Polish Journal of Microbiology
2017, Vol. 66, No 2, 151–161

MINIREVIEW

Biochar-Rhizosphere Interactions – a Review

SŁAWOMIR GŁUSZEK, LIDIA SAS-PASZT, BEATA SUMOROK and RYSZARD KOZERA

Research Institute of Horticulture, Skierniewice, Poland

Submitted 25 April 2016, revised 18 November 2016, accepted 2 December 2016

Abstract

Biochar is a solid material of biological origin obtained from biomass carbonization, designed as a mean to reduce greenhouse gases emission and carbon sequestration in soils for a long time. Biochar has a wide spectrum of practical utilization and is applied as a promising soil improver or fertilizer in agriculture, or as a medium for soil or water remediation. Preparations of biochar increase plant growth and yielding when applied into soil and also improve plant growth conditions, mainly bio, physical and chemical properties of soil. Its physical and chemical properties have an influence on bacteria, fungi and invertebrates, both in field and laboratory conditions. Such effects on rhizosphere organisms are positive or negative depending on biochar raw material origin, charring conditions, frequency of applications, applications method and doses, but long term effects are generally positive and are associated mainly with increased soil biota activity. However, a risk assessment of biochar applications is necessary to protect food production and the soil environment. This should be accomplished by biochar production and characterization, land use implementation, economic analysis, including life cycle assessment, and environmental impact assessment.

Key words: biochar, rhizosphere, soil bacteria, soil microbiota, soil quality

Introduction

The rhizosphere is defined as the layer of soil around the roots that is influenced by the roots (Hiltner, 1904). It supports the development and activity of many diversified microbial communities, which can be up to 1000 times richer in microorganisms than bulk soil, because plant roots secrete organic compounds utilized by microbes as nutrients. Plant roots can modify the rhizosphere chemistry in a number of ways: (I) by the release and uptake of organic compounds, (II) by the gaseous exchange (CO_2/O_2) associated with the respiration of roots and rhizosphere microorganisms, and (III) by water and nutrient uptake or release, which is associated with the uptake or extrusion of protons and modification of the redox potential (Neuman and Römheld, 2012). As they grow through the soil, the roots also modify the physical properties of the rhizosphere soil, such as aggregate stability, hydrophobicity and the number and size of micropores, which are also modified by the presence of polymeric substances (Neuman and Römheld, 2012). About 5–20% of the carbon fixed by plants is secreted, mainly as root exudates (Marschner, 1995). Microorganisms living in the rhizosphere have different trophic, or living, habitats, and varied inter- and intra-relationships: saprotrophic, symbiotic or antagonistic (Kobayashi and Crouch, 2009). Benefits of mycorrhizal colonization include direct access to P and organic N and their better uptake, increased heavy metal and Al tolerance, decreased disease susceptibility, and in some cases improved water uptake. However, mycorrhizal colonization comes at a cost to plants, which have to supply the fungi with carbon (Marschner, 2012).

Biochar is a material originating from organic matter, produced by pyrolysis at high temperature in the absence of oxygen. Charred materials include: wood chips, crop residues, food industry wastes, animal manure, sewage sludge, microalgae biomass (Chan *et al.*, 2007; Sohi *et al.*, 2010; Farrell *et al.*, 2013; Marks *et al.*, 2014a; 2014b; Hosseini Bai *et al.*, 2015) and chemical co-products such as bio-oil and syngas (Bridgwater and Peacocke, 2000). The chemical and physical characteristics of biochars vary depending on the conditions of the thermochemical conversion applied to the biomass (Table I). Biochars produced from the same biomass under similar pyrolysis conditions, but in different plants can result in various properties of the final product (Spokas *et al.*, 2012a). The final product can constitute a material that contains no residual structures of the original feedstock material or can have relic structures (Spokas *et al.*, 2010). The physical structure of biochars affects the organic and inorganic composition: the pH can range from 5.6 to 13.0, the C content from 33.0% to

* Corresponding author: S. Głuszek, Research Institute of Horticulture, Skierniewice, Poland; **e-mail: slawomir.gluszek@inhort.pl**

Table I
Physicochemical parameters of selected types of biochar in comparison with compost

Feedstock material and temperature (if given)	pH (H_2O)	C (%)	N (%)	Ash (%)	Cd	Cu	Zn	P	Conductivity ($mS\ cm^{-1}$)	Density ($kg\ L^{-1}$)	CEC	References
					($mg\ kg^{-1}$)							
Compost (for comparison)	7.1*	27.0	2.2	–	0.14	86.0	321.0	–	1.4	0.77	–	Akhter *et al.*, 2015
Biochar derived from:												
Beech wood	8.78	80.3	0.4	15.2	< 2.00	16.0	93.0	–	0.54	0.36	9.83**	Akhter *et al.,* 2015
Garden waste residues	9.03	79.8	0.7	19.3	< 2.00	21.0	95.0	–	1.67	0.34	12.85**	
Oak wood (350°C)	4.80	74.9	–	1.1	–	–	–	12	–	–	294.2***	Lehmann *et al.*, 2011
Oak wood (600°C)	6.38	87.5	–	1.3	–	–	–	29	–	–	75.7***	
Corn stover (350°C)	9.39	60.4	–	11.4	–	–	–	1889	–	–	419.3***	
Corn stover (600°C)	9.42	70.6	–	16.7	–	–	–	2114	–	–	252.1***	
Poultry litter (350°C)	9.65	29.3	–	51.2	–	–	–	21256	–	–	121.3***	
Poultry litter (600°C)	10.33	23.6	–	55.8	–	–	–	23596	–	–	58.7***	
Glucose	–	64,6	0,0	–	–	–	–	–	–	–	–	Steinbeiss *et al.,* 2009
Yeast	–	67.4	5.5	–	–	–	–	–	–	–	–	
Eucalyptus wood (350°C)	7.0	82.4	0.6	–	–	–	–	0.6	–	–	–	Atkinson *et al.*, 2010

Norte: (–) Parameter not measured, * measured in $CaCl_2$, ** ($mmol\ 100\ mL^{-1}$), *** ($mmolc\ kg^{-1}$)

82.7%, N content from 0.1% to 6.0%, and the C: N ratio can range from 19 to 221 (Jha *et al.*, 2010; Spokas *et al.*, 2012b). Biochar can also contain appreciable quantities of P, K, Ca, Mg and micronutrients (Cu, Zn, Fe, Mn) with ashes accounting for 5–60% of the weight, depending on the source of the biomass and pyrolysis conditions (Cheng *et al.*, 2008b; Enders *et al.*, 2012).

The main goal of biochar applications in previous years was carbon sequestration in soil deposits (Jha *et al.*, 2010). Now the goal is also to increase crop yields (Jeffery *et al.*, 2011) and to nowadays the main focus is also to increase soil fertility (Atkinson *et al.*, 2010) using biochar-induced specific properties of soil (Blackwell *et al.*, 2010; Anderson *et al.*, 2011; Parvage *et al.*, 2013).

Biochar as a soil amendment exhibits some mechanisms that could explain its influence on soil organisms. They include:

- changing in the availability of soil nutrients and shifts soil nutrients ratios: N, P and others (Gundale and DeLuca, 2006; DeLuca *et al.*, 2006; Prendergast-Miller *et al.*, 2014; Ojeda *et al.*, 2015),
- stimulating soil microbial processes by absorbing/detoxifying inhibitory compounds (DeLuca *et al.*, 2006; Elad *et al.*, 2010),
- altering signalling dynamics between plants and their symbionts by binding both signalling or stimulatory molecules produced by soil microorganisms or plant roots and can serve as a secondary source of signal molecules (Akiyama *et al.*, 2005; Spokas *et al.*, 2010; Ni *et al.*, 2011; Masiello *et al.*, 2013).
- biochar also can serve as a refuge for soil microorganisms, which colonize biochar particles and can be protected from soil predators like large protozoans, nematodes, mites and collembola (Ezawa *et al.*, 2002; Thies and Rillig, 2009).
- biochar is also an effective sorbent of heavy metals and organic pollutants (Jiang *et al.*, 2012), which can have an influence not only on soil microbiota, but also on plants (Cao *et al.*, 2009) and soil fauna (Denyes *et al.*, 2012).

Plant growth regulation by biochar

Biochar addition to soil has a great impact on plant development and root colonization by microorganisms (*e.g.* mycorrhizal fungi) and nematodes (Table II). Experiments have shown that biochar additions to soil can increase the biomass of the roots of maize (Yamato *et al.*, 2006) and barley (Prendergast-Miller *et al.*, 2014), but low doses (2.5–10 t/ha) of charred plant biomass didn't impact corn seed germination on sand or fine sandy loam soils, in comparison to non-treated control soil group (Free *et al.*, 2005). Biochar addition influenced root growth of *Satsuma mandarin* (*Citrus unshiu* Marc.) trees on trifoliate orange (*Poncirus trifoliata* Raf.) rootstocks, which were reported to be 1.5 times longer and

Table II
Comparison of biochar effects on different horticultural crops and root colonization by AMF and nematodes

Crop plant	Type of biochar/ raw material	Effect on plants and soil	Reference
Apple	acacia hardwood	Better plant growth	Eyles *et al.*, 2015
Apple	woody residues	Higher soil microorganisms activity, increased root growth	Ventura *et al.*, 2014
Apple rootstock	Green waste	Increased nutrient content and higher dry mass	Street *et al.*, 2014
Apple seedlings	rice husk at 450 °C biochar	enhanced the plant height, fresh weight, and photosynthetic parameters	Wang *et al.*, 2016
Peach	Pinewood	Higher biomass and better nutrient content in plants	Atucha and Litus, 2015
Strawberry	Citrus wood or greenhouse wastes char	Fungal disease suppress	Meller Harel *et al.*, 2012
Tomato	Wood chips biochar (WB) mixed with compost or	According to control: WB decrease root and shoot dry weight, decreased AMF colonization	Akhter *et al.*, 2015
	green waste biochar (GWB) mixed with compost	GWB increased root and shoot dry weight, decreased AMF colonization	
Tomato	Powdered wood charcoal	Better plant growth and higher yield	Yilangai *et al.*, 2014
Tomato	rice husk and shell of cotton seed at 400°C	Better water use efficiency in reduced irrigation regimes and yield similar as in full irrigation	Akhtar *et al.*, 2014
Carrot	Spelt husk biochar and wood residues biochar	Bigger biomass of tap roots and fine roots of nematode *Pratylenchus penetrans* treated plants in comparison to control	George *et al.*, 2016
Lettuce	-sewage sludge, slow pyrolysis char gasification	-Stimulation of plant growth	Marks *et al.*, 2014a; 2014b
	-fast-pyrolysis pine and poplar wood char	-Strong inhibition of plant growth	
Lettuce Chinese cabbage	rice-husk char	increased final biomass, root biomass, plant height and number of leaves	Carter *et al.*, 2013
Beans	grass with horse dung at 300°C	No influence on height, higher number and longer leaves	William and Qureshi, 2015

had a bigger mass in biochar-treated trees, in comparison with the control (Ishii and Kadoya, 1994). There is also evidence that roots prefer to grow towards biochar particles (Prendergast-Miller *et al.*, 2014). Biochar's influence on root growth is visible as clusters of biochar particles bound to plant roots, root hairs and hyphae of mycorrhizal fungi (Joseph *et al.*, 2010; Lehmann *et al.*, 2011). The mechanisms of root-biochar interactions coincide with biochar impact on soil: pH, bulk density, aeration and water holding capacity, nutrient content and availability (Jones *et al.*, 2012; Prendergast-Miller *et al.*, 2014). Biochar has also an influence on microbial communities in soil (Rutigliano *et al.*, 2014) and on particles signalling molecules in the soil, by absorbing or releasing them (Akiyama *et al.*, 2005; Spokas *et al.*, 2010). Results of experiments show that biochar has greater impact on plants grown in nutrient-rich soils, in comparison with poor soils or poor, but fertilized soils (Noguera *et al.*, 2010). Following the application of biochar, the levels of some available nutrients in soil gradually increase in subsequent years, but this effect is not obvious immediately after raw biochar has been introduced into soil (Dong *et al.*, 2013).

The formation and growth of root hairs, which are essential for normal root growth (Gilroy and Jones, 2000), is also regulated by soil microbiota. Arbuscular mycorrhizal fungi and other soil microorganisms can inhibit the formation of root hairs and limit their length in maize roots (*Zea mays*) (Kothari *et al.*, 1990). On the other hand, application of *Azospirillum brasilense* strain ATCC 29710 onto young wheat plants increases the total number of root hairs, like applications of IAA (Martin *et al.*, 1989). Biochar addition can inhibit the development of root hairs, in comparison with the control without biochar. This observation can be explained by a higher phosphorus content of biochar-enriched soil (Prendergast-Miller *et al.*, 2014).

Biochar influence on rhizosphere microorganisms

The kind of influence of biochar on the number and biomass of microorganisms, and their effectiveness in colonizing plant roots is most likely associated with the type of the soil into which it has been introduced

Table III
Biochar influence on soil microorganisms in different soils

Type of biochar/raw material	Effect on soil microorganisms	Soil type	Reference
Willow wood and swine manure digestate feedstock:	Increased microbial biomass in both cases and:	Sandy loam	Ameloot *et al.*, 2013
slowly pyrolyzed at 350°C biochar	-Increased dehydrogenase activity		
slowly pyrolyzed at 700°C biochar	-Decreased dehydrogenase activity		
Biochars: poultry litter (PL) and pine chips (P) at 400 or 500°C	Increased SOM and microbial biomass, higher N mineralization in (PL)	Silt loam	Ameloot *et al.*, 2015
Mixed leafy tree chipped trunks and branches biochar	increased soil respiration, fungal and bacterial growth rate	Eutric cambisol	Jones *et al.*, 2012
Fast-pyrolysis wood-derived biochar	increased microbial abundance with	Sandy loam/ clay/clay loam Gram-negative bacteria-domination	Gomez *et al.*, 2014
Wheat straw pyrolysis between 350°C and 550°C	-increased in bacterial 16S rRNA gene copy -decreased fungal 18S rRNA gene copy	Hydragric anthrosol	Chen *et al.*, 2013
Compost inoculated or not with AMF as a control and:		Sterilized soil-sand-clay mixture inoculated or not with *F. oxysporum* f.sp. *lycopersici* (Fol+ or Fol-)	Akhter *et al.*, 2015
Wood biochar + compost	-Increased root colonization by AMF in Fol+ treatment in comparison to Fol-		
Green waste biochar + compost	-Decreased root colonization by AMF in Fol+ treatment in comparison to Fol-		
Empetrum nigrum L. twigs charcoal (EmpCh) forest humus charcoa (HuCh), both prepared at 450°C for 30 min	Imcreased microbial biomass carbon and number of cell in both biochar treatments in comparison to control	Scots pine and Norway spruce forest humus	Pietikäinen *et al.*, 2000

(Table III). Biochar can increase the biomass of microorganisms and their activity in soils. Kolb *et al.* (2009) observed that increased doses of charcoal increase the populations of soil microbes as measured by their respiration activity. Opposite effect of different kinds of biochar added into soil on microbial activity was observed by Chintala *et al.* (2014). Corn stover biochar (CS), switchgrass biochar (SG), and Ponderosa pine wood residue biochar (WC) decrease of microorganisms activity measures as activity of dehydrogenase and esterase. *Miscanthus* biochar addition increase abundances of genera of phosphorus and sulphur mobilizing bacteria like *Acidothermus*, *Bacillus*, *Isosphaera*, *Planctomyces*, *Bradyrhizobium*, *Rhodobium*, *Pseudolabrys* and *Rhodanobacter* (Fox *et al.*, 2016). Rice stem biochar (3% in soil) increased the abundance of living cells of *Neorhizobium huautlense* T1-17 strain in soil in a pot experiment (Wang *et al.*, 2016).

Microorganisms can also change the properties of biochar, especially when causing it to oxidize the surface of particles, which increases the oxygen content (from 7% to 24%) and decreases the carbon content (from 91% to 71%) in biochar particles (Cheng *et al.*, 2008a). These results in the formation of oxygen-containing groups, which form negatively-charged surfaces, leading to a greater cation exchange capacity (CEC) of biochar (Glaser *et al.*, 2002) and nutrient retention in soil (Liang *et al.*, 2006), in comparison to new, non-oxidized biochar. Microbial oxidation of biochar is more effective when it is conducted in the presence of organic matter, whereas in the absence of organic matter it does not produce oxidation effects as measured by CEC (Cheng *et al.*, 2006).

Biochar activity in the rhizosphere and bulk soil

Various mechanisms, such as water holding, changes in soil pH, mineral nutrient content, shifts in soil nutrient ratios, absorption or detoxification of inhibitory compounds, altering signalling dynamics between plants and their symbionts, have great impact on soil microbiota (Table IV). Biochar modifies water infiltration and soil water retention (Ajayi *et al.*, 2009; Ojeda *et al.*, 2015). Biochar affects soil pH (liming effect) (Chan *et al.*, 2007; Beesley *et al.*, 2010; van Zwieten *et al.*, 2010), has positive impact on cation exchange capacity and electrical conductivity (DeLuca *et al.*, 2009). Nutritional properties of biochar are associated with nutrients as nitrogen, phosphorus or sulphur content of biochars (DeLuca *et al.*, 2009; Atkinson *et al.*, 2010; Sohi *et al.*, 2010). Biochar addition modifies nitrogen flux in soil and reduces gaseous N emission (Rondon *et al.*,

Table IV
Summary of possible mechanisms by which microbial abundance is affected by biochar additions to soil

Mode of action	Rhizobia or other N assimilators	Other bacteria	Mycorrhizal fungi	Other fungi	References
Better soil hydration	rnk	+	rnk	+	Pietikäinen *et al.*, 2000; Thies and Rilling, 2009
Increased N availability	+ or –	rnk	rnk	rnk	Laird *et al.*, 2010; Wang *et al.*, 2013; Güereña *et al.*, 2015; Wang *et al.*, 2015,;
Improved other macronutrient availability	rnk	+	+	rnk	Laird *et al.*, 2010; Yao *et al.*, 2012; Postma *et al.*, 2010; Hammer *et al.*, 2014
Increased pH	+	+	rnk	rnk	Beesley *et al.*, 2010
Habitat formation and/or protection from grazers	rnk	+	+ or -	rnk	Ishii and Kadoya, 1994; Pietikäinen *et al.*, 2000; Gryndler *et al.*, 2006, Birk *et al.*, 2009, Rillig *et al.*, 2010; Warnock *et al.*, 2010, Jaafar, 2014
Sorption/transformation of inhibitory compounds	rnk	+	rnk	+	Kim *et al.*, 2013; Mitchell *et al.*, 2015
Sorption of signalling compounds	rnk or -	rnk	rnk	rnk	Ni *et al.*, 2011, Masiello *et al.*, 2013
Biofilm formation	+	+	rnk	rnk	Piscitelli *et al.*, 2015
Sorption of dissolved OM as an energy source for microorganisms	rnk	+	nc	rnk	Pietikäinen *et al.*, 2000; Steiner *et al.*, 2008

Note: (+) indicates that relative abundance may increase (not necessarily better growth conditions); (–) indicates that relative abundance decreases; (nc) – no change; (rnk) – reaction not known.

2006). As another positive factor biochar increases nitrification activity (nitrification potential, net nitrification, gross nitrification) in forest soils, whereas such changes are not observed in grassland soils. This effect may be caused by the absorbing properties of biochar, which can alleviate the factors inhibiting soil microbes (DeLuca *et al.*, 2006). Biochar also contributes to the reduction in N_2O emissions from soil (Rondon *et al.*, 2006), but this is not associated with the liming properties of biochar (Yanai *et al.*, 2007). In a laboratory experiment, biochar addition resulted in a decrease in low weight aromatic acids (cinnamic and coumaric acids), which are important allelochemicals (Ni *et al.*, 2011). Additionally biochar modifies nitrogenase dynamics in soil. Mia *et al.* (2014) showed that application of biochar had an influence on nodules formation and N fixation (lower rate at high biochar doses). On the other hand, biochar can decrease soil enzymes activity by blocking or absorption of substrates (Bailey *et al.*, 2011). Biochar has been also found to decrease nutrient leaching on its own (Downie *et al.*, 2007; Dünisch *et al.*, 2007), as well as after incorporation within soil (Lehmann *et al.*, 2003). Soil phosphorus seems to be more available for plants in biochar-enriched soils (Edelstein and Tonjes, 2011) due to less binding to non-soluble forms (Cui *et al.*, 2011). Animal bone char (ABC) is a suitable material as a source of phosphate for plants and as a carrier for beneficial soil bacteria, meanwhile reusing P from wastes of the food chain (Postma *et al.*, 2010). ABC, as fertilizer, should be supported by microorganisms which can solubilize phosphorus from char. These beneficial microorganisms belong, for example, to the genera: *Arthrobacter*, *Bacillus*, *Burkholderia*, *Collimonas*, *Paenibacillus*, *Pseudomonas*, *Serratia, Streptomyces* and *Aspergillus* (Postma *et al.*, 2010; Vassilev *et al.*, 2013).

Biochar particles as microbial habitats

Thanks to its physicochemical properties, biochar can be utilized as a habitat by soil microorganisms. Biochar's properties of absorbing organic compounds from the environment may help form new habitats for soil microbiota, different from those formed in *e.g.* soil humus (Pietikäinen *et al.*, 2000). Biochar as a refuge for soil microorganisms can reduce the extent of predation caused by predatory soil micro- and mesofauna like large protozoas, nematodes, mites or collembola (Ezawa *et al.*, 2002; Thies and Rillig, 2009).

Biochar changes the physical and chemical properties of the soil. One of the biochar's modes of action on rhizosphere microbes is to shift soil microbial populations into PGPRs or soil beneficial fungi (Graber *et al.*, 2010). On the other hand, biochar additions can also decrease the abundance of mycorrhizal fungi by reduced mycorrhizal symbiosis requirements due to increased nutrient and water availability, changes in soil physical or chemical properties and direct negative effect on mycorrhiza formation, including high levels of nutrients or heavy metals (Gryndler *et al.*, 2006; Birk *et al.*, 2009; Warnock *et al.*, 2010). However, Ishii and Kadoya (1994) observed higher rates of root colonization by arbuscular mycorrhizal fungi in the roots of *S. mandarin* (*C. unshiu* Marc.) trees grafted on rootstocks of trifoliate orange (*P. trifoliata* Raf.) planted in soil with biochar. Rillig *et al.* (2010) have shown that hydrochar (biochar obtained from hydropyrolysis process) produced from beet root chips had positive effects on AM fungal root colonization up to an addition rate of 20% (by volume), and demonstrated that the material could stimulate germination of spores of an AM fungus.

Upon improving soil water capacity, biochar additions can also favour some zoospore-forming pathogens like *Pythium* or *Phytophtora*, in comparison with bulk soil (Thies and Rilling, 2009).

The role of biochar in plant disease reduction

Biochar addition to soil or other growing media can reduce the susceptibility of plants to diseases. There are a few mechanisms of this action.

One of them is a modification of metabolic pathways. It has been observed that biochar is capable of mediating plant systemic resistance against diseases, for example, of greenhouse pepper and tomato, in which the severity of the disease caused by *Botrytis cinerea* was reduced in biochar-amended treatments (Mehari *et al.*, 2015). A similar effect of increased systemic resistance against *B. cinerea*, *Colletotrichum acutatum* and *Podosphaera apahanis* was also observed in strawberry plants, which was confirmed by the results of a qPCR study of defence-related gene expression (Meller Harel *et al.*, 2012). Biochar reduced the susceptibility of *Asparagus officinalis* to *Fusarium* root rot so that the extent of root infection is 50% in biochar-containing soils, in comparison with 93% in soil-only treatment. Supplementing of biochar also increased the colonization of *Asparagus* roots by AM fungi (Matsubara *et al.*, 2002). The effect of improved root colonization by AMF in biochar-enriched soils has also been observed in other trials (Elmer and Pignatello, 2011). In addition, it has also been observed that biochar can increase the resistance of plants to leaf mites, *e.g.* in pepper (Elad *et al.*, 2010).

Another mechanism of biochar protective properties is absorption and detoxification of xenobiotics, like for example phenolic compounds, noted by Wang *et al.* (2014). Besides direct absorption of allelochemicals, biochar also offers other mechanisms, which enhance soil microorganisms and plant growth and their resistance to biotic and abiotic stresses. Biochar is initially a sterile material and its compounds in residual tars may have direct toxic properties on soil pathogens. There is a number of identified biochar compounds that are known to adversely affect microbial growth and survival. These include ethylene glycol and propylene glycol, hydroxy-propionic and butyric acids, benzoic acid and o-cresol, quinones and 2 phenoxyethanol (Schnitzer *et al.*, 2007; Graber *et al.*, 2010). When used in low doses, these compounds could suppress the sensitive species of soil microbiota, thereby resulting in the proliferation of resistant communities and inducing resistance mechanisms in plants (Graber *et al.*, 2010).

Biochar influence on soil meso- and macrofauna

There has been so far only a minor number of studies on the influence of charcoal/biochar on soil fauna, but there have been a lot of studies on wildfire charcoals in forest soils, not on biochar in agricultural soils, so the results of those studies are not applicable to research on synthesized biochars (McCormack *et al.*, 2013). Dry biochar introduced into the soil causes desiccation of the soil environment. Earthworms, for example, avoided the soil freshly enriched with biochar but wetted biochar reduced this problem (Li *et al.*, 2011). Addition of biochar to the soil also has a direct influence on soil fauna. Liesch *et al.* (2010) observed that the addition of a biochar derived from poultry manure caused higher mortality and weight loss in earthworms *Eisenia fetida* than the biochar obtained from pine chips. The toxic effect of the poultry manure biochars can be explained by high Na and Mg content, which led to high salinity and subtoxic levels of some metals ions (Fe, Cu, Zn, Al, As). Weight loss in *E. fetida* was also observed by Gomez-Eyles *et al.* (2011) in treatments with hardwood-derived biochar.

On the other hand, biochar reduces the adverse effects of organic pollutants on soil fauna. For example, the reduction in PCB (polychlorinated biphenyl) in the tissues of *E. fetida* earthworm was from 52% (2.8% of biochar) up to 88% (11.1% of biochar) (Denyes *et al.*, 2012). Biochar also decreased the amounts of 4-ring and heavier polycyclic aromatic hydrocarbons (PAH) and heavy metal ions in earthworm tissues, but increased the amount of 2-ring PAH (Gomez-Eyles *et al.*, 2011). Biochar addition positively influenced the growth and reproduction of *E. fetida* used for vermicomposting of the mixture of sewage sludge and wheat straw (Malińska *et al.*, 2016). Preference for biochar in soil by *E. fetida* was also evident in another study, in which another earthworm species, *Aporectodea caliginosa*, was susceptible to biochar amendments (Hale *et al.*, 2013). Combining together biochars and earthworms in different types of soils increases the biomass (total, shoot and root), yield and grain number, and weight of rice plants grown in three different types of soils, and the effects are clearly visible on both nutrient-rich and poor soils, but mineral fertilization decreases the benefits of using biochar and earthworms (Noguera *et al.*, 2010). Other soil macroorganisms, for example collembolas also respond positively to biochar-amended soil (Hale *et al.*, 2013; Marks *et al.*, 2014a; 2014b).

Biochar as an ingredient for fertilizers and biofertilizers

Biochar, thanks to its physico-chemical properties is promising carrier for beneficial microorganisms and can replace current carriers like peat, lignite, vermiculite or perlite (Saranya *et al.*, 2012; Hale *et al.*, 2015; Głodowska *et al.*, 2016) (Table V). Of course not all types of biochar are applicable for this purposes (Hale *et al.*, 2015). Conditions of feedstock material pyrolysis, additives and biochar particles surface treatment with chemical reagents or dissolving agents also has big influence on survival rate of bacterial inoculum (Vanek *et al.*, 2016). The improvements of biochar based biofertilizers are focused on shelf life and inoculum potential of different strains of microorganisms (Sun *et al.*, 2016). Another trials are focused on selection of the most efficient strains of microorganisms for the best utilization of nutrients contained in biochar (Postma *et al.*, 2010; Zwetsloot *et al.*, 2016). These works will allow to develop new microbiologically enriched biochar preparations for wide range of crops.

Biochars of different origins are also tested as a support material for slow release mineral fertilizers (Steiner *et al.*, 2009; González *et al.*, 2015) or as a fertilizer itself. This is conducted with another properties of biochar, especially cation exchange capacity (an important parameter in retaining inorganic nutrients in soil) and water holding capacity (Lee *et al.*, 2013; Glaser *et al.*, 2015). Biochar made from *Miscanthus* was tested as a slow release silicon fertilizer (Houben *et al.*, 2014) whereas animal bone biochar seems to be good phosphorus fertilizer (Vassilev *et al.*, 2013; Siebers *et al.*, 2014).

Biochar alone is widely offered as a soil conditioner but there are only some biochar based bioorganic fertilizers on the market containing except biochar also beneficial microorganisms and another ingredients. For example SEEK Organic BamBoo Power BBP No. 2 is bio-organic fertilizer, which consists bamboo biochar, bamboo vinegar, humic acids, amino acids, beneficial soil organisms (not specified in product description) ($20 \times 10^6 \cdot g^{-1}$) and other amendments. This granular preparation is recommended for organic horticulture, including vegetables, fruits and flowers, especially for berries, such as blueberry, strawberry, raspberry, grapes, *etc.* (www.seekfertilizer.com). Another biopreparation enriched in biochar are available on local and global markets like: Biochar Organic Bio Fertilizer Bacteria Fertilizer made by Hebei Woxin Bio-Technology Co., Ltd but they are not characterized and described as good as biochar based fertilizer of SEEK company.

Conclusions

Biochar, when incorporated into soil, has a great impact on dynamics and modification of rhizosphere processes. It has direct effect on soil pH, nutrients content and moisture of treated soils. On the one hand biochar increase content of some nutrients like K or P in soil, but contrarily absorbs nitrogen ions and causes possible deficiencies of this nutrient for soil microorganisms and plants. Effects of biochar applications will include not only changes to the chemical and physical soil properties, but also its impact on the composition of the soil biological community and

Table V
Selected utilization of biochar as a microorganism carrier or ingredient of fertilizers

Type of biochar/raw material	Utilization	Effects	Reference
Hardwood or softwood biochar fast pyrolyzed at 700°C	Carrier for bacteria *Pseudomonas libanensis* for seed coating	Life cells of bacteria viable more than twenty weeks	Głodowska *et al.*, 2016
Softwood slow pyrolyzed at 450°C		Life cells of bacteria viable not more than two weeks	
Pinewood biochar slow pyrolyzed at 600°C, supplemented with LB broth	Carrier for bacteria *Pseudomonas putida* UW4	Life cells of bacteria detectable up to five months	Sun *et al.*, 2016
Miscanthus, draff pyrolyzed at 650°C mixed with mineral fertilizer or organic residues	Ingredient of fertilizer	Increased yield according to mineral fertilizer	Glaser *et al.*, 2015
Miscanthus straw pyrolyzed at 600°C	Slow release silicon fertilizer	Increased Si amount in com parison to bulk soil	Houben *et al.*, 2014
Pig bone char pyrolized 1 h at 850°C	Bacteria carrier and slow release phosphorus fertilizer	Lifespan of majority of bacterial strains longer than 100 days	Postma *et al.*, 2010

plant-soil-microbial interactions. Understanding these complex interactions is crucial for developing on-farm soil management and conservation practices to improve soil properties and agricultural productivity in environmentally sustainable ways.

Adsorbing properties of biochars are applicable in contaminated soils improvement, when toxic for microorganisms and plants compounds like heavy metal ions or organic xenobiotics are inactivated on biochar particles. On the other hand biochar itself can be source of compounds which negatively affects soil microorganisms and plant roots. It is especially related to poly aromatic hydrocarbons (PAH) and heavy metals ions.

The wide spectrum of possible consequences of biochar use in soil is still unknown and requires further scientific inquiry, especially in natural landscapes, to avoid the negative consequences of these works.

The work has been supported by a grant from the EU Regional Development Fund through the Polish Innovation Economy Operational Programme, contract No. UDA-POIG.01.03.01-10-109/08-00.

Literature

Ajayi A.E., P. Oguntunde, A. Joseph, and M.dS. Dias Júnior. 2009. Numerical analysis of the impact of charcoal production on soil hydrological behaviour, runoff response and erosion susceptibility. *Rev. Bras. Cienc. Solo*. 33: 137–146.

Akhtar S.S., G. Li, M.N. Andersen and F. Liu. 2014. Biochar enhances yield and quality of tomato under reduced irrigation. *Agric. Water Manag*. 138: 37–44.

Akhter A., K. Hage-Ahmed, G. Soja and S. Steinkellner. 2015. Compost and biochar alter mycorrhization, tomato root exudation, and development of *Fusarium oxysporum* f. sp. *lycopersici*. *Frontiers in Plant Science* 6(529): 1–13.

Akiyama K., K.-I. Matsuzaki and H. Hayashi. 2005. Plant sesquiterpenes induce hyphal branching in arbuscular mycorrhizal fungi. *Nature* 435: 824–827.

Ameloot N., S. de Neve, K. Jegajeevagan, G. Yildiz, D. Buchan, Y.N. Funkuin, W. Prins, L. Bouckaert and S. Sleutel. 2013. Short-term CO^2 and N_2O emissions and microbial properties of biochar amended sandy loam soils. *Soil Biology and Biochemistry*. 57: 401–410.

Ameloot N., S. Sleutel, K.C. Das, J. Kanagaratnam and S. de Neve. 2015. Biochar amendment to soils with contrasting organic matter level: effects on N mineralization and biological soil properties. *GCB Bioenergy* 7: 135–144.

Anderson C.R., L.M. Condron, T.J. Clough, M. Fiers, A. Stewart, R.A. Hill and R.R. Sherlock. 2011. Biochar induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen and phosphorus. *Pedobiologia* 54: 309–320.

Atkinson C., J. Fitzgerald and N. Hipps. 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant Soil.* 337: 1–18.

Atucha A. and G. Litus. 2015. Effect of biochar amendments on peach replant disease. *HortSci.* 50: 863–868.

Bailey V.L., S.J. Fansler, J.L. Smith and H. Bolton Jr. 2011. Reconciling apparent variability in effects of biochar amendment on soil enzyme activities by assay optimization. *Soil Biol. Biochem*. 43: 296–301.

Beesley L., E. Moreno-Jiménez and J.L. Gomez-Eyles. 2010. Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. *Environ. Pollut*. 158: 2282–2287.

Birk J., C. Steiner, W. Teixiera, W. Zech and B. Glaser. 2009. Microbial response to charcoal amendments and fertilization of a highly weathered tropical soil. pp. 309–324. In: Woods W., W. Teixeira, J. Lehmann, C. Steiner, A. Winkler Prins and L. Rebellato (eds). *Amazonian dark earths: Wim Sombroek's vision*. Springer, Netherlands.

Blackwell P., E. Krull, G. Butler, A. Herbert and Z. Solaiman. 2010. Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: an agronomic and economic perspective. *Aust. J. Soil. Res*. 48: 531–545.

Bridgwater A. and G.V. Peacocke. 2000. Fast pyrolysis processes for biomass. *Renew. Sust. Energ. Rev*. 4: 1–73.

Cao X., L. Ma, B. Gao and W. Harris. 2009. Dairy-Manure derived biochar effectively sorbs lead and atrazine. *Environ. Sci. Technol.* 43: 3285–3291.

Carter S., S. Shackley, S. Sohi, T.B. Suy and S. Haefele. 2013. The impact of biochar application on soil properties and plant growth of pot grown lettuce (*Lactuca sativa*) and cabbage (*Brassica chinensis*). *Agronomy*. 3: 404–418.

Chan K.Y., L. van Zwieten, I. Meszaros, A. Downie and S. Joseph. 2007. Agronomic values of greenwaste biochar as a soil amendment. *Aust. J. Soil Res.* 45: 629–634.

Chen J., X. Liu, J. Zheng, B. Zhang, H. Lu, Z. Chi, G. Pan, L. Li, J. Zheng, J. Zhang and others. 2013. Biochar soil amendment increased bacterial but decreased fungal gene abundance with shifts in community structure in a slightly acid rice paddy from Southwest China. *Appl. Soil Ecol.* 71: 33–44.

Cheng C.-H., J. Lehmann, J.E. Thies, S.D. Burton and M.H. Engelhard. 2006. Oxidation of black carbon by biotic and abiotic processes. *Org. Geochem*. 37: 1477–1488.

Cheng C.-H., J. Lehmann and M.H. Engelhard. 2008a. Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence. *Geochim Cosmochim Ac.* 72: 1598–1610.

Cheng C.-H., J. Lehmann, J.E. Thies and S.D. Burton. 2008b. Stability of black carbon in soils across a climatic gradient. *J. Geophys. Res-Biogeo*. 113: G02027(1–10).

Chintala R., T.E. Schumacher, S. Kumar, D.D. Malo, J.A. Rice, B. Bleakley, G. Chilom, D.E. Clay, J.L. Julson, S.K. Papiernik and others. 2014. Molecular characterization of biochars and their influence on microbiological properties of soil. *J. Hazard Mater.* 279:244–256.

Cui H.-J., M. Wang, M.-L. Fu and E. Ci. 2011. Enhancing phosphorus availability in phosphorus-fertilized zones by reducing phosphate adsorbed on ferrihydrite using rice straw-derived biochar. *J. Soil Sediment*. 11: 1135–1141.

DeLuca T.H., M.D. MacKenzie, M.J. Gundale and W.E. Holben. 2006. Wildfire-produced charcoal directly influences nitrogen cycling in ponderosa pine forests. *Soil Sci. Soc. Am. J.* 70: 448–453.

DeLuca T.H., M.D. MacKenzie and M.J. Gundale. 2009. Biochar effects on soil nutrient transformations, pp. 251–270. In: Lehmann J. and S. Joseph (eds). *Biochar for environmental management: Science and Technology*. Earthscan, London.

Denyes M.J., V.S. Langlois, A. Rutter and B.A. Zeeb. 2012. The use of biochar to reduce soil PCB bioavailability to *Cucurbita pepo* and *Eisenia fetida*. *Sci. Total Environ*. 437: 76–82.

Dong D., M. Yang, C. Wang, H. Wang, Y. Li, J. Luo and W. Wu. 2013. Responses of methane emissions and rice yield to applications of biochar and straw in a paddy field. *J. Soils Sediments*. 13: 1450–1460.

Downie A., L. van Zwieten, K.Y. Chan, W. Doughtery and S. Joseph. 2007. Nutrient retention characteristics of agrichar and the agronomic implications. International Agrichar Initiative Conference, April 2007, Terrigal, NSW, Australia.

Dünisch O., V. Lima, G. Seehann, J. Donath, V. Montóia and T. Schwarz. 2007. Retention properties of wood residues and their potential for soil amelioration. *Wood Sci. Technol*. 41: 169–189.

Edelstein D.M. and D.J. Tonjes. 2011. Modeling an improvement in phosphorus utilization in tropical agriculture. *J. Sustain. Agr*. 36: 18–35.

Elad Y., D.R. David, Y.M. Harel, M. Borenshtein, H.B. Kalifa, A. Silber and E.R. Graber. 2010. Induction of systemic resistance in plants by biochar, a soil-applied carbon sequestering agent. *Phytopathology* 100: 913–921.

Elmer W.H. and J.J. Pignatello. 2011. Effect of biochar amendments on mycorrhizal associations and *Fusarium* crown and root rot of *Asparagus* in replant soils. *Plant Dis*. 95: 960–966.

Enders A., K. Hanley, T. Whitman, S. Joseph and J. Lehmann. 2012. Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresource Technol*. 114: 644–653.

Eyles A., S.A. Bound, G. Oliver, R. Corkrey, M. Hardie, S. Green and D.C. Close. 2015. Impact of biochar amendment on the growth, physiology and fruit of a young commercial apple orchard. *Trees* 29: 1817–1826.

Ezawa T., K. Yamamoto and S. Yoshida. 2002. Enhancement of the effectiveness of indigenous arbuscular mycorrhizal fungi by inorganic soil amendments. *Soil Sci. Plant Nutr*. 48: 897–900.

Farrell M., T.K. Kuhn, L.M. Macdonald, T.M. Maddern, D.V. Murphy, P.A. Hall, B.P. Singh, K. Baumann, E.S. Krull and J.A. Baldock. 2013. Microbial utilisation of biochar-derived carbon. *Sci. Total Environ*. 465: 288–297.

Fox A., J. Gahan, I. Ikoyi, W. Kwapinski, O. O'Sullivan, P.D. Cotter and A. Schmalenberger. 2016. *Miscanthus* biochar promotes growth of spring barley and shifts bacterial community structures including phosphorus and sulfur mobilizing bacteria. *Pedobiologia* 59: 195–202.

Free H., C. McGill, J. Rowarth and M. Hedley. 2010. The effect of biochars on maize (*Zea mays*) germination. *New Zeal. J. Agr. Res*. 53: 1–4.

George C., J. Kohler and M.C. Rillig. 2016. Biochars reduce infection rates of the root-lesion nematode *Pratylenchus penetrans* and associated biomass loss in carrot. *Soil Biol. Biochem*. 95: 11–18.

Gilroy S. and D.L. Jones. 2000. Through form to function: root hair development and nutrient uptake. *Trends Plant Sci*. 5: 56–60.

Glaser B., J. Lehmann and W. Zech. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. *Biol. Fert. Soils*. 35: 219–230.

Glaser B., K. Wiedner, S. Seelig, H.-P. Schmidt and H. Gerber. 2015. Biochar organic fertilizers from natural resources as substitute for mineral fertilizers. *Agrono. Sustain Dev*. 35: 667–678.

Głodowska M., B. Husk, T. Schwinghamer and D. Smith. 2016. Biochar is a growth-promoting alternative to peat moss for the inoculation of corn with a pseudomonad. *Agrono. Sustain Dev*. 36: 1–10.

Gomez J.D., K. Denef, C.E. Stewart, J. Zheng and M.F. Cotrufo. 2014. Biochar addition rate influences soil microbial abundance and activity in temperate soils. *Eur. J. Soil Sci*. 65: 28–39.

Gomez-Eyles J.L., T. Sizmur, C.D. Collins and M.E. Hodson. 2011. Effects of biochar and the earthworm *Eisenia fetida* on the bioavailability of polycyclic aromatic hydrocarbons and potentially toxic elements. *Environ. Pollut*. 159: 616–622.

González M.E., M. Cea, J. Medina, A. González, M.C. Diez, P. Cartes, C. Monreal and R. Navia. 2015. Evaluation of biodegradable polymers as encapsulating agents for the development of a urea controlled-release fertilizer using biochar as support material. *Sci. Total Environ*. 505: 446–453.

Graber E., Y. Meller Harel, M. Kolton, E. Cytryn, A. Silber, D. Rav David, L. Tsechansky, M. Borenshtein and Y. Elad. 2010. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant Soil*. 337: 481–496.

Gryndler M., J. Larsen, H. Hršelová, V. Řezáčová, H. Gryndlerová and J. Kubát. 2006. Organic and mineral fertilization, respectively, increase and decrease the development of external mycelium of arbuscular mycorrhizal fungi in a long-term field experiment. *Mycorrhiza*. 16: 159–166.

Güereña D.T., J. Lehmann, J.E. Thies, A. Enders, N. Karanja and H. Neufeldt. 2015. Partitioning the contributions of biochar properties to enhanced biological nitrogen fixation in common bean (*Phaseolus vulgaris*). *Biol. Fert. Soils* 51: 479–491.

Gundale M.J. and T.H. DeLuca. 2006. Temperature and source material influence ecological attributes of *Ponderosa pine* and *Douglas-fir charcoal*. *Forest Ecol. Manag*. 231: 86–93.

Hale S.E., J. Jensen, L. Jakob, P. Oleszczuk, T. Hartnik, T. Henriksen, G. Okkenhaug, V. Martinsen and G. Cornelissen. 2013. Short-term effect of the soil amendments activated carbon, biochar, and ferric oxyhydroxide on bacteria and invertebrates. *Environ. Sci. Technol*. 47: 8674–8683.

Hale L., M. Luth and D. Crowley. 2015. Biochar characteristics relate to its utility as an alternative soil inoculum carrier to peat and vermiculite. *Soil Biol. Biochem*. 81: 228–235.

Hammer E.C., Z. Balogh-Brunstad, I. Jakobsen, P.A. Olsson, S.L.S. Stipp and M.C. Rillig. 2014. A mycorrhizal fungus grows on biochar and captures phosphorus from its surfaces. *Soil Biol. Biochem*. 77: 252–260.

Hiltner L. 1904. New experiences and problems in the field of soil bacteriology with special consideration of the foundations and fallow (in German). *Arb DLG Berlin*. 98: 59–78.

Hosseini Bai S., C.-Y. Xu, Z. Xu, T. Blumfield, H. Zhao, H. Wallace, F. Reverchon and L. van Zwieten. 2015. Soil and foliar nutrient and nitrogen isotope composition ($\delta^{15}N$) at 5 years after poultry litter and green waste biochar amendment in a macadamia orchard. *Environ. Sci. Pollut. Res*. 22: 3803–3809.

Houben D., P. Sonnet and J.-T. Cornelis. 2014. Biochar from *Miscanthus*: a potential silicon fertilizer. *Plant Soil*. 374: 871–882.

Ishii T. and K. Kadoya. 1994. Effects of charcoal as a soil conditioner on citrus growth and vesicular-arbuscular mycorrhizal development. *J. Jpn. Soc. Hortic. Sci*. 63: 529–535.

Jaafar N.M. 2014. Biochar as a habitat for arbuscular mycorrhizal fungi, pp. 297–311. In: Solaiman M.Z., K.L. Abbott and A. Varma (eds.), *Mycorrhizal fungi: use in sustainable agriculture and land restoration*. Springer Berlin Heidelberg, Berlin, Heidelberg.

Jeffery S., F.G.A. Verheijen, M. van der Velde and A.C. Bastos. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agr. Ecosyst. Environ*. 144: 175–187.

Jha P., A.K. Biswas, B.L. Lakaria and A.S. Rao. 2010. Biochar in agriculture-prospects and related implications. *Curr. Sci. India* 99: 1218–1225.

Jiang J., R. Xu, T. Jiang and Z. Li. 2012. Immobilization of Cu(II), Pb(II) and Cd(II) by the addition of rice straw derived biochar to a simulated polluted Ultisol. *J. Hazard Mater*. 229–230: 145–150.

Jones D.L., J. Rousk, G. Edwards-Jones, T.H. DeLuca and D.V. Murphy. 2012. Biochar-mediated changes in soil quality and plant growth in a three year field trial. *Soil Biol. Biochem*. 45: 113–124.

Joseph S.D., M. Camps-Arbestain, Y. Lin, P. Munroe, C.H. Chia, J. Hook, L. van Zwieten, S. Kimber, A. Cowie, B.P. Singh and others. 2010. An investigation into the reactions of biochar in soil. *Aust. J. Soil Res*. 48: 501–515.

Kim S.-K., D.-H. Park, S.H. Song, Y.-J.Wee and G.-T. Jeong. 2013. Effect of fermentation inhibitors in the presence and absence of activated charcoal on the growth of *Saccharomyces cerevisiae*. *Bioproc. Biosyst. Eng*. 36: 659–666.

Kobayashi D.Y. and J.A. Crouch. 2009. Bacterial/fungal interactions: from pathogens to mutualistic endosymbionts. *Ann. Rev. Phytopathol.* 47: 63–82.

Kolb S.E., K.J. Fermanich and M.E. Dornbush. 2009. Effect of charcoal quantity on microbial biomass and activity in temperate soils. *Soil Sci. Soc. Am. J.* 73: 1173–1181.

Kothari S.K., H. Marschner and E. George. 1990. Effect of VA mycorrhizal fungi and rhizosphere microorganisms on root and shoot morphology, growth and water relations in maize. *New Phytol.* 116: 303–311.

Laird D., P. Fleming, B. Wang, R. Horton and D. Karlen. 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma* 158: 436–442.

Lee J.W., B. Hawkins, X. Li and D.M. Day. 2013. Biochar fertilizer for soil amendment and carbon sequestration, pp. 57–68. In: Lee W.J. (eds). *Advanced Biofuels and Bioproducts*. Springer New York, New York, NY.

Lehmann J., J. Pereira da Silva Jr., C. Steiner, T. Nehls, W. Zech and B. Glaser. 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant Soil.* 249: 343–357.

Lehmann J., M.C. Rillig, J. Thies, C.A. Masiello, W.C. Hockaday and D. Crowley. 2011 Biochar effects on soil biota – a review. *Soil Biol. Biochem*. 43:1812–1836.

Li D., W.C. Hockaday, C.A. Masiello and P.J.J. Alvarez. 2011. Earthworm avoidance of biochar can be mitigated by wetting. *Soil Biol. Biochem*. 43: 1732–1737.

Liang B., J. Lehmann, D. Solomon, J. Kinyangi, J. Grossman, B. O'Neill, J.O. Skjemstad, J. Thies, F.J. Luizão, J. Petersen and others. 2006. Black carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Am. J.* 70: 1719–1730.

Liesch A., S. Weyers, J. Gaskin and K. Das. 2010. Impact of two different biochars on earthworm growth and survival. *Ann. Environ. Sci*. 4: 1–9.

Malińska K., M. Zabochnicka-Świątek, R. Cáceres and O. Marfà. 2016. The effect of precomposted sewage sludge mixture amended with biochar on the growth and reproduction of *Eisenia fetida* during laboratory vermicomposting. *Ecol. Eng.* 90: 35–41.

Marks E.N., J. Alcañiz and X. Domene. 2014a. Unintended effects of biochars on short-term plant growth in a calcareous soil. *Plant Soil*. 385: 87–105.

Marks E.A.N., S. Mattana, J.M. Alcañiz and X. Domene. 2014b. Biochars provoke diverse soil mesofauna reproductive responses in laboratory bioassays. *Eur. J. Soil Biol*. 60: 104–111.

Marschner H. 1995. Mineral nutrition of higher plants, 2nd ed. Academic Press, London.

Marschner P. 2012. Rhizosphere biology, pp. 369–388. In: Marschner P. (ed). *Marschner's mineral nutrition of higher plants*, 3rd ed. Academic Press, San Diego.

Martin P., A. Glatzle, W. Kolb, H. Omay and W. Schmidt. 1989. N_2-fixing bacteria in the rhizosphere: quantification and hormonal effects on root development. *Z Pflanzenernähr Bodenkd.* 152: 237–245.

Masiello C.A., Y. Chen, X. Gao, S. Liu, H.-Y. Cheng, M.R. Bennett, J.A. Rudgers, D.S. Wagner, K. Zygourakis and J.J. Silberg. 2013. Biochar and microbial signaling: production conditions determine effects on microbial communication. *Environ. Sci. Technol.* 47: 11496–11503.

Matsubara Y., N. Hasegawa and H. Fukui. 2002. Incidence of *Fusarium* root rot in *Asparagus* seedlings infected with arbuscular mycorrhizal fungus as affected by several soil amendments. *J. Jpn. Soc. Hortic Sci*. 71: 370–374.

McCormack S.A., N. Ostle, R.D. Bardgett, D.W. Hopkins and A.J. Vanbergen. 2013. Biochar in bioenergy cropping systems: impacts on soil faunal communities and linked ecosystem processes. *GCB Bioenergy*. 5: 81–95.

Mehari Z.H., Y. Elad, D. Rav-David, E.R. Graber and Y. Meller Harel. 2015. Induced systemic resistance in tomato (*Solanum lycopersicum*) against *Botrytis cinerea* by biochar amendment involves jasmonic acid signaling. *Plant Soil* 395: 31–44.

Meller Harel Y., Y. Elad, D. Rav-David, M. Borenstein, R. Shulchani, B. Lew and E. Graber. 2012. Biochar mediates systemic response of strawberry to foliar fungal pathogens. *Plant Soil* 357: 245–257.

Mia S., J.W. van Groenigen, T.F.J. van de Voorde, N.J. Oram, T.M. Bezemer, L. Mommer and S. Jeffery. 2014. Biochar application rate affects biological nitrogen fixation in red clover conditional on potassium availability. *Agr. Ecosyst. Envir*. 191: 83–91.

Mitchell S.M., M. Subbiah, J.L. Ullman, C. Frear and D.R. Call. 2015. Evaluation of 27 different biochars for potential sequestration of antibiotic residues in food animal production environments. *J. Environ. Chem. Eng.* 3: 162–169.

Neuman G. and V. Römheld. 2012. Rhizosphere chemistry in relation to plant nutrition, pp. 347–368. In: Marschner P. (ed). *Marschner's mineral nutrition of higher plants*, 3rd ed. Academic Press, San Diego.

Ni J., J.J. Pignatello and B. Xing. 2011. Adsorption of aromatic carboxylate ions to black carbon (biochar) is accompanied by proton exchange with water. *Environ. Sci. Technol*. 45: 9240–9248.

Noguera D., M. Rondón, K.-R. Laossi, V. Hoyos, P. Lavelle, M.H. Cruz de Carvalho and S. Barot. 2010. Contrasted effect of biochar and earthworms on rice growth and resource allocation in different soils. *Soil Biol. Biochem*. 42: 1017–1027.

Ojeda G., S. Mattana, A. Àvila, J.M. Alcañiz, M. Volkmann and J. Bachmann. 2015. Are soil-water functions affected by biochar application? *Geoderma.* 249–250: 1–11.

Parvage M., B. Ulén, J. Eriksson, J. Strock and H. Kirchmann. 2013. Phosphorus availability in soils amended with wheat residue char. *Biol. Fert. Soils*. 49:245–250.

Pietikäinen J., O. Kiikkilä and H. Fritze. 2000. Charcoal as a habitat for microbes and its effect on the microbial community of the underlying humus. *Oikos*. 89: 231–242.

Piscitelli L., A. Shaaban, D. Mondelli, G.N. Mezzapesa, T.M. Miano and S. Dumontet. 2015. Use of olive mill pomace biochar as a support for soil microbial communities in an Italian sandy soil. *Soil Horizons.* 56: 1–7.

Postma J., E.H. Nijhuis and E. Someus. 2010. Selection of phosphorus solubilizing bacteria with biocontrol potential for growth in phosphorus rich animal bone charcoal. *Appl. Soil Ecol*. 46: 464–469.

Prendergast-Miller M.T., M. Duvall and S.P. Sohi. 2014. Biochar-root interactions are mediated by biochar nutrient content and impacts on soil nutrient availability. *Eur. J. Soil Sci*. 65: 173–185.

Rillig M.C., M. Wagner, M. Salem, P.M. Antunes, C. George, H.-G. Ramke, M.-M. Titirici and M. Antonietti. 2010. Material derived from hydrothermal carbonization: effects on plant growth and arbuscular mycorrhiza. *Appl. Soil Ecol*. 45: 238–242.

Rondon M.A., D. Molina, M. Hurtado, J. Ramirez, J. Lehmann, J. Major and E. Amezquita. 2006. Enhancing the productivity of crops and grasses while reducing greenhouse gas emissions through bio-char amendments to unfertile tropical soils, pp. 9–15. In: Eighteenth World Congress of Soil Science, Philadelphia, Pennsylvania, USA.

Rutigliano F.A., M. Romano, R. Marzaioli, I. Baglivo, S. Baronti, F. Miglietta and S. Castaldi. 2014. Effect of biochar addition on soil microbial community in a wheat crop. *Eur. J. Soil Biol*. 60: 9–15.

Saranya K., P.S. Krishnan, K. Kumutha and J. French. 2011. Potential for biochar as an alternate carrier to lignite for the preparation of biofertilizers in India. *Int. J. Agric. Environ. Biotech.* 4: 167–172.

Schnitzer M.I., C.M. Monreal and G. Jandl. 2007. The conversion of chicken manure to bio-oil by fast pyrolysis. III. Analyses of chicken manure, bio-oils and char by Py-FIMS and Py-FDMS. *J. Environ. Sci. Heal B*. 43: 81–95.

Siebers N., F. Godlinski and P. Leinweber. 2014. Bone char as phosphorus fertilizer involved in cadmium immobilization in lettuce, wheat, and potato cropping. *J. Plant Nutr. Soil Sci.* 177: 75–83.

Sohi S.P., E. Krull, E. Lopez-Capel and R. Bol. 2010. A review of biochar and its use and function in soil. *Adv. Agron*. 105: 47–82.

Spokas K., J. Baker and D. Reicosky. 2010. Ethylene: potential key for biochar amendment impacts. *Plant Soil* 333: 443–452.

Spokas K.A., K.B. Cantrell, J.M. Novak, D.W. Archerk, J.A. Ippolito, H.P. Collins, A.A. Boateng, I.M. Lima, M.C. Lamb, A.J. McAloon and others. 2012a. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. *J. Environ. Qual.* 41: 973–989.

Spokas K., J. Novak and R. Venterea. 2012b. Biochar's role as an alternative N-fertilizer: ammonia capture. *Plant Soil*. 350: 35–42.

Steiner C., K.C. Das, M. Garcia, B. Förster and W. Zech. 2008. Charcoal and smoke extract stimulate the soil microbial community in a highly weathered xanthic Ferralsol. *Pedobiologia* 51: 359–366.

Steiner C., M. Garcia and W. Zech. 2009. Effects of charcoal as slow release nutrient carrier on N-P-K dynamics and soil microbial population: pot experiments with Ferralsol substrate, pp. 325–338. In: Woods W., W. Teixeira, J. Lehmann, C. Steiner, A. WinklerPrins and L. Rebellato (eds.). Amazonian Dark Earths: Wim Sombroek's Vision. Springer, Netherlands.

Street T.A., R.B. Doyle and D.C. Close. 2014. Biochar media addition impacts apple rootstock growth and nutrition. *Hort Sci.* 49: 1188–1193.

Sun D., L. Hale and D. Crowley. 2016. Nutrient supplementation of pinewood biochar for use as a bacterial inoculum carrier. *Biol. Fertil Soils* 52: 515–522.

Thies J.E. and M. Rillig. 2009. Characteristics of biochar: biological properties, pp. 85–105. In: Lehmann J. and S. Joseph (eds). *Biochar for environmental management: science and technology*. Earthscan, London.

Van Zwieten L., S. Kimber, S. Morris, K.Y Chan., A. Downie, J. Rust, S. Joseph and A. Cowie. 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant Soil* 327: 235–246.

Vanek S.J., J. Thies, B. Wang, K. Hanley and J. Lehmann. 2016. Pore-size and water activity effects on survival of *Rhizobium tropici* in biochar inoculant carriers. *J. Microb. Biochem. Technol*. 8: 296–306.

Vassilev N., E. Martos, G. Mendes, V. Martos and M. Vassileva. 2013. Biochar of animal origin: a sustainable solution to the global problem of high-grade rock phosphate scarcity? *J. Sci. Food Agr*. 93: 1799–1804.

Ventura M., C. Zhang, E. Baldi, F. Fornasier, G. Sorrenti, P. Panzacchi and G. Tonon. 2014. Effect of biochar addition on soil respiration partitioning and root dynamics in an apple orchard. *Eur. J. Soil Sci*. 65: 186–195.

Wang Q., L. Chen, L.-Y. He and X.-F. Sheng. 2016. Increased biomass and reduced heavy metal accumulation of edible tissues of vegetable crops in the presence of plant growth-promoting *Neorhizobium huautlense* T1-17 and biochar. *Agr. Ecosyst. Environ*. 228: 9–18.

Wang Y., F. Pan, G. Wang, G. Zhang, Y. Wang, X. Chen and Z. Mao. 2014. Effects of biochar on photosynthesis and antioxidative system of *Malus hupehensis* Rehd. seedlings under replant conditions. *Sci. Hortic.* 175: 9–15.

Wang Z.Y., H. Zheng, Y. Luo, X. Deng, S. Herbert and B.S. Xing. 2013. Characterization and influence of biochars on nitrous oxide emission from agricultural soil. *Environ. Pollut*. 174: 289–296.

Wang Z., H. Zong, H. Zheng, G. Liu, L. Chen and B. Xing. 2015. Reduced nitrification and abundance of ammonia-oxidizing bacteria in acidic soil amended with biochar. *Chemosphere* 138: 576–583.

Warnock D.D., D.L. Mummey, B. McBride, J. Major, J. Lehmann and M.C. Rillig. 2010. Influences of non-herbaceous biochar on arbuscular mycorrhizal fungal abundances in roots and soils: results from growth-chamber and field experiments. *Appl. Soil Ecol*. 46: 450–456.

William K. and R.A. Qureshi. 2015. Evaluation of biochar as fertilizer for the growth of some seasonal vegetables. *J. Bioresource Manage* 2(1): 41–46.

Yamato M., Y. Okimori, I.F. Wibowo, S. Anshori and M. Ogawa. 2006. Effects of the application of charred bark of *Acacia mangium* on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia. *Soil Sci. Plant Nutr*. 52: 489–495.

Yanai Y., K. Toyota and M. Okazaki. 2007. Effects of charcoal addition on N_2O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. *Soil Sci. Plant Nutr*. 53: 181–188.

Yao Y., B. Gao, M. Zhang, M. Inyang and A.R., Zimmerman. 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere* 89: 1467–1471.

Yilangai M.R., A.S. Manu, W. Pineau, S.S. Mailumo and K.I. Okeke-Agulu. 2014. The effect of biochar and crop veil on growth and yield of tomato (*Lycopersicum esculentus* Mill) in Jos, North central Nigeria. *Curr. Agri. Res*. 2(1): 37–42.

Zwetsloot M.J., J. Lehmann, T. Bauerle, S. Vanek, R. Hestrin and A. Nigussie. 2016. Phosphorus availability from bone char in a P-fixing soil influenced by root-mycorrhizae-biochar interactions. *Plant Soil* 1–11.