020; Jeffery et al., 2011; Kamau et al., 2019; Liu et al., 2013a; Martinsen et al., 2014; dos Santos et al., 2021; Spokas et al., 2012; Zhang et al., 2015), biochar can offer further benefits to agriculture, for example promoting livestock health and growth by addition of biochar to animal feed (e.g. Boonanuntanasarn et al., 2014; Chen et al., 2019; Han et al., 2014; Villalba et al., 2002; Watarai & Tana, 2005).

Biochar is also applied to remove organic and inorganic contaminants from water, in particular excess of nutrients in wastewater (e.g. Ahmad et al., 2014; Durn et al., 2016; Ghezzehei et al., 2014; Li et al., 2019). Biochar can also add value to unused biomass wastes by nutrient recycling (e.g. Krause et al., 2015; Moreira et al., 2017; Roberts et al., 2010; You & Wang, 2019) and the production of biofuel and bioenergy (e.g. Bartoli et al., 2020; Chen et al., 2019; Jeffery et al., 2015; Krause et al., 2015; Liao et al., 2013).

5. Conclusions and Outlook

Biochar has the potential to meliorate soils, increase their long-term fertility, and hence contribute to food safety within a region. By the use of currently unused residues, biochar can also contribute to close nutrient cycles and sequester carbon in soils. The numerous types of biochars exhibit a broad range of properties, mainly controlled by feedstock and pyrolysis temperature. When incorporated into the soil, biochar characteristics change over time. Even though numerous studies have been conducted with a myriad of biochars of all kinds and properties, the majority of studies focused on short-time effects. Still, there is a lack of field experiments, in particular over longer time scales of more than just one or two years. This would generate knowledge about the prolonged effects of biochar addition on soil properties that is crucial to upscale biochar application at farm level. In the future, a more systematic testing of biochar effects in the long-term and on larger scales involving different soil types and crops is needed to help bring the benefits of biochar into practice.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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