Biochar Role in Soil Carbon Stabilization and Crop Productivity

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Abstract

In the presented chapter, various aspects related to carbon stabilization and storage in the form of biochar (an important soil amendment) are discussed. The following questions were considered: (i) what is the current general knowledge on biochar and its physicochemical composition, (ii) how manufacturing conditions affect biochar characteristics, including their role in carbon stabilization, (iii) how biochar contributes to soil carbon balance and storage, (iv) what are the effects of biochar on water retention in soil, soil erosion, production yields and economic productivity in agriculture, (iv) what are the effects of biochar on soil microbial community and activity, and (v) how biochar affects other soil amendments and their roles in soil. The present studies assess scientific outcomes and results which conclude that soil organic matter gained by organic residues can be used to enhance soil carbon storage. Following the published scientific results, the biochar amendment appears to be a promising way for increasing the stocks of recalcitrant carbon in the soil from a long-term perspective. Future research should focus on the designing, production, and use of enriched biochar, e.g. with nutrients, minerals, or microorganisms, to improve soil physicochemical properties, supply nutrients, and prevent their leaching. The fertilizer supplies accessible nutrients available to plants, and biochar can sequester depleted elements and prevent leaching of the added ones.

Keywords

Biochar · Carbon · Fertilizer · Soil amendment · Carbon sequestration

Abbreviations

AEC	Anion Exchange Capacity
AMF	Arbuscular Mycorrhizal Fungi
BC	Biochar
CEC	Cation Exchange Capacity
FT-ICR-MS	Fourier Transform Ion Cyclotron Resonance Mass Spectrometry
GHG	Greenhouse Gas
IBI	International Biochar Initiative
LOC	Labile Organic Carbon
NMR	Nuclear Magnetic Resonance
Nr	Nutrients
OM	Organic Matter
R_{50}	Recalcitrance Index
SEM	Scanning Electron Microscopy
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SPAC	Stable Polycyclic Aromatic Carbon
TOC	Total Organic Carbon

1 Introduction

Biochar (BC) is produced during high-temperature (300–800 °C) combustion of biomass under oxygen-limited conditions (i.e. pyrolysis), and therefore it contains a high proportion of stable carbon (Singh et al. 2012). Although a broad spectrum of biochar definitions exist in the literature, all of them concern conditions of biochar production and its characterization. For example, biochar is defined as solid carbonaceous residue, produced under oxygen-free or oxygen-limited conditions at temperatures ranging from 300 to 1000 °C (Saifullah et al. 2018) or as a carbon-rich product that has a high proportion of aromatic C and high chemical and biological stability (Li et al. 2017). If applied to the soil, it is thought to improve soil fertility and mitigate climate change due to its potential for storing anthropogenic carbon dioxide (CO_2) (Lehmann et al. 2011; Seifritz 1993). The annual capacity to sequester carbon in the form of thermally stabilized (charred) biomass (considering the utilization of all existing organic sources) applied to soil was estimated to be 1 Gt per year (Sohi et al. 2010). BC is not only produced artificially but can also be found in soils located in humid tropics, especially in Amazonia, as a result of ancient human activities and/or fires. These soils are referred to as Amazonian dark earth or Terra preta (Taketani et al. 2013). Unlike other tropical soils, they contain high levels of nitrogen, carbon, calcium, potassium, magnesium, phosphorus, and stable organic matter (Glaser et al. 2001). According to Gaskin et al. (2008), these nutrients are easily extractable and may be available for plants, which contributes to the high fertility of these soils. On the other hand, other authors stated that biochar could not be considered as a primary supply of nutrients. However, biochar is an adsorption matrix and may enrich the soil with several beneficial elements and minerals, which are the main perspective to improve the condition of the soil (Glaser et al. 2002; Lehmann et al. 2003a; Meena et al. 2018; Shenbagavalli and Mahimairaja 2012b).

2 Role of Biochar in Soil Carbon Stabilization

Despite the substantial topic, the processes of carbon stabilization have not been fully uncovered, and it is affected by many factors (Wiesmeier et al. 2019; Yang et al. 2020). Mechanisms to stabilize carbon stock include physical interactions, such as the reaction of soil mineral matrix with carbon compounds forming bonds inaccessible for decomposers; rigid chemical structure of some carbon substances, such as biochar, some humic acids or lipids; or by biological protection given by formation of micro-aggregates bound by hyphae or by some changes to residues within organisms intestine (Goh 2004).

Understanding of carbon stabilization is pivotal to improve agricultural management to store soil organic matter, soil structure, or to mitigate the greenhouse effect (Singh et al. 2018). Carbon stabilization is tightly related to carbon sequestration, which is the transformation of atmospheric carbon dioxide into soil carbon (Liao et al. 2020). Increased stabilization of sequestered carbon may help to mitigate the greenhouse effect (Goh 2004; Singh et al. 2018).

Biochar content can be roughly divided into leachable carbon, ash, and recalcitrant carbon (Lehmann et al. 2011). Carbon stabilization in the soil is involved in the global carbon cycle (Singh et al. 2018). However, not all the carbon inputs into soil resist to processes of mineralization, leaching, or erosion losses. Thus, soil carbon is assessed as labile (with a short half-life 1–20 years) or stable (20–100 years) (Goh 2004). Stable carbon stock is decisive to assess susceptibleness of soil organic carbon or services of ecosystems (Buytaert et al. 2011; Rolando et al. 2017; Yang et al. 2020). Biochar application is one of the ways to increase carbon sequestration and stabilization in soil, as it contains 20–80% of stable carbon which is not released into the atmosphere in the form of carbon dioxide within a couple of years (Llorach-Massana et al. 2017; Masek et al. 2011; McBeath et al. 2015). Compared to other organic matter resisting rapid mineralization and containing aromatic carbon compounds (such as lignin), biochar is primarily composed of fused aromatic carbon, hydrocarbons consisting of polycyclic aromatic compounds (Lehmann et al. 2011; Schmidt and Noack 2000). It has been reported that biochar application increases a humic-like fluorescent component in soil, and reduces co-localization of aromatic-C: polysaccharides-C. These changes, coupled with reduced C metabolism (decreased respiration), seem as important features of C stabilization in biochar-amended soils (Hernandez-Soriano et al. 2016). There are two forms of labile carbon, determined as dissolved organic carbon and fraction of unstable organic carbon (Al-Wabel et al. 2013). Biochar seems to be a material composed of micropores primarily consisting of aromatic carbon and less of carboxyl and phenolic carbon (Braida et al. 2003). The labile part of biochar can be indicated as volatile matter, and ash content which includes essential nutrients representing valuable sources for soil biota (Lehmann et al. 2011).

2.1 Effect of Feedstock on Biochar Properties

Biochar chemical composition is highly variable and depends mainly on its original feedstock and combustion settings (Spokas 2010).

A wide range of biochar is derived from all types of biological resources as well as from waste. Classification of biomass feedstocks to produce biochar can be based on different criteria such as initial moisture content, biomass growing conditions, or source of biomass (Fig. 1).

As a result, biochar may contain various amounts of elements, such as carbon, oxygen, hydrogen, nitrogen, sulfur, phosphorus, or heavy metals (Granatstein et al. 2009; Preston and Schmidt 2006). The general overview of elements loss from original biomass during the pyrolysis is shown in Fig. 2, in comparison with the initial biomass feedstock (Lehmann and Joseph 2015). In general, there is a vast difference between the contents of nutrients in biochar originating from the nutrient-rich feedstocks such as manure and sewage sludge from those prepared from lignin-based feedstocks (Yadav et al. 2018).

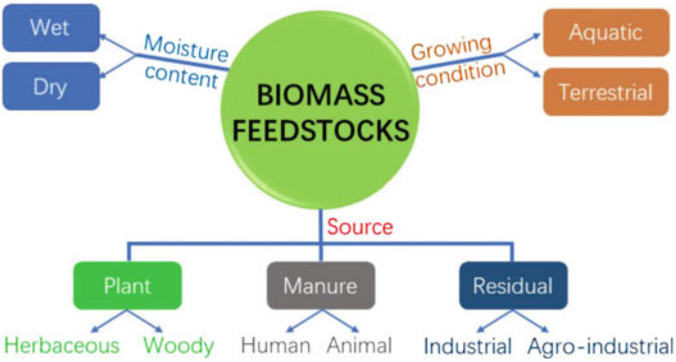

Fig. 1 Types of biomass feedstocks for biochar production. (Adopted from Yuan et al. 2019)

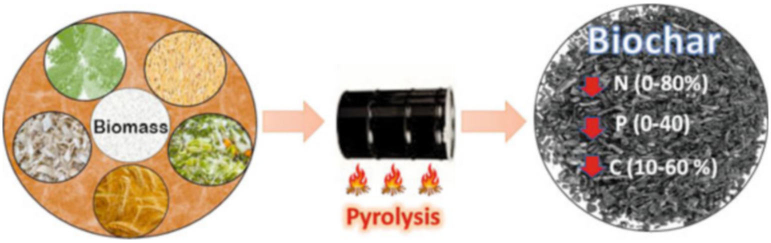

Fig. 2 Loss in nutrients from original biomass within the pyrolysis process. (Adopted from Lehmann and Joseph 2015)

Apart from elementary composition, the functional chemistry of biochar surfaces may differ depending on the original feedstock and pyrolysis conditions. The functional chemistry of biochar affects its sorption ability, and therefore it is important to understand how the production and ambient conditions affect functional groups in biochar. For example, it has been observed that high pyrolysis temperature reduces the number of functional groups, and consequently, biochar loses its negative charge, and its CEC decreases (Novak et al. 2009). On the other hand, the opposite situation occurs during the biochar weathering process, where enhancement of polar acid groups appears causing natural oxidation of its surface.

(Spokas 2013). According to a study by Li et al. (2013), carbonization cleaves hydroxyl and hydrogen groups at simultaneous aromatization which stabilizes biochar carbon making it less prone to mineralization.

Moreover, the feedstock also affects electrical conductivity and final pH (Singh et al. 2010), e.g. wheat straw feedstock was found to provide high CEC and low pH biochar, which is beneficial for soil organic matter (SOM) (Naeem et al. 2014). Wood feedstock biochar tends to have low to medium ash contents, while biochar derived from wheat or corn contains generally higher ash contents (Zhu et al. 2019). Higher content of minerals is negatively correlated with carbon in biochar (Gaskin

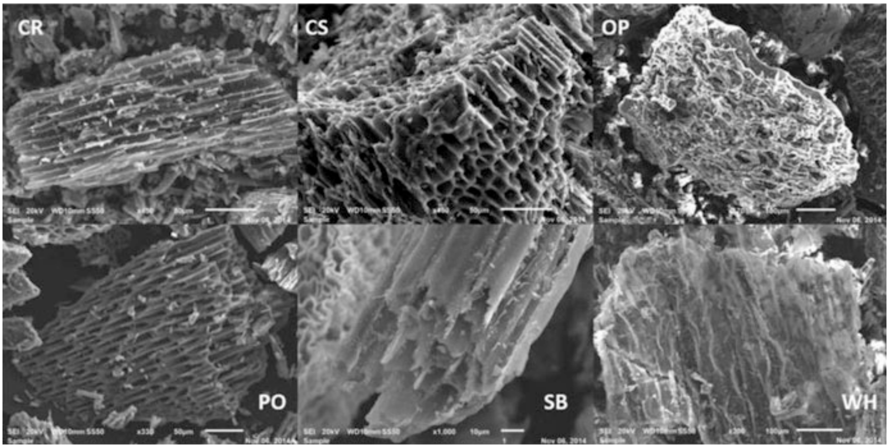

Fig. 3 SEM images of biochar samples (*CR* charcoal fines, *CS* coconut shell, *OP* orange peel, *PO* palm oil bunch, *SB* sugarcane bagasse, *WH* water hyacinth). (Adopted from Batista et al. 2018)

et al. 2008). The type of feedstock and pyrolysis temperature also significantly affects biochar yield in production. While low temperature results in a higher yield, higher temperature causes a lower yield, but the nature of the produced biochar is more recalcitrant (Jindo et al. 2014).

The appearance of BC is determined by the material used for its production. For illustrative purposes, scanning electron microscope (SEM) images of various BC samples derived from different feedstocks are shown in Fig. 3. Wood biochar retains its exoskeleton structure while manure–biochar is highly heterogeneous and comprises residues of digested food, seeds, and other fragments (Joseph et al. 2010). Thus, the feedstock is tightly related to biochar porosity, the character of pores, their size, surface area, and size layout (Downie et al. 2009).

2.2 Effect of Pyrolysis Temperature on Biochar Properties and Carbon

Chemical and physical properties of biochar depend on the feedstock type as well as on pyrolysis conditions (Nguyen et al. 2008; Jindo et al. 2014; Biederman and Harpole 2013; Novak et al. 2009). The suitable production procedure is decisive for biochar's further usability. By adjusting specific conditions of pyrolysis such as temperature, heating rate, and residence time, different biochar yields and composition can be obtained. Table 1 presents the influence of selected process conditions on biochar production and characterization (Bruckman et al. 2015). The relation between temperature and time during the pyrolysis process is depicted in Fig. 4.

The main factor affecting the properties of the final product is the temperature of pyrolysis, which does not usually exceed 700 °C (Lehmann and Joseph 2009). Pyrolysis carried out at low temperatures is beneficial for a higher yield of biochar,

Table 1 The effect of pyrolysis conditions on biochar production and characterization

Pyrolysis conditions	Specification	Effects
Temperature	Low (<400 °C)	More biochar, less C in biochar
	Moderate (~500 °C)	Less biochar, more C in biochar
	High (>700 °C)	Less biochar, more gas products
Heating rate	Low (<10 °C/min)	Slow heating, more biochar
	High (>300 °C/min)	Rapid heating, less biochar
Residence time	Low (<10 min)	Less carbonization, more C in biochar
	High (>1 h)	More carbonization, more C in biochar

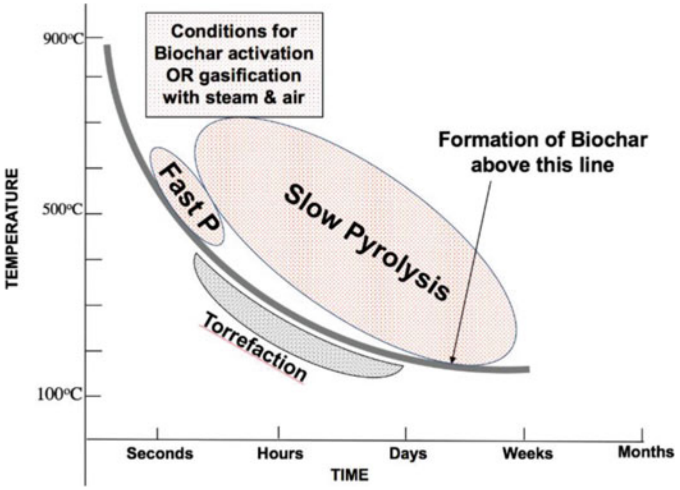

Fig. 4 Relation of time and temperature within the process of biochar production. (Adopted from Joseph et al. 2018)

better mineralization (Downie et al. 2009), and an increase in cation exchange capacity (CEC) (Mukherjee et al. 2011). Low-temperature production retains more nitrogen (Naeem et al. 2014) in biochar while high-temperature pyrolysis allows larger surface area (above 550 °C), higher carbon content, better sorption ability, and greater resistance to decomposition (Downie et al. 2009; Jindo et al. 2014; Naeem et al. 2014; Fischer and Glaser 2012). Higher temperature increases the pH (Mukherjee et al. 2011), decreases CEC, and raises concentrations of nutrients in biochar (Keiluweit et al. 2010). However, it also reduces the bioavailability of nutrients such as Ca, Mg, P, or K (Naeem et al. 2014). To reveal, how temperature affects physicochemical properties, the research by Jindo et al. (2014) assessed characteristics of a particular BC, e.g. apple branch-based biochar produced at 800°Cshowed surface area 12 m^2g^{-1}, yield 28%, pH 7. Biochar production proceeds at three stages: pre-pyrolysis, main-pyrolysis, and formation of carbonaceous soil products (Lee et al. 2010) (Fig. 5). The pyrolysis temperature is strongly correlated with changes in the structure and physicochemical properties of biochar.

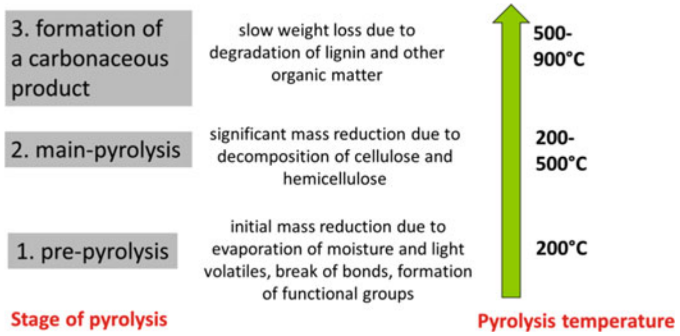

Fig. 5 Stages in biochar production

When using biochar in agriculture, the procedure could be adjusted in order to increase CEC and available nutrients and to improve soil fertility (Gaskin et al. 2008; Van Zwieten et al. 2010). It has been found that low-temperature biochar has the best results in agrochemical management (Gaskin et al. 2008). According to the study (Alotaibi and Schoenau 2019), low-temperature biochar (300 °C) exhibited better results in wheat growth and soil chemical properties (consistent positive influence on pH, CEC, and organic matter) while high-temperature biochar had a better effect on physical properties of soil (soil bulk density, total porosity, etc.). A lower temperature (up to 400 °C) is better either for stable aromatic backbone containing more C=O and C–H which can be used as nutrient exchanging sites (Novak et al. 2009; Glaser et al. 2002), or due to higher ash content of biochar contributing to better yield compared to recalcitrant biochar raising from higher temperature pyrolysis (Chan et al. 2008). The feedstock type and temperature also affect biochar properties in terms of the stable polycyclic aromatic carbon (SPAC) fraction content. The SPAC fraction controls resistance to mineralization and carbon stabilization. SPAC formation in biochar was $<20\%$ of the total organic carbon (TOC) at <450 °C and $> 80\%$ of TOC at above 600–700 °C (McBeath et al. 2015).

2.3 Cation/Anion Exchange Capacity, pH, and Carbon Mineralization

Cation exchange capacity (CEC) and anion exchange capacity (AEC) characterize the capacity of materials to exchange cations and anions, respectively. For biochar, CEC typically ranges between 77 and 119 cmol kg^{-1} (Lichtfouse 2014) while AEC varies between 0.602 and 27.7 cmol kg^{-1} (Lawrinenko and Laird 2015). These parameters are important for the extent of sorption abilities of biochar in soil that is influenced mainly by pH of the soil solution (Weil and Brady 2017). If the pH of the soil solution is above the point of zero biochar charge, biochar will be able to exchange cation nutrients because of the negative electrical charge on its surface (Mukherjee et al. 2011). Biochar immersed in water suspension is related to functional groups present on the surface of biochar. Functional groups are given by a carbonization procedure producing fused-ring and anomeric O-C-O or alkylated HCOH carbons depending on the indigenous feedstock (Li et al. 2013). CEC depends on the number of sites containing oxygen such as alcohol, carbonyl, and carboxyl groups bearing a negative charge and binding cations (Lawrinenko and Laird 2015). Nevertheless, not all acidic groups contribute to CEC. It has been found there were ten times fewer sites capable of binding cations than was the number of functional groups on the surface of biochar (Appel et al. 2003; Mukherjee et al. 2011). Coupled increases of CEC and decreases in carbon mineralization rates were observed under soil treatments with biochar, as the consequence of pH rising, and as an evidence of a relationship between carbon stabilization and high CEC (de Andrade et al. 2015).

Biochar pH measured in a water solution is alkaline to neutral (Solaiman and Anawar 2015). As other chemical properties, pH is highly dependent on biochar feedstock and production temperature. The high temperature usually provides biochar with higher pH while the lower temperature leads to reduced pH due to different ratio of dehydrogenation and aromatization in the process of pyrolysis (Li et al. 2013; Lichtfouse 2014; Mukherjee et al. 2011). Thus, high-temperature biochar can be used for liming, i.e. to increase the pH of acidic soils (Cheng et al. 2006, 2008; Chia et al. 2014; Liu et al. 2013; Granatstein et al. 2009). On the contrary, the addition of low-temperature biochar to already alkaline soils may eventually result in the decrease of soil pH (Lichtfouse 2014; Shenbagavalli and Mahimairaja 2012a; Gaskin et al. 2008; Liu and Zhang 2012). Soil solution pH can be affected by biochar. Low pH is not given only by a high concentration of H^+ but also by the presence of aluminium. Biochar has been found to not only adjust pH by its buffering capacity, but it can even sorb Al (Berek et al. 2011). However, the liming effect can be only short-term as the pH decreases during the weathering process (Spokas 2013). In addition, biochar in higher concentrations does not alter the soil pH as its exchangeable acidity is replaced by its buffering capacity (Solaiman and Anawar 2015). Thus, both the properties of biochar and its dosing should be taken into account when an increase of soil pH is one of the desired benefits of biochar application to soil.

Biochar pH may also affect short-term changes (negative or positive) in the mineralization rate of native SOC (Luo et al. 2011; Meena et al. 2020b). Higher pyrolysis temperature biochar shows decreased size of the priming effect, whereas lower temperature biochar is coupled with increased mineralization, which is further enhanced in the low pH soil and depressed in the high pH soil (Luo et al. 2011). The water-soluble components of biochar are the inducers of the priming effect for accelerated mineralization and decreased SOC, which is corroborated by observation of how water regimes (saturated, unsaturated and alternating conditions) that promote the differences in carbon mineralization and CEC in the BC materials (Nguyen and Lehmann 2009). Unsaturated and alternating conditions changed the CEC and O/C values of BCs and the evidenced increase in the oxidation rate was probably the key mechanism controlling biochar carbon stability (Nguyen and Lehmann 2009). With respect to the fact that biochar C mineralization is essentially a biological process, the pH is a fundamental determinator of microbial processes in soil. Whereas low-temperature BC increases the available and microbial biomass C concentration in both the low and high pH soil, high-temperature BC showed pronounced microbial colonization in the low pH soil but very low available C in the high pH soil (Luo et al. 2013). Other authors evidenced that the BC application to the soil can cause increases in soil pH due to labile carbon-derived changes in the soil microbial community (Farrell et al. 2013; Prayogo et al. 2014), for instance, increased abundance of Gram-negative bacteria (Prayogo et al. 2014) and actinobacteria (Prayogo et al. 2014; Liao et al. 2016). As it is known that most soil actinobacteria prefer and confer neutral to acidic soil pH (Basilio et al. 2003), these facts may link the higher microbial colonization of large surface high-temperature BC, which is coupled with low C mineralization rate, with higher pH soil.

2.4 Recalcitrance and Carbon Storage

Black carbon, which is similarly as biochar a purely natural origin matter, represents stable stock with a very slow rate of its turnover. It is because of its recalcitrance nature due to aromatic, graphitic, and refractory carbon (Glaser et al. 1998; Major et al. 2010a) in the form of aryl-C structures (Atkinson et al. 2010; Solomon et al. 2007). Black carbon is present in the sea in the form of sediments which are thousands of years older than the sediments without carbon (Masiello and Druffel 1998). Terrestrial land also has stabilized carbon storage as in the case of the aquatic environment (Glaser et al. 2001; Taketani et al. 2013).

Biochar is known to be a highly stable material, yet its initial decomposition has been observed by some researchers (Major et al. 2010a). For example, the study by Nguyen et al. (2008) observed that the decomposition of black carbon in soil originating from forest fire 2–100 years ago was rapid during the first 30 years, and then it slowed down. The most significant changes were observed on the surface of biochar with a decreasing tendency towards inner parts. Ageing caused gradual decomposition of biochar to CO_2, leaching, and dissolving of organic carbon. The nuclear magnetic resonance (NMR) analysis revealed higher aromaticity of SOM in charcoal-enriched soils. In contrast, the Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR-MS) results indicated an increased presence of lignin- and tannin-like compounds in the water-extractable SOM. It was evidenced that recent charcoal additions (>60 years) enhanced soil capacity to retain and stabilize C and N (Abdelrahman et al. 2018). Generally, biochar protects original soil organic matter and alleviates the priming effect (Granatstein et al. 2009). The protection of soil organic matter is caused mainly by refractory aryl-carbon structures (Atkinson et al. 2010; Solomon et al. 2007). Despite that our knowledge on the role of biochar in organic matter protection is incomplete, two main factors have been proposed to be relevant in this matter, i.e. the structure of small-size pores that mechanically prevent leaching and enzymatic breakdown of organic matter and the role of the chemical surface structure of biochar that depends on the character of either black carbon or biochar (Kasozi et al. 2010).

Table 2 Recalcitrance index (R_{50}) of different types of biochar (Harvey et al. 2012; Zhao et al. 2013)

Temperature of pyrolysis	Cellulose	Honey mesquite	Loblolly pine	Cordgrass	Pig manure	Wheat straw
unburnt	37	39	37	37	–	–
200 °**C**	37	38	37	39	46	41
400 °**C**	57	48	51	49	–	–
600 °**C**	61	53	56	52	71	71

The O/C ratio is considered as one of the essential factors of biochar recalcitrance (Harvey et al. 2012; Spokas 2010). Natural weathering leads to an increase in this ratio (Spokas 2013), and thus, biochar becomes more recalcitrant. A comprehensive study by Granatstein et al. (2009) reported biochar resistance time to be hundreds of years. Some types of biochar can be promptly mineralized, while others can remain intact thousands of years. It is difficult to determine biochar stability precisely as this would require long-term monitoring (Lehmann 2007). However, it appears that biochar with a low carbon content is more easily mineralized (Shenbagavalli and Mahimairaja 2012b). Similarly, biochar that contains aliphatic, apart from aromatic, structures of organic carbon are likely to be mineralized with higher speeds. The mineralization is processed from the outer parts; thus, another important aspect of biochar propensity to decomposition is the character of biochar particles (Lehmann 2007).

One of the methods developed to assess the propensity to degradation of biochar is the determination of recalcitrance index (R_{50}). The index relies on the thermal energy needed for the oxidation of biochar compared to graphite. There are three categories: R_{50} above 70, less than 70, and less than 50. The increasing number indicates higher recalcitrance; thus, a smaller portion of the carbon is mineralized within 1 year (Harvey et al. 2012). Examples of R_{50} values for different types of biochar are given in Table 2.

The carbon sequestration (CS) potential of the biochar is another tool to determine biochar recalcitrance. The CS is the amount of the original feedstock carbon that would be retained in biochar for long time periods upon addition to soil. This is calculated by subtracting the carbon lost during pyrolysis from the initial C in raw biomass and multiplying by the recalcitrance (R_{50}) of C in the biochar (Zhao et al. 2013).

To develop the biochar carbon stability, International Biochar Initiative (IBI) proposed a system of biochar classification based on carbon storage value in biochar (www.biochar-international.org). According to this system, the carbon storage value (sBC_{+100}) is referred to C_{org} in biochar and the estimated fraction of C_{org} in the biochar that remains stable in soil for more than 100 years (BC_{+100}). The BC_{+100} is based on the ratio of hydrogen to organic carbon (H/C_{org}) in biochar. The H/C_{org} ratio is an approximate measure of aromatic carbon structures in biochar. The sBC_{+100} can be used when estimating the long-term soil carbon sequestration potential of specific biochar. The sBC_{+100} is divided into 5 classes: 1st (<300 gkg), 2nd (300–400 gkg), 3rd (400–500 gkg), 4th (500–600 gkg), and 5th (>600 gkg). If long-term soil carbon sequestration is a goal, then biochar with a high sBC_{+100} would be desirable.

2.5 Role of Biochar Porosity in Improving Soil Functions and Soil Carbon Stabilization

One of the significant characteristics of biochar is its porosity, and related high surface area (Quilliam et al. 2013). Biochar pores are of different sizes and have different roles when biochar is applied to the soil. Larger pores promote airflow (Ezawa et al. 2002) and water retention capacity while the small ones surpass the transportation and adsorption abilities. The diameter of pores is dependent on the material used for biochar production. Charcoal fines have a pore size of 10 μm, oil palm bunch and sugarcane bagasse have a pore size of 6 μm, whereas activated biochar has a pore size up to few nanometres (Kasozi et al. 2010). Jindo et al. (2014) reported that the surface area from different feedstocks produced at different temperatures ranged between 5.6 and 545 m^2g^{-1}. The different feedstocks of biochar and their appearance are displayed in Fig. 3, e.g. water hyacinth biochar has coarse outer space as the pores are filled with ash (Batista et al. 2018); on the other hand, wood-based biochar is denser when compared to grass feedstock biochar (Brewer et al. 2014).

The porous structure of biochar determines its ability to sorb allelochemicals, such as phenols, which is evident from many studies (e.g. Jin et al. 2015). While larger pores are accessible for plants as a source of water or nutrients, tiny pores are sites for only chemical interactions where water cannot enter due to strong capillary forces (Antal and Grønli 2003; Brewer et al. 2014). The presence of charcoal particles elevated C and N stored in large particulate OM fractions (>20 mm), which presumably increased soil porosity and thus the soil capacity to retain water (Abdelrahman et al. 2018). Special issue in the topic of biochar porosity is the usage of biochar/charred materials as cost-effective and efficient adsorbents for CO_2 capture. Biochar is considered to be the most preferred carbon dioxide adsorbent material owing to its texture, modulative porosity and low cost, thus contributing also this way to the aspect of biochar-mediated carbon stabilization (Singh et al. 2019).

In addition, biochar is capable of providing a habitat for microorganisms, but the possibilities are limited (Jaafar et al. 2014). The most desirable place for fungal microorganisms to settle were tubular pores along biochar tissue remains, suggesting it as a route joining external and internal parts of biochar (Quilliam et al. 2013). Their experiment on woody feedstock biochar provided the evidence. The electron microscopy has shown extended fungal networks along the outer surface of biochar. Outer space of biochar was significantly more often colonized than inner pores.

3 Effect of Biochar Amendment on Soil Carbon Balance

The agriculture may profit from using biochar as a soil amendment, as it shows many positive impacts on soil. One of the essential notes on promising biochar effect is prevention from soil degradation by amending physical and chemical soil characteristics, which results not only in increased crop yield but also in sustainable soil management. Biochar application is considered to be useful agriculture management practise to support soil microbial community (Kolb et al. 2009) as it enriches the soil with available nutrients, such as carbon (Ippolito et al. 2016). Upon the long-term application, biochar interaction with soil enhances soil carbon storage via the sorption of SOM to biochar and physical protection (Zimmerman et al. 2011).

Biochar made under different conditions and from various feedstocks has various properties. Biochar with different properties can be utilized in solving a particular problem in the soil as the biochar properties can be designed according to the needs (Novak et al. 2009). Figure 6 shows the properties of individual types of biochar related to their pyrolysis temperature. The optimal temperature is between 500 and 600 °C, which is a range achieved by natural wildfire creating black carbon (Brady and Weil 2008).

3.1 Beneficial Effect of Biochar Application on Soil Carbon Storage

The addition of biochar changes the chemical and physical characteristics of the soil. These changes comprise alteration in the soil pH, increase in CEC and water retention capacity together with lower bulk density, promotion of the stability of organic matter and of crop yields (Jeffery et al. 2011; Liang et al. 2006; Nguyen et al.

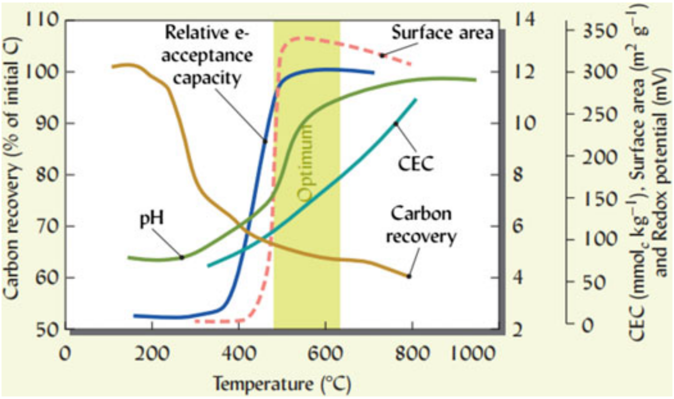

Fig. 6 Biochar properties depending on the temperature of pyrolysis. (Adopted from Brady and Weil 2008; Klüpfel et al. 2014; Lehmann 2007)

2018; Tryon 1948; Van Zwieten et al. 2010). One of the significant benefits of biochar application is that carbon is sequestered back to the soil, it also has fertilizing capabilities because it is a tool for retaining soil organic matter and nutrients (Gaskin et al. 2008). Biochar made of animal manure (so-called nutrient biochar) supports crop productivity and soil fertility. On the other hand, plant-based biochar (so-called structural biochar) improves the structure of soil but sometimes offsets chemical fertilizers (Sadaf et al. 2017). Biochar made of poultry litter seemed to have the best results for crop productivity while biochar based on lignin feedstock showed opposite results of decreased yield (Jeffery et al. 2011). Biochar can be used as an alternative to lime due to its ability to raise pH; however, higher expenditures must be expected (Granatstein et al. 2009). The opposite effect of different types of biochar was also reported for the carbon stabilization properties of biochar, where low temperature-pyrolysed biochar (250–400 °C) from grasses increased C mineralization rates in soils with lower organic C contents (in the early incubation stage – first 90 days). In contrast, soils combined with biochar produced at high temperatures (525–650 °C) showed lowered C mineralization during the later incubation stage (250–500 days) (Zimmerman et al. 2011).

3.1.1 Effect on Water Retention

Amendment of biochar could improve soil hydrological properties independence to biochar and soil conditions. Use of biochar could mean a viable option to improve moisture storage and water use efficiency for soils deficient in organic carbon in arid/semiarid zones (Omondi et al. 2016). An indirect effect of biochar on soil water retention and subsequent grain yield was caused even by promoting mycorrhiza during the period of drought (Solaiman et al. 2010). It seems that low-temperature pyrolysis provides biochar with better water retention because it creates biochar with more sites containing oxygen groups on its surface, determining hydrophobic properties (Alotaibi and Schoenau 2019). The water retention capacity highly depends on biochar feedstock. The study by Novak et al. (2009) assessed different feedstocks and found that switchgrass-made biochar showed the best results with regard to water retention capacity. However, the improvement of water retention depended not only on the character of biochar. Biochar can offset worse water retention only in soils with coarse structure. In fine-particles soil, the improvement was limited as clay particles clog pores (Wang et al. 2019).

Pores in biochar provide ample space retaining water due to capillary action. This can help to reduce soil propensity to drought. Water retention is also affected by the character of pores as biochar with a higher volume of pores can enhance water retention capacity, especially in soil with coarse structure. High doses of biochar led to the best results in improving soil structure such as a higher number of water-stable aggregates mean weight diameter and a lower coefficient of vulnerability (Juriga et al. 2018; Karhu et al. 2011).

Water retention is also affected by zeta potential and CEC. It is related to the content of hydrated ions adsorbed onto biochar. Biochar with a higher amount of substances with polar character shows better water holding capacity (Batista et al. 2018; Fischer and Glaser 2012; Ippolito et al. 2016; Liu et al. 2013). Water flow is improved as biochar application decreases soil bulk density (Abel et al. 2013) and positively affects saturated hydraulic conductivity and water infiltration (Major et al. 2010a), which may even support rooting (Lehmann et al. 2011). Such contributions to soil physical properties suggest that biochar is a suitable amendment to arid areas with a lack of water sources (Ippolito et al. 2016; Liu et al. 2017).

3.1.2 Effect on Soil Erosion

Biochar amendment significantly affects the physical properties of soil, which results in altered soil structure (Singh et al. 2018). The factor affecting the propensity of biochar to erosion is the ability to form macroaggregates, mean weight diameter of soil aggregates, bulk density, and stability of soil aggregates (Juriga et al. 2018). There is evidence that biochar can positively affect soil degradation by the impact on loosing soil particles. Its application significantly reduced the erosion of highly weathered soil while improving soil pH, cation exchange capacity, and microbial biomass carbon (Jien and Wang 2013). Its application decreased bulk density and enlarged soil aggregates, which is crucial for erosion resistance. Efficient improvement of soil was reported at a dose of 5% biochar (Jien and Wang 2013; Soinne et al. 2014). The results are supported by the study (Juriga et al. 2018), which found an increase in water-stable macro-aggregates after biochar amendment. Therefore, the optimal application dose of biochar to protect highly degraded soil in humid climate was set to 5% (Jien and Wang 2013). Biochar amendment to more weathered soils with high native SOM content may lead to more excellent stabilization of incorporated C and result in decreased loss of soil because of erosion and transport, as compared with the soils dominated by clays and low native SOM content (Kelly et al. 2017). However, there is a great risk of wind erosion of biochar particles within the simple surface application as biochar is composed of light particles that can be carried away by the wind. Such a situation can be expected in sandy soils (Verheijen et al. 2010).

3.2 Effect on Crop Yield and Economic Productivity in Agriculture

Agriculture productivity is often indicated as crop yield. It is difficult to predict if biochar addition will affect the productivity of crops as it largely depends on the type of biochar, climate, or soil conditions (Lehmann and Joseph 2009). The rate of yield increase is dependent on the dose of biochar. In the study estimating different agricultural systems (Liu et al. 2013), it was found that agricultural profit is achievable below 30 tha^{-1} of biochar dose with the mean profit between 10 and 11% (Jeffery et al. 2011; Liu et al. 2013). A comprehensive study analysing data on crop productivity (Jeffery et al. 2011) reports the average best dose of biochar to be 100 t ha^{-1}.

Biochar effect is more pronounced in acidic sandy soils than in alkaline clayey soils, which correlates with a higher yield of crops grown on dry land. It is related to the increased liming effect and improved water retention ability of the biochar-amended soils (Liu et al. 2013). Amendment of boreal clay soil with a high rate of biochar seems unviable from the farmer's perspective but could play a role in climate change mitigation, as it will likely serve as long-term C storage (Soinne et al. 2020).

Agriculture focused on non-food purposes often produces bioenergy. This leads to withdrawing of large amounts of biomass, resulting in the degradation and depletion of soils. Returning the organic matter in the form of biochar back to soils presents an effective solution for this issue where half of the carbon can be returned to the soil while improving the soil fertility (Lehmann 2007), which is the main factor of agriculture profitability. The meta-analysis (Biederman and Harpole 2013) investigated many studies assessing different biochar characteristics on the aboveground productivity of the crops. They found the biochar effect was more pronounced in tropical than in temperate zones. Manure- and grass-based biochar showed increased productivity. Many studies have confirmed that the lower temperature of pyrolysis had a more pronounced effect in agricultural use (Alotaibi and Schoenau 2019; Gaskin et al. 2008; Song and Guo 2012).

The study by Jindo et al. (2014) found that feedstock of biochar strongly correlated with crop yield. Wood-derived biochar provided worse results than biochar based on rice feedstock. A positive effect of biochar addition was observed in the case of the growth of rice (Nguyen et al. 2018). This positive effect can be attributed to the increased content of available nutrients (phosphorus and potassium) and CEC. Increased yield after biochar addition was also observed in the cultivation of maize (Major et al. 2010b; Yamato et al. 2006), wheat (Vaccari et al. 2011), soybean (Oka et al. 1993), carrots and beans (Rondon et al. 2004), and sorghum (Steiner et al. 2007). Nevertheless, it needs to be mentioned that most of the experiments using biochar amendments were carried out in the tropic climate. However, there is increasing evidence that the application of biochar can be beneficial for sustainable soil and productivity properties, also in a temperate climate (Cooper et al. 2020).

Studies by (Chan et al. 2007; Jeffery et al. 2011) provide a balanced picture of the impact of biochar use on agricultural yields. The worst results which were reported observed a 28% drop in yield (Jeffery et al. 2011). According to an in-depth evaluation (Brady and Weil 2008), it was estimated that a positive effect on yield reached a 30% increase and negative up to 20% decrease, but there were more results of positive effects with an average increase of 5–10%. Negative results can be explained by an increased content of volatile substances emerging during pyrolyses, such as pyrolytic substances from lignin or cellulose, gasses trapped inside biochar pores or low weight molecules including ketones, phenols, which can either stimulate or inhibit plant or microbial growth (Spokas et al. 2011). The study by Gale et al. (2016) suggests such labile substances negatively affect plants and soil microorganisms and are the reason for no or adverse effect of biochar addition. These unfavourable properties might be alleviated by weathering as the compounds are gradually lost from the soil and their toxicity reduced. Consequently, weathering may eventually lead to an increase in species diversity as some biota may be able to metabolize such substances, thus further mitigating their toxicity.

4 Biochar–Soil Community Interactions and Its Effect on Soil Carbon

4.1 Microorganisms

Biochar instantly interacts with roots, microorganisms, and soil organic matter in the soil. Microorganisms adapted to biochar presence were studied in the Amazonia. In the indigenous black earth, the most abundant phyla were *Actinobacteria, Acidobacteria, Verrucomicrobia,* and *Proteobacteria* (Taketani et al. 2013). However, the consequences and extent of the biochar effect on soil communities are not well understood (Downie et al. 2009; Joseph et al. 2010). For example, it is not clear under what circumstances biochar promote the growth of microorganisms in the soil (Gao et al. 2017; Chen et al. 2013; Ippolito et al. 2016; Lehmann et al. 2011). Yet, it becomes evident that soil enzyme activities, soil structure (Rillig and Mummey 2006), and nutrient cycling of mainly carbon and nitrogen are affected by the application of biochar to the soil (Chen et al. 2013; Steiner et al. 2008). Similarly, the amendment results in a direct impact on plants (Warnock et al. 2007), their growth (Graber et al. 2010; Kolton et al. 2011), or resistance to pathogens (Elad et al. 2010). Furthermore, biochar application may increase the activity of microorganisms and their biomass, crop yield, reduce nitrous oxide release, increase methane uptake by soil, and retain nutrients in the soil (Kolb et al. 2009; Naeem et al. 2014; Quilliam et al. 2013; Van Zwieten et al. 2009; Warnock et al. 2007).

Interestingly, experiments, where glucose was applied into soil amended with biochar, revealed increased microbial abundance but not respiration, which is similar to the microbial behaviour reported in Tera pretta (Steiner et al. 2004). This suggests that microorganisms are capable of reproduction at low-available soil organic matter environments with a sufficiency of nutrients (Fischer and Glaser 2012). Therefore, before the broad application of biochar, the land shall be inspected (Quilliam et al. 2013). It is mainly because the successful promotion of microorganisms depends on the properties of both biochar and soil. Soil analyses could comprise primarily physical and chemical characteristics, and attention should be paid to production methods and feedstock of biochar (Downie et al. 2009). Microbial changes, such as species composition and their activity, might be triggered even by the recalcitrant character of biochar as it largely depends on the number of available substances in the chromosphere. In the long term, the settlement of microorganisms can be enhanced by biochar addition along with gradual microbial and abiotic disintegration of biochar. The process can be accelerated by using powder biochar, which is decomposed and mineralized at a higher rate (Quilliam et al. 2013).

Biochar pores can provide shelter for bacteria. These may then be protected from predators (Ezawa et al. 2002). The pores must be large enough to be inhabited by bacteria or fungi but too small for predators to penetrate inside (Warnock et al. 2007). Not all the pores can be inhabitable by soil microbiota. In the study by Quilliam et al. (2013), the number of unprofitable pores reached 17%. However, these tiny pores provide a space for biochemical reactions. Microorganisms thrive well also in the vicinity of biochar even better when compared to its inner and outer surface (Quilliam et al. 2013).

From physical changes, reduced tensile strength is notable in biochar-amended soil (Chan et al. 2007), which enables better accessibility of nutrients for hyphae (Lehmann et al. 2011). Further, the increased surface area is probably the most significant factor in promoting mycorrhizal fungi (Ezawa et al. 2002) as it is an essential space for biological processes. Fragments of biochar act like soil aggregates as they protect organic matter and retain water and nutrients (Lehmann et al. 2011; Zimmerman et al. 2011). Though the significant effect of biochar on microorganisms is evident from many studies, the exact manner of the effect is still unknown. It is often caused by inconclusive results of field and laboratory experiments (Jones et al. 2011b; Quilliam et al. 2013; Ameloot et al. 2014).

Additionally, soil microorganisms may be affected by organic substances released from fresh biochar, either negatively or positively (Lehmann et al. 2011). Kolb et al. (2009) suggest that carbon is not a limiting factor in biochar amended soils; thus, microorganism biomass increase is dependent on other nutrients such as nitrogen and phosphorus.

Negative results could be related to short-term experiments investigating the application of fresh biochar. Sorption of cations and anions can affect the availability of carbon and other nutrients in fresh biochar. Thus, microorganisms are sometimes forced to use sources of C outside of biochar. Such a situation with a deficiency of nutrients potentially containing toxins can pose biochar as unhostile and poor nutrient habitat for microbes to live at (Quilliam et al. 2013) and/or cause problems related to low oxygen content and impaired conditions for aerobic microorganisms. Such issues might be solved by using powder biochar that seems to be more beneficial compared to large biochar clumps.

A comparison between microbiology of biochar incubated in medium without and with soil resulted in the evidence of greater fungal abundance in biochar incubated in a soil-less medium. Soil particles presented obstructions for fungal hyphae, and thus biochar colonization was more accessible in the absence of soil (Jaafar et al. 2014). Kolb et al. (2009) found different responses to biochar addition with regard to microbial biomass increase, depending on soil fertility, its texture, and nutrient availability. In contrast, other authors (Elzobair et al. 2016) found no impact on the microbial community, soil enzyme activity, or arbuscular mycorrhizal fungi colonization of roots. It has also been observed that biochar amendment can result in negative effects, especially in nutrient-poor sites. The experiment using biochar addition to reduce the number of phenolic compounds revealed that the positive effect was negated by reduced availability of nutrients sorbed on biochar. This resulted in the reduction of microbial biomass and inhibition of spruce seedlings (Glaser et al. 2002; Wallstedt et al. 2002). Another reason might be unfavourable living conditions for fungi, such as altered pH, heavy metals, or increased soil salinity (Killham and Firestone 1984). This illustrates that there is a number of factors that influence biochar–soil–microorganism interactions and add to the complexity of this issue. So far, our understanding of this issue is limited due to the mixed findings published so far and the general lack of knowledge on whether the amendment of biochar promotes or suppresses bacteria (Quilliam et al. 2013).

Ippolito et al. (2016) showed that upon the application of biochar, there was a slight decrease in Gram-positive bacteria and an increase in Gram-negative bacteria. Biochar addition also resulted in an increased rate of nitrification in sites low in nitrification ability, such as boreal forest. However, sites abundant in nitrification ability, such as grassland or agricultural soil, were not enhanced (DeLuca et al. 2015; Meena and Lal 2018; Rondon et al. 2007). This suggests that biochar affects even nitrification bacteria. Biochar seems to increase the rate of biological nitrogen fixation, which may help to reduce nitrogen inputs in agriculture. However, high rates (60 g per kg) of biochar resulted in adverse effects (Rondon et al. 2007), possibly caused by the lower availability of nitrogen in biochar-amended soil, which led to the stimulation of biological nitrogen fixation.

The first experiments carried out in the 1990s showed evidence that the addition of biochar to soil increased abundance in mycorrhizal fungi (Ishii and Kadoya 1994), followed by other studies confirming the same conclusion (e.g. Solaiman et al. 2010). Biochar interaction with mycorrhizal fungi may affect the physical and chemical properties of soils (Ishii and Kadoya 1994; Mori and Marjenah 2000; Solaiman et al. 2010). There is also a possibility of using biochar together with fungi, which could have a positive impact on soil quality (Warnock et al. 2007). Elzobair et al. (2016) studied soil community in arid soil and found that biochar did not negatively affect root colonization while the manure application did. The positive effect of biochar on mycorrhizal fungi is still not clear; it could result from the presence of a significant amount of carbon in biochar or might be induced by the properties and characteristics of the biochar itself (Warnock et al. 2007).

Biochar and mycorrhizal associations contribute to sustainable plant production, ecosystem restoration, and soil carbon sequestration by hyphae access of biochar microsites within biochar, that are too small for most plant roots to enter, and by subsequent translocation of nutrients to plants (Hammer et al. 2014). Thus, fungi can reach distant nutrients from their long hyphae far from roots (Saito and Marumoto 2002; Steiner et al. 2008). AMF can easily extend their extra-radical hyphae into charcoal buried in soil and sporulate in the porous particles (Saito and Marumoto 2002). Those pores may offer a microhabitat to the AMF, which can obtain nutrients through mycelia extended from roots (Nishio 1996). However, the ability to provide refuge for microorganisms does not occur several years after biochar application but requires a significantly longer time to occur (Quilliam et al. 2013).

The changes in the microbiological associations that were studied in a crop field after biochar application consisted of higher bacterial but lower fungal gene occurrence (Chen et al. 2013). It appears that fungi abundance does not increase following biochar addition if the environment contains sufficient amounts of nutrients (Lehmann et al. 2011) because, under such circumstances, the plants do not need to associate with mycorrhizal microorganisms.

4.2 Plants

Plant development and growth may be promoted by the addition of biochar via several mechanisms. Biochar speeds up the germination of seeds by its black colour changing thermo-dynamical characteristics of soil (Genesio et al. 2012) and by reducing in tensile strength of soil enabling easier penetration of first roots (Chan et al. 2007; Lehmann et al. 2011). It enhances water retention capacity and raises wilting point (the minimum amount of water in the soil that the plant requires not to wilt) (Abel et al. 2013; Laird et al. 2010), thus reducing moisture stress. Plant development is also affected by altered nutrition conditions, such as P and K (Biederman and Harpole 2013; Dempster et al. 2012; Nguyen et al. 2018).

Plant–soil–biochar interactions increase the stable C content in the soil. A study performed with ryegrass showed that field-aged biochar increased belowground recovery and stabilization of root-derived carbon. It also facilitated negative rhizosphere priming as a consequence of slowed soil organic carbon mineralization (SOC) in subtropical ferralsol (Weng et al. 2017). Graber et al. (2010) hypothesized that biochar stimulated plant growth in their study by alternation in the microbial community in soil, or by phytopathogenic compounds, which are toxic at high doses but stimulate plant growth at low concentrations. Kolton et al. (2011) found that biochar added to the community of microorganisms associated with plants had a positive effect on its growth and prosperity. Biochar was able to alleviate even unfavourable conditions of drought and salinity and thus supported plant growth, yield and increased photosynthesis (Ali et al. 2017).

There is also evidence that biochar may enhance plant protection against some pathogens, specifically some fungi (Elad et al. 2010; Meller Harel et al. 2012). Pathogen resistance is a consequence of cooperation between bacteria and roots known as induced systemic resistance. A possible way to explain the phenomena is the association between elicitors of microbial origin, which is promoted by added biochar (Kolton et al. 2011). Prendergast-Miller et al. (2013) revealed that roots are attracted to biochar via available nutrients such as nitrogen and phosphorus. Biochar acts either as a nutrient source for roots or influence nutrient availability and, thus, may affect roots in two different ways. It has been found that rhizosphere was more extent in soil amended with biochar indicating root's preference of soil comprising biochar (Prendergast-Miller et al. 2013).

4.3 Soil Fauna

Impact of soil fauna on the soil ecosystem is significant as it is a factor affecting the redistribution of nutrients from surface to subsoil (Domene 2016; Wilkinson et al. 2009). In general, biochar presence in soil is probably beneficial for soil fauna because it has been reported that mesofauna is more diverse and abundant in temperate zones naturally containing ancient charcoal (Uvarov 2000). Lower tensile strength caused by biochar addition (Chan et al. 2007) may enable more effortless mobility of vertebrate through soil (Lehmann et al. 2011). Biochar is ingested and released by soil organisms, though biochar is not considered to provide nutrients. As biochar goes through the digestive tract, it is enriched with microorganisms and enzymes. Those residues then resist on the surface of released biochar particles (Augustenborg et al. 2012; Domene 2016; Paz-Ferreiro et al. 2016).

Several studies have focused on earthworms, which preferred soils amended with biochar (Van Zwieten et al. 2010), and on nematodes, which showed higher abundance in biochar-enriched soils (Matlack 2001). In addition, biochar was able to eliminate increased N_2O release by earthworms by 90% in soils rich in organic matter (Augustenborg et al. 2012). This effect can have a direct positive impact on agricultural profit as a co-application of biochar and earthworms increased productivity of crops in the study by Paz-Ferreiro et al. (2014).

Biochar bioactivation methodologies based on the mechanisms of coating biochar with enzymes represent an emerging and promising approach in biochar applications. The new earthworm-biochar model can be used as a framework to produce a new product "vermichar": vermicompost produced from the blended feedstock, earthworms, and biochar that may improve soil quality, enhance soil carbon storage, and remove soil contaminants (Sanchez-Hernandez et al. 2019).

5 Biochar Role in Metabolic Processes in Soil

The characteristics of biochar are interrelated and affect soil properties and soil biota. Thus, the addition of biochar may alter the nutrient cycling, soil physicochemical properties, species composition and their abundance, underground and above ground

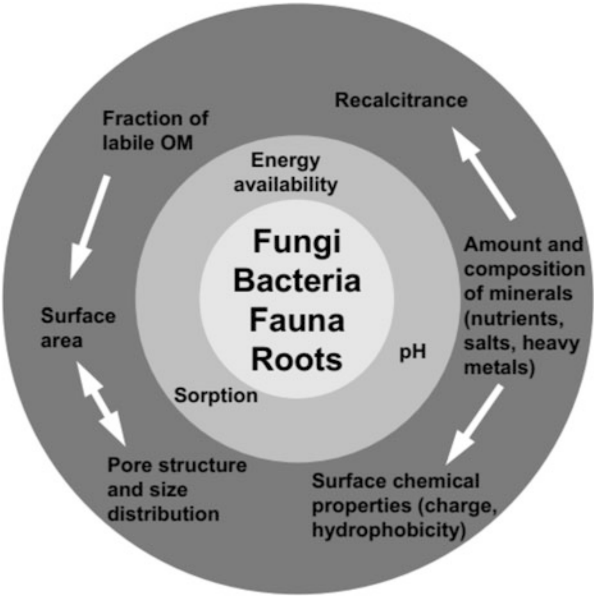

Fig. 7 The overview of biochar effects on soil properties and soil biota. (Adopted from Lehmann et al. 2011)

biomass growth, and the overall health and quality of the soil ecosystem. Figure 7 displays these various attributes of biochar.

The addition of biochar to soil may provide additional benefits related to the increase in the content of stable organic matter. The addition of organic matter into soils rich in black carbon/biochar results in slower mineralization compared to black carbon-poor soils. Moreover, biochar-poor soils were also observed with higher mineralization rates of indigenous C (Liang et al. 2010).

Biochar presents a source of recalcitrant C that remains in soil over hundreds of years (Fischer and Glaser 2012). Thus, the application of biochar to soil contributes to C sequestration in soil and counteracts C emissions released by fossil fuels (Quilliam et al. 2013). The rate of organic mineralization is typically fast except the winter season, while biochar typically shows excellent stability, which is decisive in sustainable soil fertility (Yadav et al. 2018; Meena et al. 2020). Yet, the situation may be different on nutrient-poor sites where a particular fraction of nutrients in biochar is leachable. Under these specific conditions, the mineralization of organic matter can be supported by adding biochar (Wardle et al. 2008).

Furthermore, it has been found that mineralization rates of biochar can be accelerated by agriculture interventions such as sowing, planting, or ploughing with a direct effect on carbon storage (Lehmann et al. 2003b; Ameloot et al. 2014; Solaiman and Anawar 2015). It was observed that the application of biochar to forest soil increased the rate of nitrification due to the presence of phenolic compounds in biochar. In the case of agricultural soils, the addition of biochar inhibited or promoted C mineralization rates (Berglund et al. 2004; Dempster et al. 2012; Jones et al. 2011b; Wardle et al. 2008; Dodor et al. 2018; Zimmerman et al. 2011). Jones et al. (2011b) suggest that the alterations in soil physical properties induced by biochar addition have no significant effect on the rate of soil respiration.

Soil enzymes react variably to the presence of biochar in soil. The results of studies are often inconsistent and unclear with regard to the relationships between biochar and soil enzymes (Bailey et al. 2011). However, it is evident that biochar can alter enzyme activities (Foster et al. 2016; Chen et al. 2013). For example, a decrease in the activities of β-glucosidase and an increase in the activity of alkaline phosphatase and dehydrogenase were observed in biochar-amended soils. Changes in enzymatic activities were further observed by (Foster et al. 2016), where the activities of α-1,4-glucosidase, β-D-cellobiohydrolase, and β-1,4-N-acetylglucosaminidase increased while the activities of β-1,4-glucosidase and phosphatase significantly decreased upon biochar addition to soil. These results point to the shift in behalf of bacteria (Chen et al. 2013), which can be related to increased enzyme activities. On the other hand, decreased enzyme activities can occur especially in the case of biochar with high porosity and specific surface due to the blocking or sorption of enzymes substrates (Bailey et al. 2011; Lammirato et al. 2011).

5.1 Nutrients and Their Availability

Biochar cannot be considered as a primary supply of nutrients. It enriches the soil with several beneficial elements and minerals; thus, its main prospective is to condition soil properties (Glaser et al. 2002; Lehmann et al. 2003a; Shenbagavalli and Mahimairaja 2012b). Nevertheless, biochar amendment results in increased concentration of soil elements, such as P, K, N_{total}, and C (Biederman and Harpole 2013; Nguyen et al. 2018). Content of nutrients is highly dependent upon feedstock (Shenbagavalli and Mahimairaja 2012b). The nutrient and chemical values of biochar made of different feedstock are presented in Table 3. The resulting properties of biochar such as pH and CEC further influence the availability of nutrients in soils to which the biochar was added (Yadav et al. 2018). For example, biochar addition to soil usually results in higher pH, which in turn increases Ca and Mg intake by plants and crop yield (Major et al. 2010a). However, there are reports of widely variable effects of biochar on soil organic carbon and C sequestration among different agricultural soils despite the same biochar dose was used. Following this observation, it was concluded that site-specific soil properties must be carefully considered to maximize long-term soil organic carbon sequestration after biochar application (Bi et al. 2020).

The availability of nitrogen with regard to biochar use in the soil is discussible. While some authors reported low availability of N (bound into the heterocycles) (Gaskin et al. 2008), the others found that N was available for plants especially in

Table 3 Chemical characteristics of biochar prepared from different feedstocks (Shenbagavalli and Mahimairaja 2012b)

Factor	Paddy straw	Maize stover	Coconut shell	Groundnut shell	Coir waste	Prosopis wood
pH (1:5 solid water suspension)	9.68	9.42	9.18	9.30	9.40	7.57
EC (dSm^{-1}) (1: 5 soil water extract)	2.41	4.18	0.73	0.39	3.25	1.3
CEC (cmol kg^{-1})	8.2	6.5	12.5	5.4	3.2	16
Exchangeable acidity (mmol kg^{-1})	22	27	32	14	9.5	49
Total organic carbon (g kg^{-1})	540	830	910	770	760	940
Total nitrogen (g kg^{-1})	10.5	9.2	9.4	11	8.5	1.12
C/N ratio	51.4	90.2	96.8	70	89.4	83.9
Total phosphorus (g kg^{-1})	1.2	2.9	3.2	0.6	1.5	1.06
Total potassium (g kg^{-1})	2.4	6.7	10.4	6.2	5.3	29
Sodium (g kg^{-1})	14	21.5	16.8	5.2	9.6	38
Calcium (g kg^{-1})	4.5	5.6	8.5	3.2	1.8	11
Magnesium (g kg^{-1})	6.2	4.3	5.8	2.1	1.4	0.36

manure–feedstock biochar (Clough et al. 2013; Chan et al. 2008), where the available nitrogen content is related to hydrolysable forms, e.g. amino acids (Wang et al. 2012). Cantrell et al. (2012) assessed different manure-based biochar and found that the most substantial amounts of volatile matter, carbon, and energy were in dairy manure-based biochar while poultry manure-based biochar contained the highest amounts of S, P, and N contents.

Charred material contains a large amount of aromatic C resistant to microbial mineralization. With higher temperatures of pyrolysis, lower mineralization rates of biochar can be expected (Baldock and Smernik 2002). This can potentially result in adverse effects on plant growth, especially in the case of biochar with a high C/N ratio, where N availability can be reduced. The resulting mineralization or immobilization of N is driven by N content in the original soil and by the C/N ratio of the amended soil. The C/N ratio of <20 leads to N mineralization, while higher ratios lead to the immobilization of N (Dodor et al. 2018). Thus, if the biochar amendment high in C/N ratio is applied to soil depleted from nitrogen, immobilization of mineral nitrogen immobilization can be expected.

The higher dose of biochar caused a greater concentration of extractable phosphorus at the simultaneous decrease in extractable nitrogen (Kolb et al. 2009). However, the nitrogen was increased during incubation time, which can be related to the increase in microbial biomass and subsequent mineralization. This finding was verified by other findings by Biederman and Harpole (2013) who analysed an exhaustive number of studies and concluded that soil is enhanced by P and K following the addition of biochar.

The nutrients are released as the charred material is weathered. Nevertheless, Dempster et al. (2012) found out that the addition of either fresh or aged biochar is unlikely to affect the mineralization of small N substances. However, there is an alteration difference in fresh and weathered biochar. It seems that fresh biochar is more abundant in elements and minerals compared to weathered biochar that had lower contents of Ca, Mg, C, and P and increased O/C ratios (Spokas 2013). These factors significantly impact production yields (Warnock et al. 2007) as also observed by Gao et al. (2017) who found a decrease in dissolved organic C and available N contents despite the increase of their total contents. They suggest that nutrients were adsorbed to biochar surface where P bioavailability could be controlled by biochar-induced surface organic matter stabilization or adsorption/desorption of P associated with organo-mineral complexes (Gao and DeLuca 2018). Figure 8 shows the various effects of biochar on nutrients turnover.

5.2 Sorption Ability of Biochar and Carbon Binding

Soil profits from biochar application via biochar ability to sorb/immobilize nutrients and contaminants. Thus, biochar application to soil indirectly impacts the quality of water and of agricultural watersheds (Laird et al. 2009).

The electrical surface charge of biochar causes high cation exchange capacity resulting in strong binding ability of cations (Mg^{2+}, Ca^{2+}, K^+, and NH_4^+) available

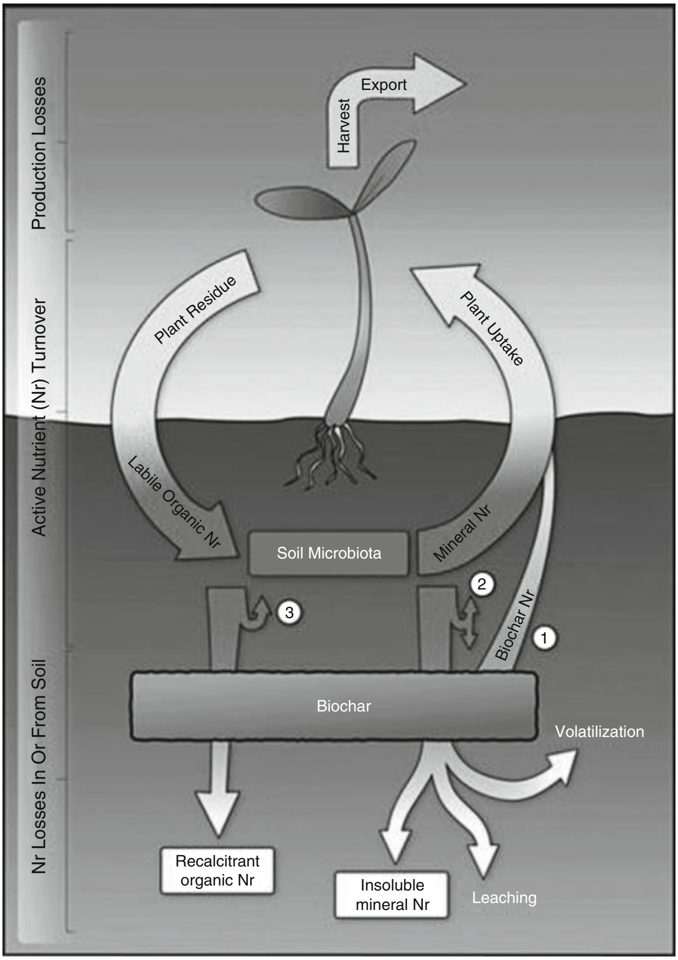

Fig. 8 Effect of biochar on nutrients (Nr) turnover (Adopted from DeLuca et al. 2015)

for plants (Gai et al. 2014; Manyà 2012; Meena et al. 2020a; Yuan et al. 2011) or anion exchange capacity which is less known and is adhesive mainly for negatively charged phosphates (Lawrinenko and Laird 2015; Mukherjee et al. 2011).

Biochar produced from different feedstocks and temperatures of pyrolysis characterizes with different surface area and pore volume, which are important physical properties affecting the sorption capacity of given biochar. Higher surface area and porosity enhance sorption capacity of biochar. In Table 4, there are some examples of surface area and pore volume for different biochar.

Biochar addition starts immediate interaction with organic substances (Jones et al. 2011a; Quilliam et al. 2013; Smernik 2009) through chemical bonds such as hydrogen, cation-anion and covalent bonds (Joseph et al. 2010). Nutrients, e.g. P or N in the form of nitrates are also absorbed to biochar which helps to slow down

Table 4 Surface area and pore volume for different biochar

Type of feedstock	Pyrolysis temperature (°C)	Surface area (m^2g^{-1})	Pore volume (cm^3g^{-1})	References
Broiler litter	350	60	0.000	Uchimiya et al. (2010)
	700	94	0.018	
Orange peel	350	51	0.010	Chen and Chen (2009)
	700	201	0.035	
Soybean Stover	300	5.6	–	Ahmad et al. (2012)
	700	420.3	0.190	
Pine needles	400	112.4	0.044	Chen et al. (2008)
	700	236.4	0.095	
Rapeseed plant	400	16	1.244	Karaosmanoğlu et al. (2000)
	700	19.3	1.254	
Sewage sludge	300	4.5	0.010	Ahmad et al. (2012)
	700	54.8	0.050	

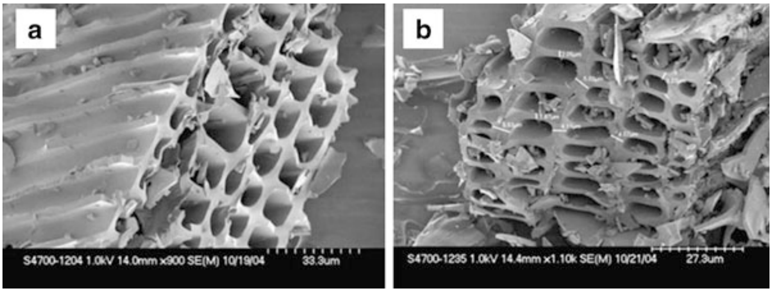

Fig. 9 Biochar with high (**a**) and low (**b**) sorption capacity. (Adopted from DeLuca et al. 2015)

their leaching (Laird et al. 2010; Prendergast-Miller et al. 2013; Granatstein et al. 2009). This is consistent with this study (Gao et al. 2017) which reported an increased content of nutrients, such as total carbon and nitrogen, but a decreased amount of dissolved organic carbon and available nitrogen. The sorption properties of biochar are illustrated in Fig. 9, showing an example of fresh/aged biochar with high/low sorption capacity. The letter “a” refers to fresh immature biochar where pores are still unclogged with particles and are ready to bind substances and particles. The letter “b” indicates pores of old biochar occluded with particles of organic matter bound to its surface (DeLuca et al. 2015). Keech et al. (2005) claimed in his study that sorption highly depends on the number of macropores rather than on their density.

Sorption ability is given mainly by the surface of the biochar. Fresh biochar is hydrophobic with not many polar sites. Processes of oxidation and exposure to water create groups containing oxygen, mainly carboxyl. Biochar surface is abundant in carbon, and therefore, it tends to be hydrophobic and allows sorption of non-polar substances depending on layout and concertation of functional sites (Lawrinenko and Laird 2015). However, its surface is both hydrophobic and hydrophilic, characterized by acidity and basicity (Lehmann and Joseph 2009; Zhu et al. 2018). The study on sorption activity of catechol, a highly hydrophilic contaminant, and humic acid, a less hydrophilic part of organic matter, assessed whether biochar could protect organic matter and be used in soil remediation. It was observed that biochar produced under high temperature showed better sorption activity to catechol into micropores with specific sorption-sites. Humic acid was less sorbed due to its exclusion from micropores (Kasozi et al. 2010).

The sorption ability of biochar is relevant not only form the viewpoint of nutrients but also with regard to a plethora of other (in)organic substances such as pesticides (Yu et al. 2009; Zheng et al. 2010), polycyclic aromatic hydrocarbons (Chen and Yuan 2011), and herbicides (Granatstein et al. 2009). Promising results were also observed regarding the (partial) immobilization of highly mobile and toxic elements such as cadmium and arsenic (Beesley and Marmiroli 2011). Additionally, the immobilization of heavy metals resulted in increased yield and plant biomass in biochar amended soil (Park et al. 2011). Sorption capability of biochar may mitigate pollution of water bodies by preventing leaching of N and P from soil to water. Another indirect effect of nutrient retention is the reduced need for fertilizers (Lehmann 2007; Troy et al. 2014). The addition of biochar to soil resulted in the elimination of stress associated with higher salt concentrations in soil. Excessive concentrations of salts tied to biochar which implies that biochar can be used as a tool for alleviating salt stress in agriculture (Ali et al. 2017; Amini et al. 2015; Solaiman and Anawar 2015).

5.3 Biochar Potential to Affect Soil Carbon Stock

Soil organic carbon is introduced to the soil by organisms enduring therefore a short time to millennia. SOC is a major part of soil organic matter providing nutrients and retaining water availability, fertility, and crop productivity (Lefèvre et al. 2017). Carbon is lost as dissolved organic carbon by leaching or is transformed to CO_2 or CH_4 and released back to the atmosphere (Lefèvre et al. 2017). Global warming is tightly joined with the carbon cycle. Biochar could affect the global carbon cycle by removing excessive carbon originated from the burning of fossil fuels from the atmosphere (Nguyen et al. 2008). Change of natural systems into agriculturally used land leads to a rapid increase in CO_2 emissions and depletes soil from organic carbon, especially by deforestation. This seems to be a critical factor in the global carbon cycle (Zhang et al. 2018). Intensive agriculture, arable land and changes in land use exhale greenhouse gases (GHGs). However, the soil management is able to even increase the stock of carbon, e.g. in the form of thermally stabilized sequestered carbon present in biochar (Ippolito et al. 2016; Sohi et al. 2010). Precious organic matter is lost due to burning or disposing of large amounts of residues, which could have been transformed to biochar (Yadav et al. 2018).

As already mentioned, biochar is anthropogenically obtained by pyrolysis. The process can effectively solve two issues. It offers renewable energy and alternative solution to bio-waste disposal. The thermo-chemical procedure converts waste into valuable product omitting CO_2 emissions (Granatstein et al. 2009). Carbon added in the form of biochar into soil resists there much longer than if initial feedstock material is mixed with soil, thus increases the content of recalcitrant carbonaceous substances (Yadav et al. 2018) and of soil carbon stock in soils (Granatstein et al. 2009). However, crucial for carbon sequestration are the consequences and potential effects of biochar on soil communities that are yet not completely understood (Downie et al. 2009; Joseph et al. 2010). The amount of carbon sequestered in soil depends on C content in biochar. Biochar made from plant-based materials is higher in carbon stock; biochar based on herbaceous or fibrous feedstocks comprises of approx. 65% of C and have a high content of N, and wood-based biochar contains approx. 75% of C with the C/N ratio ranging between 178 and 588. According to Gaskin et al. (2008), poultry-litter biochar contains 40% of C while pine-biochar contains 78% of C. In the study by Foster et al. (2016), biochar dose of 30 t ha^{-1} increased the total carbon in soil by 80%.

Inconsistent results have been reported with regard to the priming effects of biochar that were shown to be positive (Dodor et al. 2018; Jones et al. 2011b; Luo et al. 2011) as well negative (Ippolito et al. 2016; Jones et al. 2011b; Zimmerman et al. 2011). Carbon mineralization was shown to be primarily influenced by the temperature of pyrolysis at which biochar is produced; a higher temperature can be expected to result in negative priming effects after longer incubation times, e.g. 200 days (Fischer and Glaser 2012). The duration of the experiment seems to play a significant role. Short-term experiments can result in higher priming effects compared to long-term studies when the labile organic matter of biochar is depleted. In the experiment by Cross and Sohi (2011), the priming effect increased within 2 weeks of the experiment compared to non-amended soil. The positive priming effect decreased with increasing pyrolysis temperature. It has been found that the initial increase in priming effect is caused by the labile part of organic matter present in biochar and not by the organic matter present in the soil. Thus, carbon addition does not trigger higher mineralization of organic matter in the soil. This also may explain the inconsistencies between studies resulting in either increased or decreased priming effects or mineralization after biochar addition. Short-term CO_2 increase is a consequence of mineralization of an equal amount of organic C originating in the added biochar (Jones et al. 2011b; Luo et al. 2011). Mineralization of C can be enhanced by limited access to nutrients (Cross and Sohi 2011). However, a long-term observation implied a decrease in soil organic matter mineralization and reduced CO_2 release (Jones et al. 2011b; Zimmerman et al. 2011). In another study, the decreased values of SOC mineralization (carbon sequestration) were explained by the accelerated conversion of SOC into dissolved inorganic C and by the sorption of labile organic C (LOC) and microorganisms onto biochar (Luo et al. 2016).

All carbon types in biochar are not stable. There is also mobile carbon, especially in young biochar, coming from oil produced during pyrolysis. Smith et al. (2010)

found out that only about 10% of extractable carbon is mineralized to CO_2 as the substances precipice to larger molecules, they probably become a part of recalcitrant carbon stock in the soil. The initial short-termed increase in CO_2 release may result from microbial mineralization of unstable carbon which could be contained in immature biochar (Jones et al. 2011b; Smith et al. 2010; Zimmerman 2010). Cross and Sohi (2011) investigated whether biochar addition initializes mineralization of C already present in the soil. The results confirmed that all the evolved CO_2 originated from the labile fraction in the added biochar.

The global C cycle is related to black carbon as it slows down its turnover by carbon sequestration (Major et al. 2010a). Woolf et al. (2010) estimated that the biochar could eliminate 12% of CO_2 originating from anthropogenic sources. On average, one metric ton of biochar added to the soil can offset 2.93 metric tons of CO_2 (Granatstein et al. 2009). The study by Laird (2008) assumes that the USA can produce an enormous amount of biomass. Implementation of such biomass into biochar could save 25% fuel oil enabling permanent sequestration and save 10% of CO_2 emissions. The study about smokeless biomass pyrolysis consider the creation of biochar carbon energy storage reserves: it was estimated that about 428 Gt of carbon could be worldwide annually stored as a biochar carbon into agricultural soils (1411 million hectares) (Lee et al. 2010).

Carbon dioxide is captivated by photosynthesis in the form of organic biomass which is then used to create biochar (Renner 2007). The biochar created by pyrolysis blocks the fast decomposition of biomass feedstock. The outcome of the high-temperature process serves as energy bypassing GHGs emissions and provides a soil amendment to return carbon (Woolf et al. 2010). The complex process of carbon cycling is shown in Fig. 10. Types of biochar produced at conditions of zero-oxygen are less studied. Their energy and carbon turnover demand more investigation for agronomic compensation (Sohi et al. 2010). The zero-oxygen pyrolysis is advantageous even for better sorption of volatile compounds released during biochar production (Spokas et al. 2011). However, Woolf et al. (2010) suggested not to clear forests or rainforest to get feedstock for biochar production because the carbon pay-back would take many years, and this land-use would be highly ineffective. They suggested abandoned and degraded land to be prospective for energy and biochar production intentions.

One of the non-carbon GHGs is a nitrous oxide that is even more potent GHG than $CO_{2,}$ and its main release can be attributed to the use of nitrogen fertilizers (Renner 2007). It has been found that fluxes of N_2O and CH_4 may be reduced due to biochar application to soil (Van Zwieten et al. 2010; Augustenborg et al. 2012; Rondon et al. 2006). The mechanisms behind this action are not clear, but most probably, a mix of various biotic and abiotic factors come into play here, along with other factors such as climate, soil type, land use and properties of the biochar applied (Van Zwieten et al. 2009). The ability to retain N_2O is likely affected by the type of biochar. While biochar made from poultry litter or high-temperature grass feedstock showed no emissions of N_2O, low-temperature waste grass biochar releases 100% emissions compared to control (Rondon et al. 2006).

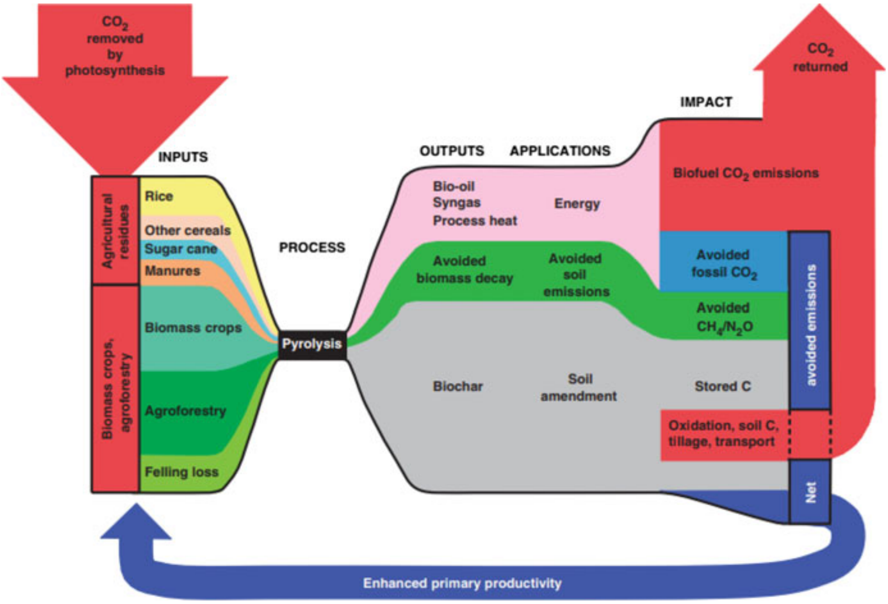

Fig. 10 Sustainable carbon cycling using biochar. (Adopted from Woolf et al. 2010)

6 Interaction of Biochar with Other Amendments and Impact on Soil Carbon

The beneficial properties of biochar can be enhanced by the synergic effect using co-application of biochar together with other soil amendments. Biochar may increase the efficiency of mineral fertilizers by promoting nutrient retention and eliminating their environmental threats. Thus, it may address many problems of nowadays agriculture and environment (Naeem et al. 2014). It may even contribute to economic savings because of the reduced amount of fertilizers applied to land (Lehmann 2007; Troy et al. 2014). Despite the fact that the biochar can increase nutrients in the soil, it is still deficient in nutrients, and possible effectivity of its combination with other soil amendments is obvious. Accumulation and retention of nitrogen in the rhizosphere were improved by the combined effect of biochar and mineral fertilizer (KNO_3, $(NH_4)_2SO_4$, and urea) resulting in higher microbial abundance and pH in soil (Yu et al. 2018). Used co-application of NPK and biochar have increased the nutrients and yield of wheat. It resulted in higher N content, microbial carbon, and microbial nitrogen which are the main driving factors having a positive impact on soil microbial community and activity of soil enzymes (Song et al. 2018). Experiments with combined application of biochar and mineral fertilizers confirmed that this is a promising strategy for increased yield without unnecessary loss in nitrogen by leaching. Biochar combined with nitrogen caused alteration in soil organic matter and soil structure that affected in soil improvement. The co-application increased the content of organic carbon. On the other hand, a particular combination of biochar and nitrogen caused a drop in humic and fulvic acids (Juriga et al. 2018). It also significantly increased yield as the biochar promoted mineral nitrogen fertilizer efficiency (Chan et al. 2007). The enhancing effect of combined biochar and mineral fertilizer application may lie in the ability of biochar to retain some nitrous compounds (Granatstein et al. 2009), to prevent nitrogen leaching and to protect nutrients in the soil. It has been found that biochar addition improved N uptake and biomass production. The experiment was carried out using wheat in fertilized ferrosol (Van Zwieten et al. 2010). On the other hand, biochar did not show any improvement without added fertilizers (Van Zwieten et al. 2010). Solaiman et al. (2010) applied biochar to soil together with mycorrhizal fungi and mineral fertilizer. The yield was significantly increased in sandy soil. There was even noted improved resistance to drought.

Application of pig manure caused an increase in the leaching of nutrients, such as nitrates and organic carbon. The amendment of manure-fertilized soil by wood-feedstock biochar reduced the leaching as biochar retained nutrients (Troy et al. 2014). Brtnicky et al. (2019) observed the decrease of soil microbial carbon and dehydrogenase activity 3 years after the incorporation of biochar (from agricultural waste) into the soil. On the other hand, the highest values were reached after the co-application of biochar with cattle manure in their study. Dodor et al. (2018) have studied the effect of the simultaneous application of biochar and cattle manure on carbon mineralization in sandy soil. Pure biochar and manure application caused an increase in positive priming effect by 45–125%. However, their combined amendment has decreased C decomposition caused due to labile C adsorption and net N immobilization. The priming effect was negative by 35%. A completely different situation was observed by Ippolito et al. (2016). They found a positive priming effect by the co-application of manure with biochar and negative priming effect increasing with the application of biochar only. These contradictory findings could have arisen from the different nature of the biochar used (hardwood biochar with a very high C/N ratio versus rice-husk biochar). Elzobair et al. (2016) observed short-term effects when the manure–biochar mixture was applied to arid soils. While the application of biochar alone did not affect microorganism, the sole application of manure caused an increase in some microbial characteristics and a decrease in AMF colonization.

Nevertheless, some studies show no improvement upon the co-application of manure and biochar. For instance, in the study by Nguyen et al. (2018) cow manure was co-applied with biochar, which resulted in an initial decrease of nitrates and their subsequent increase after the manure was mineralized (Ippolito et al. 2016). The co-application of compost-biochar mixtures is another type of relevant mixed amendments. The components in the mixed amendments interact with each other and have similar effects on soil properties. These synergetic interactions enhance the efficiency of the improvement of soil properties (Wu et al. 2017). Liu and Zhang (2012) reported that the synergism provides positive impacts on soil organic matter, nutrients, and water retention capacity. In the study by Wei et al. (2014), the combination arising from composting the tomato stalk and chicken manure was

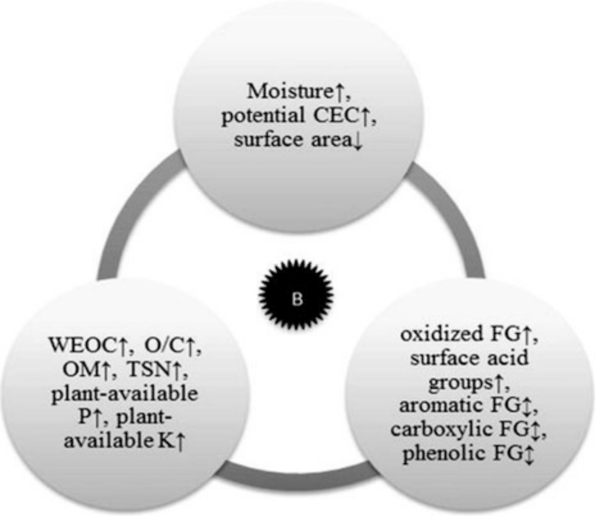

Fig. 11 The effects of biochar on composting. (Adopted from Wu et al. 2017)
CEC Cation exchange capacity, *WOEC* water-extractable organic carbon, *O/C* oxygen/carbon ratio, *OM* organic matter, *TSN* total soluble nitrogen, *FG* functional group, ↑ increase, ↓ decrease, ⍰ sometimes increase and sometimes decrease

reported to be most effective. Changes in the microbial diversity and an increase in the C/N ratio together with volatile fatty acids were observed (Wei et al. 2014). Doan et al. (2015) found a positive effect of co-amendment of biochar with vermicompost, which resulted in higher N retention and protection from erosion and nitrogen leaching. In addition to the benefits above, the co-application of compost and biochar was shown to reduce the bioavailability of toxins (Zeng et al. 2015). Wu et al. (2017) summarized the main positive effects arising from of co-application of biochar and compost which were: changes in physicochemical soil properties, reduction of greenhouse emissions, promotion of plant growth, and alteration of microbial activities (Fig. 11).

Because humic substances are important for carbon sequestration in soil, Jindo et al. (2016) have found that the addition of biochar to composted manure improved the formation and the composition of humic substances. Biochar addition reinforced the stability of the fractions of humic substances in compost. The fulvic acids were enriched in carboxylic and aromatic groups, while humic acids characterized by more condensed molecular structure. This could increase the stability of humic substances when compost blended with biochar is applied as soil organic amendment. Wang et al. (2014) have observed more intensive humification in pig manure compost amended with biochar. With the ^{13}C-NMR spectroscopy higher O-alkyl C/alkyl C ratio and higher aromaticity for humic acids have been revealed.

7 Future Perspective

The future perspective can be seen in designing enriched biochar to improve soil physical and chemical as well as biological properties. The procedure imitating weathering process coats biochar with other substances which could have a significant positive effect on the soil ecosystem. Co-application of available fertilizers (mineral or organic) with biochar or enriched biochar can be persuaded as a solution to offset biochar and fertilizer deficiencies. The fertilizer supplies accessible nutrients available to plants and biochar can sequester depleted elements and prevent leaching of the added ones. This leads to increased crop yields and, simultaneously, alleviation of water pollution by excessive amounts of nutrients.

8 Conclusion

The literature suggests that biochar presents a promising solution for the high energy demands and carbon sequestration efforts, in addition to its positive effects on the functions of the soil ecosystem (Biederman and Harpole 2013). Unlike to organic residues that are mineralized in usually less than 30 years (Liu et al. 2013; Lehmann et al. 2006), biochar withstands microbial decomposition and weathering processes and thus contributes to the soil carbon stock in a long-term perspective, prevent soil degradation, and supports the idea of sustainable agriculture.

However, when the results of individual studies are compared, contradictory findings can be found. This can be explained by the plethora of properties of biochar arising from the initial feedstock and production conditions as well as from the highly diverse and complex systems of soils that are further affected by climate, moisture conditions, and soil biota. Nevertheless, biochar application to soil is associated with many benefits that are likely to outweigh the potential risks, especially if our understanding of biochar effects in soils further improves. In this respect, the co-application of biochar with fertilizers and the use of enriched biochar offers promising ways for increasing the positive effects of biochar for soils and carbon stabilization.

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