Environ Monit Assess (2019) 191: 251
https://doi.org/10.1007/s10661-019-7400-9

Role of biochar and plant growth promoting rhizobacteria to enhance soil carbon sequestration—a review

Rubab Sarfraz · Azhar Hussain · Asma Sabir · Ibtissem Ben Fekih · Allah Ditta · Shihe Xing

Received: 22 October 2018 / Accepted: 17 March 2019 / Published online: 27 March 2019

Abstract Global climate is undergoing significant changes due to extensive release of greenhouse gases (GHGs) such as CO_2 and methane in the atmosphere. These gases are produced and released as a result of anthropogenic activities and fossil fuel burnings which also result in depletion of soil carbon resources. Biochar has various distinctive properties, which contribute to make it an effective, economical, and eco-friendly approach for soil carbon sequestration. The versatility in physicochemical properties of biochar provides an opportunity to optimize its efficacy to obtain desired benefits. A critical review of the literature indicates that biochar and plant growth–promoting microbes have the potential to improve soil organic carbon (SOC). Recent studies have depicted a significant role of the combined application of plant growth–promoting microbes and biochar on SOC dynamics. In future, these areas need to be explored as these have the potential to improve SOC dynamics and it could be a better strategy to sustain natural resources and ultimately mitigation of the climate change.

R. Sarfraz (✉) · S. Xing
Fujian Provincial Key Laboratory of Soil Environmental Health and Regulation, College of Resources and Environment, Fujian Agriculture and Forestry University, Fuzhou, China
e-mail: rubabsarfraz@hotmail.com

A. Hussain
Department of Soil Science, University College of Agriculture and Environmental Sciences, The Islamia University of Bahawalpur, Bahawalpur, Pakistan

A. Sabir
Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

I. Ben Fekih
Institute of Environmental Microbiology, College of Resources and Environment, Fujian Agriculture and Forestry University, Fuzhou, China

A. Ditta
Department of Environmental Sciences, Shaheed Benazir Bhutto University, Sheringal, Dir (U), Sheringal, Khyber Pakhtunkhwa 18000, Pakistan

A. Ditta
School of Biological Sciences, The University of Western Australia, 35 Stirling Highway, Perth, WA 6009, Australia

Keywords CO_2 emission · SOC · Climate change · Carbon stock · Greenhouse gases

Abbreviations

C	Carbon
N	Nitrogen
SOC	Soil organic carbon
PGPR	Plant growth–promoting rhizobium
$CaCO_3$	Calcium carbonate
$MgCO_3$	Magnesium carbonates
eCO_2	Elevated CO_2
SOM	Soil organic matter
AMF	Arbuscular mycorrhizal fungi

Introduction

Climate change is a serious global issue and is a topic of interest for the worldwide scientific community. The main driving force for climate change is the rise in temperature due to various human activities. Earth's average surface temperature has increased about 0.9 °C since the late nineteenth century and this rise is greatly driven by increased CO_2 through anthropogenic activities (https://climate.nasa.gov/evidence/). For example, a rapid increase in CO_2 concentration from 277 to 400 ppm in the atmosphere has been observed since the initiation of the Industrial Era in the 1750s (Xu et al. 2016). Before the advent of Industrial Revolution, the emission of CO_2 was primarily caused by progressive land use changes and deforestation (Lou et al. 2015). Around 1920, fossil fuel burnings became the top most emission source to add CO_2 into the atmosphere (Archer et al. 2009) creating a perturbation in natural C cycle which subsequently resulted into drastic changes in C storage in the land and ocean reservoirs giving rise to the need of carbon sequestration.

Carbon sequestration is associated to C accumulation in a stable solid form. Black C typically known as "biochar" is derived from plant biomass, woody materials, and straw residues obtained under high temperature and pressure in the absence of oxygen, i.e., via the process of pyrolysis (Dungait et al. 2012). Pyrolyzing feedstock results in the accumulation of 50% of C in its original biomass (Conz et al. 2017; Laird 2008) which is highly recalcitrant and persists in the soil for relatively longer periods. Moreover, it is highly stable against microbial attack in soil and takes millions of decades to degrade, thereby gradually slowing down the process of SOC release into the atmosphere (Lehmann et al. 2006). In Terra Preta soil, where black C was buried for thousands of years, the total C stock is reckoned to be around 250 Mg C ha^{-1} compared with general assessments of 100 Mg ha^{-1} in Amazonian soil from a similar origin (Glaser et al. 2002). Application of biochar in soil improves microbial activity (Glaser et al. 2002; Lehmann and Joseph 2009) and soil structure which is necessary to keep intact the C stock balance in soil. Another novel approach in this scenario is the application of plant growth–promoting rhizobacteria (PGPR). The PGPR reside in the soil around or in the vicinity of roots and root hairs, i.e., rhizosphere, feeding on root exudates. These PGPR devour C exuded from plant roots and pursue on it to release more in a way, which directly or indirectly affects the plant growth and root development via secretion of regulatory substances or enzymes in the rhizosphere (Figueiredo et al. 2011). The PGPR in the soil act as the biochemists which can influence soil pH, contribute to plant biomass, increase enzyme activity, and improve mineralization (C, N) process.

A lot of efforts have been put to find out the strategies and methods to sequester C which usually emphasize on adopting proper land use management practices. The role of biochar to rectify soil organic contents has also been studied but there is a research gap on the use of biochar and PGPR which can be a novel approach to mitigate climate challenges and reduce global warming. In this review, we have comprehensively described the factors affecting SOC stocks, use of biochar as an environmental savior, behavior of microbes in soil to influence C contents, and their interaction with biochar which can be adopted as a strategy in the future to replenish C resources, ultimately resulting into a sustainable environment.

Carbon sequestration

Carbon sequestration is a process which involves long-term capturing and binding of atmospheric CO_2 into the soil through crop debris and other organic solids to enhance the concentration of C in soil (Izaurralde et al. 2001). Generally, it refers to direct or indirect storage of atmospheric CO_2 into a more stable form. Indirect sequestration occurs through chemical processes that convert CO_2 into inorganic compounds such as calcium carbonate ($CaCO_3$) or magnesium carbonates ($MgCO_3$) while direct C sequestration involves fixation of CO_2 into plant biomass through photosynthesis (SSSA 2001). All living entities contain C and depending upon their absorbing and desorbing capacity, they are referred as C sources or sinks. Natural sources of C include volcanoes, organic matter decomposition, respiration and digestion activities, and water bodies while C sinks include forest, photosynthesis, Earth's crust, soil, as well as ocean and fresh water bodies. To keep up the C balance in the atmosphere, the release of C from sources and sinks must be in proportions (Han et al. 2017; Tarin et al. 2018).

Carbon sequestration is controlled by several factors, e.g., production and decomposition rate of soil organic matter (SOM), parent material (PM), landscape position, temperature and precipitation, living biota, and other management operations (Jenny 1980). Among all these factors, SOM contributes significantly to alter C stocks of soil thereby influencing C sequestration in soil. In soil, a number of factors release and transport SOM thereby affecting soil physicochemical and biological characteristics and ultimately reducing C sequestration potential of soil (Krull et al. 2004). Erosion plays an inevitable role in deciding the fate of SOM while mineralization is thought to be irreversible in a landscape (Matson et al. 1997).

Carbon sequestration is important in a way that it reduces greenhouse effect and restores the soil activities. It improves ecological approaches as well as ensures sustainable developments by reducing pollution and mitigating global warming (Lal 2004). Water also influences C storage capacity of the soil as wet soils are likely to lose more C than dry soils hence changing C fluxes in the atmosphere (Sofi et al. 2016). Studies report that approaches are still needed to manage C sequestration in dry land areas. Soil erosion in dry land areas is leading to 0.21–0.26 Pg C year^{-1} emission of C with additional 0.02–0.03 Pg C year^{-1} due to exposed carbonaceous compounds to climatic afflictions by surface soil erosion. The process of soil erosion has expedited SOC depletion and it is demonstrated that the total annual C emission in a dryland ecosystem would be 0.23–0.29 Pg C year^{-1} (Lal et al. 2007).

Plant's net primary productivity (NPP) plays a dominating role in global C cycle. The NPP refers to capturing and storing of solar energy through photosynthesis as well as releasing of oxygen and energy, which living organisms need to breathe. The NPP also affects the global C cycle positively by absorbing CO_2 released during burning of coal, oil, and other fossil fuels. In semi-arid regions, both NPP and degrading rate of plant residues fasten with water accessibility (Shahzad et al. 2019). The SOC consumption also deteriorates when yield supper passes input which may reach up to 20–80 tons C ha^{-1} into the atmosphere. Excessive consumption of SOC pools deteriorates soil quality, decreases biomass productivity, and adversely affects C sequestration potential. Therefore, strategies should be adopted to mitigate projected global climate changes and preserve C stocks in soil.

Biochar: state-of-the-art technology for soil carbon sequestration

Biochar is produced sustainably as a co-product of the bioenergy being made from the biomass. Biochar has substantial environmental implications due to its versatile heterogeneous nature such as buffering capacity, high adsorption potential, specific surface area, and cation exchange capacity (Jones 2008; Sarfraz et al. 2017). Physicochemical characters of the biochar play an integral role to define the extent and direction of reactions inferred by biochar application. Moreover, kinds of feedstock and pyrolysis conditions used during biochar production are two parameters which greatly influence the physicochemical and structural properties of biochar such as surface area, pH, functional groups, and polarity thus defining overall surface properties of the biochar (Ahmed et al. 2014; Ronsse et al. 2013). These alterations in biochar characteristics have significant impacts on its suitability and efficiency in remediating soil fertility, nutritional status, and environmental applications. Upon application to soil, biochar improves physical, chemical, and biological properties of the soils (Tayyab et al. 2018). Biochar acts as a soil conditioner that can increase soil water holding capacity (Gaskin et al. 2007) and nutrient level in soil (Yuan et al. 2016) consequently increasing seed germination, plant growth, and crop yield (Xu et al. 2012). These biochar characters eventually lead to increasing soil carbon sequestration (Stewart et al. 2013) and decreasing greenhouse gases (GHGs) emission (Windeatt et al. 2014), and therefore contributing to an overall beneficial effect on soil health and properties (Zhang et al. 2017).

Biochar tailoring for soil C sequestration

Carbon contents (%) of biochar can be used as predictors of biochar persistence in soil. High C contents reported for biochar derived from elevated temperatures are key indicators of the aromatic characteristics, stability against decaying in soils, and subsequently greater C retention time in biochar-amended soils (Kuzyakov et al. 2014; Dominghetti et al. 2015). Pyrolysis temperature and feedstock types are crucial determinants of char properties (Sun et al. 2017; Sarfraz et al. 2019). Biochar obtained at higher pyrolysis temperature (such as more than 500 °C) has more ability to remove organic contaminants (Cheng et al. 2008) whereas biochars obtained at lower pyrolysis temperature (250–400 °C) are more suitable for removing inorganic contaminants from the environment (Verheijen et al. 2010). Biochar produced at lower temperature usually contains less amount of C, hence has more capacity to be degraded by soil microorganisms favoring priming effect in soil (Lin et al. 2012). Generally, biochar produced from switch grass and corn stover has low aromatic C contents than that from woody materials (Brewer et al. 2012). Similarly, biochars produced from animal manure and municipal wastes also contain less C contents than woody plants. Table 1 clearly predicts the effect of various temperatures and feedstock on the fate of C contents in biochar. Bruun et al. (2017) highlighted that application of biochar with possible high residence times may come out as an important approach to increase C sequestration in soils thus reducing greenhouse gas emissions. The release of greenhouse gases through various anthropogenic activities such as burning of fossil fuels, deforestation, and soil degradation contributes to major climate changes (Smith 2016). Mitigation strategies are adopted to sequester excess CO_2 from the environment. Biochar being recalcitrant in nature is often debated as a useful strategy to reduce GHG release. Biochar application involves drawing of C from the atmosphere, providing C sink to terrestrial environment while improving soil and water quality (Lehmann 2009). Production of biochar and its field application has been proposed as a strategy to cope climate change issues (Table 2).

Since ages, CO_2 emitted during decomposition of organic matter and fossil fuel burning was captured by plants through the process of photosynthesis (Lehmann and Joseph 2015). During the pyrolysis of these plant residues, C contents in biomass are converted into stable forms which are bound to the resulting material (biochar) and persist in soil for centuries (Liu et al. 2015). It has been assessed that accumulating C in biochar could prevent the release of CO_2, thereby adding less CO_2 to the environment and keeping C balance in soil and environment (Liu et al. 2015).

Plant growth–promoting bacteria

Plant growth–promoting bacteria reside in the soil around or in the root surface which directly or indirectly affects the plant growth and root development via secretion of regulatory substances or enzymes in the vicinity of rhizosphere (Vejan et al. 2016). The PGPR are responsible in stimulating plant growth, nutrient mobilization, and plant protection from pathogens in soil, sequestering heavy metals and degrading toxic elements present in soil. These PGPR positively affect the plant growth and they are adapted to replicate, survive, and complete their life cycle during plant growth–promoting activities (García-Fraile et al. 2015).

Soil is an integral abode of various PGPR species. These PGPR are classified into various groups based on their functional activities. They act as biofertilizers which colonize the rhizosphere and increase the nutrient supply to host plants hence promoting plant growth (Vessey 2003). As phytostimulators, bacteria stimulate the biological compounds, cells, or tissues by using light to activate the growth of certain organs and sometimes the whole plant using sunlight. The PGPR as biopesticides control disease in plants by producing antibiotics and antifungal metabolites as well as degrading toxic pollutants (Leonardo et al. 2006; Francis et al. 2010). Hence, the use of PGPR is considered to be a multifunctional approach for improving plant growth either directly or indirectly facilitating resource acquisition (C, N, P, and essential minerals) or modulating plant hormone levels as well as acting as inhibitory agents to overcome pathogens in the form of biological entities.

Role of PGPR to assist soil carbon sequestration

The PGPR have the potential to optimize soil microbial functioning thus contributing positively to global climate changes. They retain the highest proportion in the whole microbial community which can play an important role in carbon sequestration. The mechanism of PGPR to mitigate climate changes and sequester C involves several ways. The PGPR play an important role on nutrient cycles like C and N (Velivelli 2011). They enhance glomalin production in rhizosphere by increasing mycorrhizal colonization. Glomalin are important reservoirs of C and N in soil. The PGPR have potential to increase plant growth directly and allocate more C in plant biomass which is ultimately a prominent option for C recycling. They have also been observed to affect soil quality which regulates the proportion of C in micro and macro aggregates (Walley et al. 2014). Elevated temperature and carbon dioxide levels directly or indirectly influence soil microbial activities. During high-temperature regimes, microbial activities are enhanced which further provide positive feedback for climate change and vice versa in case of low moisture conditions (Sofi et al. 2016). The aggregation of ecosystem C is maintained by the balanced proportion between plant productivity and heterotrophic respiration through soil organic matter decomposition (Schlesinger and Andrews 2000). Several studies have documented the positive effect of elevated CO_2 (eCO_2) on plant growth and photosynthetic C input to soils. These elevated C inputs can act to promote microbial growth, consequently increasing soil microbial communities under eCO_2 which may accelerate SOM decomposition and potentially result

Table 1 C contents of biochar using various feedstock and pyrolysis temperature

Feedstock	Feedstock C %	Temperature °C	Biochar C %	Reference
Cattle manure and silage digestate	44	250	52.2	Pituello et al. 2015
		350	60.7	
		450	63.2	
		550	65.9	
Municipal organic waste digestate	31	250	33.7	
		350	34.8	
		450	29.4	
		550	26.2	
Poultry litter	40	250	43.7	
		350	51.2	
		450	51.2	
		550	51.1	
Pruning residues	45	250	48.7	
		350	65.9	
		450	69.3	
		550	75.1	
Sewage sludge	27	250	28.3	
		350	27.5	
		450	22,5	
		550	20.1	
Giant reed herb	43.16	200	48.53	Wang et al. 2013
		300	62.17	
		350	66.32	
		400	72.28	
		500	74.64	
		600	77.10	
Wood	–	550	54.9	Lusiba et al. 2017
Sugarcane straw	42.4	350	60.1	Conz et al. 2017
		450	65.6	
		550	67.6	
		650	69.4	
Rice husk	36.1	350	32.8	
		450	48.6	
		550	49.1 b	
		650	49.5	
Poultry litter	30.4	350	38.1	
		450	29.8	
		550	35.3	
		650	32.6	
Saw dust	45.6	350	71.6	
		450	72.4	
		550	79.8	
		650	84.6	
Chicken manure	–	350	31.2	Domingues et al. 2017
		450	27.2	

Table 1 (continued)

Feedstock	Feedstock C %	Temperature °C	Biochar C %	Reference
		750	24.7	
Eucalyptus sawdust		350	70.4	
		450	78.6	
		750	90.9	
Coffee husk		350	60.5	
		450	61.3	
		750	66	
Sugarcane bagasse		350	74.7	
		450	81.6	
		750	90.5	
Pine bar		350	67.6	
		450	75.2	
		750	86.3	
Wheat-straw biochar	–	400	57.8	Gai et al. 2014
		500	70.3	
		600	73.4	
		700	73.9	
Corn-straw biochar		400	56.1	
		500	58	
		600	58.6	
		700	59.4	
Peanut-shell biochar		400	58.4	
		500	64.5	
		600	71.9	
		700	74.4	
Rice straw	–	100	39.19	Mei et al. 2017
		200	40.02	
		300	49.68	
		400	61.24	
		500	69.78	
		600	77.24	
		700	86.99	
		800	88.12	
Rica bran	–	100	42.39	
		200	46.53	
		300	50.68	
		400	64.05	
		500	71.72	
		600	77.58	
		700	82.03	
		800	83.14	

in net C losses in soil. Elevated CO_2 promotes rhizosphere priming effects which enhances SOM decomposition related with microbial activity (Nie et al. 2015).

Table 2 Potential of biochar for carbon sequestration

Source of biochar/other feedstock	Crop(s)/experimental condition	Response/results	References
Wheat straw biochar	Rice/field experiment	Reduced C intensity of rice production from - 36.9 to − 18.6% by decreasing methane and CO_2 from paddy soil	Zhang et al. 2012
Mangrove (*Rhizophora apiculata*)	Sweet sorghum/field experiment	An increase in 26.55 Mg C ha^{-1} in soil organic carbon (SOC) stocks was observed	Suekhum et al. 2012
Woodchips	Leaf beat/pot experiment	Reduced the cumulative CO_2 emissions from 46 to 52%	Lai et al. 2013
Rye grass (*Dactylis glomerata*)/plant litter	Forest and grass land	Biochar has less mineralization and priming effects in subsoil as compared to uncharred plant residues which shows that substrate mineralization and priming effects induced on subsoil organic matter are dependent on the composition of the added substrate, as well as soil characteristics	Naisse et al. 2014
Soil charcoal	Anthroposols	Charcoal additions between 650 and 1609 years, resulted in long-lived, significantly elevated soil carbon (SC) stocks as compared to the adjacent soils	Downie et al. 2011
Eucalyptus saligna tree biochar/*Tithonia diversifolia* green manure	Humic Nitosols/field experiment	Manure additions increased CO_2 C loss by 22% while biochar addition reduced soil CO_2 carbon loss by 27% and increased intra-aggregate C per respired C by 6.8 times relative to the green manure.	Kimetu and Lehmann 2010
Biochar/miscellaneous	Upland cropping system, rice paddy, and grassland	Biochar amendment greatly enhanced SOC contents up to 40%	Liu et al. 2016
Guazuma ulmifolia and *Crescentia alata* tree maize (*Zea mays* L.) silage	Silvopastoral system of Central America poplar, willow/field experiment	The presence of trees enhanced carbon (C) contents of subsoil The decomposition rate of original SOM was decreased at both cropping sites after biochar addition, suggesting a positive influence of biochar on SOM	Hoosbeek et al. 2018 Ventura et al. 2015

Enzymatic activity of PGPR can decompose SOM in soil. Moisture plays an important role in microbial-assisted climate change activities. Under drought and water stress in various soils, microbial activity will be increased because of lower water level and oxygen introduction into previously anaerobic soils (Zibilske and Bradford 2007). Peat lands and wetlands are among the greatest reservoirs of terrestrial C (Ward et al. 2007) being rich in C stocks, hence such an increased degradation of recalcitrant and stable organic matter under dry conditions could have major implications for the global C cycle (Freeman et al. 2004).

Mechanism of soil carbon sequestration in biochar and PGPR systems

Application of biochar affects physicochemical properties of soil and crop yield in several ways which contribute in C sequestration, e.g., increased crop yield and productivity through improved soil structure and microbial activity, reduced use of fertilizers for increasing soil fertility, and ultimately reduced emission of greenhouse gases (Kookana et al. 2011). It adsorbs agrochemicals in such a way that can increase microbial activity (Zimmerman et al. 2011). High surface area of biochar facilitates habitat for microorganisms such as PGPR while improvement in soil cation exchange capacity makes more availability of nutrients for plants and microbes (Atkinson et al. 2010). The interactive effect of biochar and PGPR on C sequestration is summarized in Table 3.

Priming effects of added C on mineralization rates of SOM are now well documented. Incorporation of biochar into soil increases microbial population in microsphere which promotes the process of priming effect by inducing fresh OM into the soil (Fontaine and Barot

Table 3 Interactive effect of biochar and PGPR on C sequestration

Crop	Treatments	Impacts	References
Corchorus capsularis, *Lycopersicon esculentum*, *Capsicum annuum*, *Raphanus sativus*, *Oryza sativa* ssp. *indica*	Sole or combined use of biochar (10 t ha^{-1}) and PSMs comprised by *Pseudomonas* sp., *Bacillus megaterium*, *B. subtilis*, and *Glomus intraradices*, and *G. mosseae* under multi-field conditions	Treatments with biochar and PSM entail significant yield increase in P-deficient soil, whereas in soils with high P content, biochar has no significant effect on crop yield, regardless of addition of PSM.	Deb et al. 2016
Maize (*Zea mays* L.)	Sole or combined use of biochar (0 and 5%, *w*/*w*) and two bacterial strains (*Burkholderia phytofirmans* (PsJN) and *Enterobacter* sp. (FD17)) and salinity stress under greenhouse conditions.	Integrated application of biochar and inoculation mitigated the negative effects of salinity on maize either by decreasing Na^+ concentration uptake or by maintaining nutrient balance within the plant.	Akhtar et al. 2015
Maize (*Zea mays* L.)	Three rhizobial isolates (RH1, RH2, and RH3) were used to inoculate maize growing in soil amended with for levels of biochar (0.0, 0.5, 1.0, and 1.5%) under controlled conditions.	Combined use of rhizobial inoculation and biochar significantly increased the growth and physiological attributes of maize over their sole application. Soil enzymes and microbial biomass C were also improved due to inoculation and biochar in rhizosphere.	Ahmad et al. 2015
Rye grass (*Lolium perenne* L.)	Study was comprised of 1% or 2% biochar (*Miscanthus giganteus*) or without biochar (control) for a period of 126 days on S- and P-limited soil.	Biochar amendment enhanced microbially mediated nutrient mobilization of S and P, resulting in improved plant growth.	Fox et al. 2014
Chickpea (*Cicer arietinum* L.)	PGPR blended biochar and three different levels of phosphorus (0, 30, and 60 kg P_2O_5 ha^{-1}) on yield and nutrient uptake by chickpea	Application of 60 kg P_2O_5 ha^{-1} significantly improved agronomic traits over other treatments, but the use of 60 kg P_2O_5 ha^{-1} with micronutrient-blended biochar + PGPR caused 52.14% higher grain yield than control. N and P contents in grain (4.0 and 0.50%, respectively) were also higher than control.	Budania and Yadav 2014
Maize (*Zea mays* L.)	Rice straw biochar (RSB) @ 0, 1, 2 and 3% with and without P-solubilizing bacteria (PSB)	A significant increase in soil pH, EC, and OM due to addition of 1, 2, and 3% RSB, which also enhanced the activity of photosynthesis by providing nutrients. PSB significantly reduced the pH of soil through organic secretions and OM by decomposition, while interactive effects of RSB and PSB were significant on maize plant fresh and dry weight.	Danish et al. 2014
Cranberry (*Vaccinium macrocarpon*)	Biochar + 100% standard organic fertilization rate; no biochar + 25% of the standard organic fertilization rate; no biochar + 3 PGPR (*Microbacterium gensengnii*, *Azospirillum brasilense*, and *Variovorax paradoxus*); 1% biochar + 25% of standard organic fertilization rate; 1% biochar + 25% of standard organic fertilization rate + 3 PGPR.	Shoot and root dry weights increased upon theaddition of 1% biochar and beneficial microbes at both harvesting dates compared to those inpotting mix fortified with full dose of Actisol®. addition of 1% biochar and beneficial microbessignificantly ($P < 0.05$) increased the total abundance of microbes present in the rhizosphere andbulk soil of cranberry cuttings.	Perron 2014
			Saxena et al. 2013

Table 3 (continued)

Crop	Treatments	Impacts	References
French beans (*Phaseolus vulgaris* L.)	Uninoculated control; soil + biochar @ 15 g kg^{-1} soil; soil + biochar @ 15 g kg^{-1} soil + *Bacillus*; soil + biochar @ 15 g kg^{-1} soil + biozyme; soil + *Bacillus*; soil + DAP	Integrated application of biochar and *Bacillus* sp. significantly increased the growth and yield as compared to untreated control.	
Wheat (*Triticum aestivum* L.)	Control (soil only); soil + 5% biochar (BC); soil + 5% BC + PGPR, soil + 0.5% wheat straw (WS); soil + 0.5% WS + PGPR soil + 5% BC + 0.5% WS, soil +5% BC + 0.5% WS + PGPR	Integrated use of biochar and WS with PGPR increased the grain yield and nutrient uptake over control, but WS had no promising effect on biochar C decomposition. In addition, combined application significantly improved microbial C, N, and P over control.	Zavalloni et al. 2011

2005; Dilly and Zyakun 2008; Di Lonardo et al. 2017). As soon as the microbial growth is increased, the release of microbial enzymes is enhanced thus producing positive effect on soil C reservoirs (Kuzyakov and Larionova 2005). Biochar also favors detoxification of allelochemicals (Qiu et al. 2009), thereby promoting rhizobacterial (*Rhizobium* sp., *Pseudomonas* sp., *Paenibacillus* sp., *Bradyrhizobium* sp., etc.) growth. Similarly, various O-containing functional groups on the biochar surface favor the adsorption of simple organic compounds and dissolve these organic compounds and NH_4^+ ions, which provide a suitable microbial habitat (Wardle et al. 2008). Therefore, the biochar surface undergoes favorable changes in soil to affect microbial community and microbial activity in the soil.

Biochar has the potential to alter the soil pH which can affect microbial biomass in soil. Bacterial population is likely to be enhanced with pH rising up to 7, whereas, fungal population may show no changes in total biomass (Rousk et al. 2010), or potentially drastically decrease its growth at higher pH (Rousk et al. 2009; Figueiredo et al. 2011). By enhancing plant biomass and growth rate, PGPR can reduce use of fertilizers in the future to sustain better agriculture practices thus decreasing the detrimental elements to environment. Moreover, several PGPR have also been reported to alter soil pH which affects the SOC pool by affecting physicochemical properties of soil. Biochar has the capacity to adhere microbes on its surface. Adhesion may depend on pore sizes (Rivera-Utrilla et al. 2001). Bacteria may adhere to biochar surfaces, favoring them less prone to leaching in soil (Pietikäinen et al. 2000; Tayyab et al. 2019). Pore size for optimal adhesion requires to be 2–5 times greater than cell size if microorganisms are supposed to enter the pores, or about 2–4 mm for *Acinetobacter* sp. and some *Bacillus mucilaginosus* species (Samonin and Elikova 2004).

Conclusions and recommendations

Atmospheric carbon dioxide flux is considerably varying because of rapid deforestation, fossil fuel combustion, and improper cultivation and management practices. Therefore, awareness should be created regarding the role of soil as a storehouse of C and other nutrients and its effects on climate change. Judicious application of agrochemicals can be altered by using C-rich compounds such as biochar. The efficient use of PGPR as a way to sequester C will be helpful to replenish C resources at a large scale.

Priming effects can affect C mineralization either positively or negatively but appraising priming effect in field conditions is still controversial though it is well suited in lab conditions. Moreover, it remains debatable to fully understand the effects of biochar on an ever-fluctuating environment which is influenced by biotic and abiotic stresses as well. The bacterial community succession occurred and the relative abundance of dominant species declined when treated with high rates of biochar. The PGPR have the ability to improve plant growth but the effects of PGPR on C stocks are less as compared to that of AMF in soil. Under future climate conditions, elevated CO_2 can increase PGPR dominance as plant-associated microbes enhance plant success under CO_2. However, understanding of PGPR-plant interactions to regulate SOM decomposition and potential to alleviate environmental stress imposed by elevate CO_2 is limited. In case of adhesion, much larger and smaller pores will not render a favorable site for microorganisms to be adsorbed on the surface either because pore curvature is too large to encourage adhesion or microorganisms do not settle well into the pores. It is, therefore, likely that the production of biochar to gain desirable benefits should be kept in mind before application.

Acknowledgments The authors are thankful to the Department of Soil Science, University College of Agriculture and Environmental Sciences, The Islamia University of Bahawalpur, Pakistan, and the Fujian Agriculture and Forestry University, China, for providing a favorable ambiance for the write up of a useful and constructive review.

References

Ahmad, M. T., Asghar, H. N., Saleem, M., Yahya Khan, M., & Zahir, Z. A. (2015). Synergistic effect of rhizobia and biochar on growth and physiology of maize. *Agronomy Journal, 107*(6). https://doi.org/10.2134/agronj15.0212.

Ahmed, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., & Ok, Y. S. (2014). Biochar as a sorbent for contaminant management in soil and water: a review. *Chemosphere, 99*, 19–33.

Akhtar, S. S., Andersen, M. N., Naveed, M., Zahir, Z. A., & Liu, F. (2015). Interactive effect of biochar and plant growth-promoting bacterial endophytes on ameliorating salinity stress in maize. *Functional Plant Biology, 42*(8), 770. https://doi.org/10.1071/FP15054.

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., & Tokos, K. (2009). Atmospheric lifetime of fossil fuel carbon dioxide. *Annual Review of Earth and Planetary Sciences., 37*(1), 117–134. https://doi.org/10.1146/annurev.earth.031208.100206.

Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achievingagricultural benefits from biochar application to temperate soils: a review. *Plant and Soil, 337*, 1–18.

Brewer, C. E., Brown, R. C., & Laird, D. A. (2012). *Biochar characterization and engineering*. Graduate Teses and Dissertations, 12284. http://lib.dr.iastate.edu/etd/12284.

Bruun, S., Harmer, S. L., Bekiaris, G., Christel, W., Zuin, L., Hu, Y., Lars, S. J., & Lombi, E. (2017). The effect of different pyrolysis temperatures on the speciation and availability in soil of P in biochar produced from the solid fraction of manure. *Chemosphere, 169*, 377–386. https://doi.org/10.1016/j.chemosphere.2016.11.058.

Budania, K., & Yadav, J. (2014). Effects of PGPR blended biochar and different levels of phosphorus on yield and nutrient uptake by chickpea. *Annals of Agri Bio Research, 19*(3), 408–412.

Cheng, C. H., Lehmann, J., & Engelhard, M. (2008). Natural oxidation of black carbon in soils: changes in molecular form and surface charge along a climosequence. *Geochimica et Cosmochimica Acta, 72*, 1598–1610.

Conz, F. R., Abbruzzini, T. F., de Andrade, C. A., Milori, P., DM, B., & E P Cerri, C. (2017). Effect of pyrolysis temperature and feedstock type on agricultural properties and stability of biochars. *Agricultural Sciences, 08*(09), 914–933. https://doi.org/10.4236/as.2017.89067.

Danish, S., Younis, U., Akhtar, N., Ameer, A., Ijaz, M., Nasreen, S., Huma, F., Sharif, S., & Ehsanullah, M. (2014). Phosphorus solubilizing bacteria and rice straw biochar consequence on maize pigments synthesis. *International Journal of Biosciences, 5*(12) 31–39. https://doi.org/10.12692/ijb/5.12.31-39.

Deb, D., Kloft, M., Lässig, J., & Walsh, S. (2016). Variable effects of biochar and P solubilizing microbes on crop productivity in different soil conditions. *Agroecology and Sustainable Food Systems, 40*(2), 145–168. https://doi.org/10.1080/21683565.2015.1118001.

Di Lonardo, D. P., De Boer, W., Klein Gunnewiek, P. J. A., Hannula, S. E., & Van der Wal, A. (2017). Priming of soil organic matter: chemical structure of added compounds is more important than the energy content. *Soil Biology and Biochemistry, 108*, 41–54. https://doi.org/10.1016/j.soilbio.2017.01.017.

Dilly, O., & Zyakun, A. (2008). Priming effect and respiratory quotient in a forest soil amended with glucose. *Geomicrobiology Journal, 25*, 425–431.

Dominghetti, T. F., de Barros, A. T. M., Soares, C. O., & Cancado, P. H. D. (2015). *Stomoxys calcitrans* (Diptera: Muscidae) outbreaks: current situation and future outlook with emphasis on Brazil. *Revista Brasileira de Parasitologia Veterinári, 24*, 387–395.

Domingues, R. R., Trugilho, P. F., Silva, C. A., De Melo, I. C. N. A., Melo, L. C. A., Magriotis, Z. M., & Sánchez-Monedero, M. A. (2017). Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits. *PLoS ONE, 12*(5), 1–19. https://doi.org/10.1371/journal.pone.0176884.

Downie, A. E., Van Zwieten, L., Smernik, R. J., Morris, S., & Munroe, P. R. (2011). Terra Preta Australis: reassessing the carbon storage capacity of temperate soils. *Agriculture, Ecosystems and Environment, 140*(1–22), 137–147. https://doi.org/10.1016/j.agee.2010.11.020.

Dungait, J. A. J., Hopkins, D. W., Andrew, S., Gregory, A. S., & Whitmore, A. P. (2012). Soil organic matter turnover is governed by accessibility not recalcitrance. *Global Change Biology, 18*, 1781–1796.

Figueiredo, M. V. B., Seldin, L., Araujo, F. F., & Mariano, R. L. R. (2011). Plant growth promoting rhizobacteria: fundamentals and applications. In D. K. Maheshwari (Ed.), *Plant growth and health promoting bacteria* (pp. 21–42). Berlin: Springer-Verlag.

Fontaine, S., & Barot, S. (2005). Size and functional diversity of mi- crobe populations control plant persistence and long-term soil carbon accumulation. *Ecology Letters, 8*, 1075–1087.

Fox, A., Kwapinski, W., Griffiths, B. S., & Schmalenberger, A. (2014). The role of sulfur- and phosphorus-mobilizing bacteria in biochar-induced growth promotion of Lolium perenne. *FEMS Microbiology Ecology, 90*(1), 78–91. https://doi.org/10.1111/1574-6941.12374.

Francis, I., Holsters, M., & Vereecke, D. (2010). The gram-positive side of plant-microbe interaction. *Environmental Microbialogy, 12*, 1–12.

Freeman, C., Ostle, N. J., Fenner, N., & Kang, H. (2004). A regulatory role for phenol oxidase during decomposition in peat lands. *Soil Biology and Biochemistry, 36*, 1663–1667.

Gai, X., Wang, H., Liu, J., Zhai, L., Liu, S., Ren, T., & Liu, H. (2014). Effects of feedstock and pyrolysis temperature on biochar adsorption of ammonium and nitrate. *PLoS One, 9*(12), 1–19. https://doi.org/10.1371/journal.pone.0113888.

García-Fraile, P., Menéndez, E., & Rivas, R. (2015). Role of bacterial biofertilizers in agriculture and forestry. *AIMS Bioengineering, 2*, 183–205.

Gaskin, J. W., Speir, A., Morris, L. M., Ogden, L., Harris, K., Lee, D., & Das, K. C. (2007). Potential for pyrolysis char to affect soil moisture and nutrient status of a loamy soil. In *2007 Georgia Water Resources Conference. Proceedings of the 2007 Georgia Water Resources Conference, held March 27–29, 2007, at the University of Georgia*.

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal- a review. *Biology and Fertility of Soils, 35*, 219–230.

Han, J., Meng, X., Zhou, X., Yi, B., Liu, M., & Xiang, W. N. (2017). A long-term analysis of urbanization process, landscape change, and carbon sources and sinks: a case study in China's Yangtze River Delta region. *Journal of Cleaner Production, 141*, 10401–11050. https://doi.org/10.1016/j.jclepro.2016.09.177.

Hoosbeek, M. R., Remme, R. P., & Rusch, G. M. (2018). Trees enhance soil carbon sequestration and nutrient cycling in a silvopastoral system in south-western Nicaragua. *Agroforestry Systems, 92*(2), 263–273. https://doi.org/10.1007/s10457-016-0049-2.

Izaurralde, R. C., Rosenberg, N. J., & Lal, R. (2001). Mitigation of climate change by soil carbon sequestration. *Advances in Agronomy, 70*, 1–75.

Jenny, H. (1980). *Factors of soil formation: a system of quantitative pedology.* North Chelmsford: Courier Corporation.

Jones, D. M. (2008). Polycyclic aromatic hydrocarbons (PAHs) in biochars and related materials. Biochar: sustainability and security in a changing climate. Proceedings 2nd International Biochar Iniative Conference 2008, Newcastle, UK.

Kimetu, J. M., & Lehmann, J. (2010). Stability and stabilisation of biochar and green manure in soil with different organic carbon contents. *Australian Journal of Soil Research, 48*(6–7), 577–585. https://doi.org/10.1071/SR10036.

Kookana, R., Sarmah, A., & Van, Z. L. (2011). Biochar application to soil: agronomic and environmental benefits and unintended consequences. *Advances in Agronomy, 112*, 103–143.

Krull, E., Skjemstad, J., & Baldock, J. (2004). *Functions of soil organic matter and the effect on soil properties: a literature review. Report for GRDC and CRC for Greenhouse Accounting. CSIRO Land and Water Client Report*. Adelaide: CSIRO Land and Water.

Kuzyakov, Y., & Larionova, A. A. (2005). Root and rhizomicrobial respiration: a review of approaches to estimate respiration by autotrophic and heterotrophic organisms in soil. *Journal of Plant Nutrition and Soil Science, 168*, 503–520.

Kuzyakov, Y., Bogomolova, I., & Glaser, B. (2014). Biochar stability in soil: decomposition during eight years and transformation as assessed by compound-specific 14C analysis. *Soil Biology and Biochemistry, 70*, 229–236.

Lai, W. Y., Lai, C. M., Ke, G. R., Chung, R. S., Chen, C. T., Cheng, C. H., Pai, C. W., Chen, S. Y., & Chen, C. C. (2013). The effects of woodchip biochar application on crop yield, carbon sequestration and greenhouse gas emissions from soils planted with rice or leaf beet. *Journal of the Taiwan Institute of Chemical Engineers, 44*(6), 1039–1044. https://doi.org/10.1016/j.jtice.2013.06.028.

Laird, D. A. (2008). The charcoal version: a win-win scenario for simultaneously producing bioenergy, permanently sequestering C, while improving soil and water quality. *Agronomy Journal, 100*, 178–181.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science, 304*, 1623–1627.

Lal, R., Follett, R. F., Stewart, B. A., & Kimble, J. M. (2007). Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science, 172*(12), 943–956.

Lehmann, J. (2009). Terra preta Nova – where to from here? In W. I. Woods, W. G. Teixeira, J. Lehmann, C. Steiner, & A. WinklerPrins (Eds.), *Terra preta Nova: A Tribute to Wim Sombroek* (pp. 473–486). Berlin: Springer.

Lehmann, J., & Joseph, S. (Eds.). (2015). *Biochar for environmental management: science, technology and implementation*. New York: Routledge.

Lehmann, J., & Joseph, J. (2009). *Biochar for environmental management: science and technology.* London: Earthscan.

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Biochar sequestration in terrestrial ecosystems: a review. *Mitigation and Adaptation Strategies for Global Change, 11*, 403–427. https://doi.org/10.1007/s11027-005-9006-5.

Leonardo, D., Blanca, L. F., Landa, B., & Weller, D. M. (2006). Host crop affects rhizosphere colonization and competitiveness of 2,4-diacetylphloroglucinol-producing Pseudomonas fluoresens. *Phytopathology, 96*, 751–762.

Lin, Y., Munroe, P., Joseph, S., Henderson, R., & Ziolkowski, A. (2012). Water extractable organic carbon in untreated and

chemical treated biochars. *Chemosphere, 87*, 151–157. https://doi.org/10.1016/j.chemosphere.2011.12.007.
Liu, W.-J., Jiang, H., & Yu, H.-Q. (2015). Development of Biochar-Based Functional Materials: Toward a Sustainable Platform Carbon Material. *Chemical Reviews, 115*(22), 12251–12285. https://doi.org/10.1021/acs.chemrev.5b00195.
Liu, S., Zhang, Y., Zong, Y., Hu, Z., Wu, S., Zhou, J., Jin, Y., & Zou, J. (2016). Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: A meta-analysis. *GCB Bioenergy, 8*(2), 392–206. https://doi.org/10.1111/gcbb.12265.
Lou, L., Yao, L., Cheng, G., Wang, L., He, Y., & Hu, B. (2015). Application of rice-straw biochar and microorganisms in nonylphenol remediation: adsorption-biodegradation coupling relationship and mechanism. *PLoS One, 10*(9), e0137467.
Lusiba, S., Odhiambo, J., & Ogola, J. (2017). Effect of biochar and phosphorus fertilizer application on soil fertility: soil physical and chemical properties. *Archives of Agronomy and Soil Science, 63*(4), 477–490. https://doi.org/10.1080/03650340.2016.1218477.
Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural intensification and ecosystem properties. *Science, 277*, 504–509.
Mei, X., Li, X., Shen, Q., Zhang, D., Mei, X., Ran, W., & Xu, Y. (2017). Functional groups determine biochar properties (pH and EC) as studied by two- dimensional C NMR . functional groups determine biochar properties (pH and EC) as studied by two-dimensional 13 C NMR correlation spectroscopy, (June 2013). https://doi.org/10.1371/journal.pone.0065949.
Naisse, C., Davasse, B., Girardin, C., Chabbi, A., & Rumpel, C. (2014). Effect of biochar addition on C mineralisation and soil organic matter priming in two subsoil horizons. *Journal of Soils and Sediments, 15*(4), 825–832. https://doi.org/10.1007/s11368-014-1002-5.
Nie, M., Bell, C., Wallenstein, M. D., & Pendall, E. (2015). Increased plant productivity and decreased microbial respiratory C loss by plant growth-promoting rhizobacteria under elevated CO 2. *Scientific Reports, 5*, 1–6. https://doi.org/10.1038/srep09212.
Perron, D. B. (2014). Effect of biochar amended with beneficial microbes on establishment and growth of cranberry (*Vaccinium macrocarpon* L.) cuttings under controlled conditions, (October). McGill University Montrea. Master Thesis.
Pietikäinen, J., Kiikkilä, O., & Fritze, H. (2000). Charcoal as a habitat for microbes and its effect on the microbial community of the underlying humus. *Oikos, 89*, 231–242. https://doi.org/10.1034/j.1600-0706.2000.890203.x.
Pituello, C., Francioso, O., Simonetti, G., Pisi, A., Torreggiani, A., Berti, A., & Morari, F. (2015). Characterization of chemical–physical, structural and morphological properties of biochars from biowastes produced at different temperatures. *Journal of Soils and Sediments, 15*(4), 792–804. https://doi.org/10.1007/s11368-014-0964-7.
Qiu, H., Lv, L., Pan, B. C., Zhang, Q. J., Zhang, W. M., & Zhang, Q. X. (2009). Critical review in adsorption kinetic models. *Journal of Zhejiang University Science A, 10*(5), 716–724.
Rivera-Utrilla, J., Bautilsta-Toledo, I., Ferro-Carcia, M. A., & Moreno-Catilla, C. (2001). Activated carbon surface modifications by adsorption of bacteria and their effect on aqueous lead adsorption. *Journal of Chemical Technology and Biotechnology, 76*, 1209e1215.
Ronsse, F., Hecke, S., Dickinson, D., & Prins, W. (2013). Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *GCB Bioenergy, 5*, 104–115.
Rousk, J., Brookes, P. C., & Bååth, E. (2009). Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization. *Applied and Environmental Microbiology, 75*, 1589–1596.
Rousk, J., Bååth, E., Brookes, P. C., Lauber, C. L., Lozupone, C., Caporaso, J. G., Knight, R., & Fierer, N. (2010). Soil bacterial and fungal communities across a pH gradient in an arable soil. *The ISME, 4*, 134–151.
Samonin, V. V., & Elikova, E. E. (2004). A study of the adsorption of bacterial cells on porous materials. *Mikrobiologiya, 73*, 810–816.
Sarfraz, R., Shakoor, A., Abdullah, M., Arooj, A., Hussain, A., & Xing, S. (2017). Impact of integrated application of biochar and nitrogen fertilizers on maize growth and nitrogen recovery in alkaline calcareous soil. *Soil Science and Plant Nutrition, 63*(5), 488–498. https://doi.org/10.1080/00380768.2017.1376225.
Sarfraz, R., Li, S., Yang, W., Zhou, B., & Xing, S. (2019). Assessment of physicochemical and nutritional characteristics of waste mushroom substrate biochar under various pyrolysis temperatures and times. *Sustainability, 11*(1), 277. https://doi.org/10.3390/su11010277.
Saxena, J., Rana, G., & Pandey, M. (2013). Impact of addition of biochar along with bacillus sp. on growth and yield of french beans. *Scientia Horticulturae, 162*, 351–356. https://doi.org/10.1016/j.scienta.2013.08.002.
Schlesinger, W. H., & Andrews, J. A. (2000). Soil respiration and the global carbon cycle. *Biogeochemistry, 48*, 7–20.
Shahzad, T., Anwar, F., Hussain, S., Mahmood, F., Arif, M. S., Sahar, A., Nawaz, M. F., Perveen, N., Sanaullahe, M., Rehman, K., & Rashid, M. I. (2019). Carbon dynamics in surface and deep soil in response to increasing litter addition rates in an agro-ecosystem. *Geoderma, 333*, 1–9. https://doi.org/10.1016/j.geoderma.2018.07.018.
Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology, 22*(3), 1315–1324. https://doi.org/10.1111/gcb.13178.
Sofi, J. A., Lone, A. H., Ganie, M. A., Dar, N. A., Bhat, S. A., Mukhtar, M., Dar, M. A., & Ramzan, S. (2016). Soil microbiological activity and carbon dynamics in the current climate change scenarios: a review. *Pedosphere, 26*(5), 577–591. https://doi.org/10.1016/S1002-0160(15)60068-6.
Soil Science Society of America (SSSA). (2001). *Carbon Sequestration: Position of the Soil Science Society of America*. http://lib.dr.iastate.edu/agron_pubs.
Stewart, C. E., Zheng, J., Botte, J., & Cotrufo, M. F. (2013). Co-generated fast pyrolysis biochar mitigates greenhouse gas emissions and increases carbon sequestration in temperate soils. *GCB Bioenergy, 5*(2), 153–163. https://doi.org/10.1111/gcbb.12001.
Suekhum, D., Towprayoon, S., Inubushi, K., Sarobol, E. D., Tripetchkul, S., & Chidthaisong, A. (2012). Investigation of soil carbon sequestration through biochar application: effects on greenhouse gas emissions, energy crop production and

soil carbon content. 4th International Conference on Sustainable Energy and Environment (SEE 2011): A Paradigm Shift to Low Carbon Society 27–29 February 2012, Bangkok, Thailand.

Sun, J., He, F., Pan, Y., & Zhang, Z. (2017). Effects of pyrolysis temperature and residence time on physicochemical properties of different biochar types. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science, 67*(1), 12–22. https://doi.org/10.1080/09064710.2016.1214745.

Tarin, M. W. K., Fan, L., Tayyab, M., Sarfraz, R., Chen, L., & He, T. (2018). Effects of bamboo biochar amendment on the growth and physiological characteristics of Fokienia hodginsii. *Applied Ecology and Environmental Research, 16*(6), 8055–8074. https://doi.org/10.15666/aeer/1606_80558074.

Tayyab, M., Caifang, Z., Islam, W., Khalil, F., Ziqin, P., Caifang, Z., Arafat, Y., Hui, L., Rizwan, M., Ahmad, K., Waheed, S., Tarin, M. W. K., & Zhang, H. (2018). Biochar: an efficient way to manage low water availability in plants. *Applied Ecology and Environmental Research, 16*(3), 2565–2583.

Tayyab, M., Islam, W., Lee, C. G., Pang, Z., Khalil, F., Lin, S., Weixing, L., & Zhang, H. (2019). Short-term effects of different organic amendments on soil fungal composition. *Sustainability (Switzerland), 11*(1). https://doi.org/10.3390/su11010198.

Vejan, P., Abdullah, R., Khadiran, T., Ismail, S., & Nasrulhaq Boyce, A. (2016). Role of plant growth promoting rhizobacteria in agricultural sustainability-a review. *Molecules, 21*(5), 1–17. https://doi.org/10.3390/molecules21050573.

Velivelli, S. L. S. (2011). How can bacteria benefit plants? Doctoral research at University College Cork, Ireland, published in The Boolean.

Ventura, M., Alberti, G., Viger, M., Jenkins, J. R., Girardin, C., Baronti, S., Zaldei, A., Taylor, G., Rumpel, C., Miglietta, F., & Tonon, G. (2015). Biochar mineralization and priming effect on SOM decomposition in two European short rotation coppices. *GCB Bioenergy, 7*(5), 1150–1160. https://doi.org/10.1111/gcbb.12219.

Verheijen, F., Jeffery, S., Bastosa, C., Van Der Velde, M., & Diafas, I. (2010). *Biochar application to soils: a critical review of effects on soil properties, processes and functions. EUR 24099 EN*. Luxembourg: Office for the Official Publications of the European Communities 149pp.

Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil, 255*, 571–586.

Walley, F. L., Gillespie, A. W., Adetona, A. B., Germida, J. J., & Farrell, R. E. (2014). Manipulation of rhizosphere organisms to enhance glomalin production and C sequestration: pitfalls and promises. *Canadian Journal of Plant Science, 94*(6), 1025–1032. https://doi.org/10.4141/cjps2013-146.

Wang, Z., Zheng, H., Luo, Y., Deng, X., Herbert, S., & Xing, B. (2013). Characterization and influence of biochars on nitrous oxide emission from agricultural soil. *Environmental Pollution, 174*, 289–296. https://doi.org/10.1016/j.envpol.2012.12.003.

Ward, S. E., Bardgett, R. D., McNamara, N. P., Adamson, J. K., & Ostle, N. J. (2007). Long-term consequences of grazing and burning on northern peatland carbon dynamics. *Ecosystems, 10*, 1069–1083.

Wardle, D. A., Nilsson, M. C., & Zackrisson, O. (2008). Response to comment on fire-derived charcoal causes loss of forest humus. *Science, 321*, 1295d.

Windeatt, J. H., Ross, A. B., Williams, P. T., Forster, P. M., Nahil, M. A., & Singh, S. (2014). Characteristics of biochars from crop residues: potential for carbon sequestration and soil amendment. *Journal of Environmental Management, 146*, 189–197.

Xu, G., Lv, Y., Sun, J., Shao, H., & Wei, L. (2012). Recent advances in biochar applications in agricultural soils: benefits and environmental implications. *Clean - Soil, Air, Water, 40*(10), 1093–1098. https://doi.org/10.1002/clen.201100738.

Xu, N., Tan, G., Wang, H., & Gai, X. (2016). Effect of biochar additions to soil on nitrogen leaching, microbial biomass and bacterial community structure. *European Journal of Soil Biology, 74*, 1–8. https://doi.org/10.1016/j.ejsobi.2016.02.004.

Yuan, H., Lu, T., Wang, Y., Chen, Y., & Lei, T. (2016). Sewage sludge biochar: nutrient composition and its effect on the leaching of soil nutrients. *Geoderma, 267*, 17–23. https://doi.org/10.1016/j.geoderma.2015.12.020.

Zavalloni, C., Alberti, G., Biasiol, S., Vedove, G. D., Fornasier, F., Liu, J., & Peressotti, A. (2011). Microbial mineralization of biochar and wheat straw mixture in soil: a short-term study. *Applied Soil Ecology., 50*, 45–51. https://doi.org/10.1016/j.apsoil.2011.07.012.

Zhang, A., Bian, R., Pan, G., Cui, L., Hussain, Q., Li, L., Zheng, J., Zheng, J., Zhang, X., Hana, X., & Yu, X. (2012). Effects of biochar amendment on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: A field study of 2 consecutive rice growing cycles. *Field Crops Research, 127*, 153–160. https://doi.org/10.1016/j.fcr.2011.11.020.

Zhang, X., Xia, Y. S., Shang, Y. J., Zhao, Q. Q., & Shi, J. (2017). Effects of biochar (BC) on microbial diversity of cadmium (Cd) contaminated soil. *China Environmental Science, 37*(1), 252–262.

Zibilske, L. M., & Bradford, J. M. (2007). Oxygen effects on carbon, polyphenols, and nitrogen mineralization potential in soil. *Soil Science Society of America Journal, 71*, 133–139.

Zimmerman, A. R., Gao, B., & Ahn, M. Y. (2011). Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry, 43*, 1169–1179 33–34.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.