ACTA SCIENTIARUM POLONORUM Acta Sci. Pol. Hortorum Cultus, 21(5) 2022, 61–69

https://czasopisma.up.lublin.pl/index.php/asphc ISSN 1644-0692 e-ISSN 2545-1405 https://doi.org/10.24326/asphc.2022.5.6

ORIGINAL PAPER

Accepted: 2.04.2022

INFLUENCE OF BIOCHAR ON THE VEGETATIVE AND GENERATIVE GROWTH OF 'Meredith' PEACH TREES

Mateusz Frąc✉, Lidia Sas-Paszt, Mirosław Sitarek

The National Institute of Horticulture, 96-100 Skierniewice, Konstytucji 3 Maja 1/3, Poland

ABSTRACT

Many studies have confirmed positive effect of biochar as a soil conditioner that can increase in a short time the amount of organic matter (SO) and the reserves of organic carbon (OC) in the soil. The use of biochar also contributes to eliminating the effects of soil fatigue, especially in perennial fruit crops. In our study, biochar was applied in the spring of 2014 in the cultivation of one-year-old peach trees of the cultivar Meredith. Biochar, an organic fertilizer, and microbiologically enriched compost were applied to the arable soil layer. In the experiment, three combinations with biochar were used: (1) biochar at 1.6 kg/tree, (2) biochar at 1.6 kg/tree + microbiologically enriched compost at 0.3 kg/tree, (3) biochar at 1.6 kg/tree + an organic fertilizer at 0.2 kg/tree. In the first growing season, no positive changes were found after the use of biochar. The highest number and yield of fruits in 2015 were obtained from the trees that were treated with microbiologically enriched compost, and the lowest in the combination where biochar + organic fertilizer were used to treat the peach trees. In 2016, the largest number of fruits and their greatest weight were recorded for the trees treated with biochar + organic fertilizer, whereas the control trees produced the lowest yields. The use of biochar with microorganisms and biochar with organic fertilizer improved the vegetative growth of trees compared to the growth of control trees.

Key words: biochar, peach, organic matter, organic fertilizer, microorganism

INTRODUCTION

Biochar is a product made from organic matter in the process of pyrolysis, without oxygen, in a high temperature range (250–1000°C). The organic matter subjected to carbonification includes wood chips, post-production residues, sewage sludge, food industry waste, and plant waste [Chan et al. 2007, Sohi et al. 2010, Farrell et al. 2013, Marks et al. 2014, Hosseini Bai et al. 2015]. Research results obtained by many authors [Bridgwater 2003, Jones et al. 2011, Scheer et al. 2011, Masek et al. 2013, Tan et al. 2017] indicate that biochar stability varies depending on the type of biomass subjected to pyrolysis at a given temperature. Tan et al. [2017] state that biochars obtained from oak and larch wood have similar properties, and that their specific surface area and volume of micropores are greater by 145.5% and by about 762%, respectively, than those of biochar obtained from grass. The high quality of the raw material subjected to pyrolysis significantly affects the quality of biochar. Biochar, thanks to its structure and properties, can be a valuable soil conditioner for all arable soils especially degraded ones, it also positively influences the bio-physico-chemical processes taking place in the rhizosphere of many plant species [Głuszek et al. 2017]. Matsubara

✉ mateusz.frac@inhort.pl

et al. [2002] draw attention to the beneficial effect of biochar in controlling infections by pathogens in crop plants. As a result of biochar applications, the physico-chemical properties of the soil improve, the soil density is reduced to 31% and its porosity improves to 64% [Tammeorg et al. 2016], and the water capacity to 42%, regardless of the type of soil [Hansen et al. 2016]. The use of biochar derived from various types of organic matter improves the density and porosity of sandy soils and increases the availability of water in the soil [Omondi et al. 2016, Blanco-Canqui 2017]. Long-term use of biochar also contributes to increasing soil aeration and water abundance, and favourably modifies soil biological activity [Glaser et al. 2002, Chan et al. 2007, Atkinson et al. 2010, Lehmann et al. 2011]. The addition of biochar to the soil reduces its bulk density [Abel et al. 2013, Bayabil et al. 2015, Castellini et al. 2015, Andrenelli et al. 2016, Liu et al. 2016, Obia et al. 2016, Ahmed et al. 2017]. Climatic and soil conditions can also significantly affect the diverse processes that occur in the soil following biochar application [Verheijen et al. 2012, Street et al. 2014].

Most studies on the effectiveness of biochar have been conducted in open-field conditions on annual plants [Steiner et al. 2007, Uzoma et al. 2011, Rajkovich et al. 2012, Thomas et al. 2013, Kraska et al. 2016, Gonzaga et al. 2018, Majeed et al. 2018]. Due to the beneficial effect of biochar on the growth and yielding of perennial plants, interest in the application of biochar in field cultivation of fruit crops has increased in recent years. Research conducted by Abujabhah et al. [2016] had shown that the use of biochar at a dose of 5 kg per apple tree (47 t/ha) increased soil organic carbon content by 23%, compared with the control (without biochar application). The use of biochar in a dose 2–5 t/ha positively influenced the growth and yielding of arable crops [Rajkovich et al. 2012, Gonzaga et al. 2018].

Schaffert and Percival [2016] had noted a marked increase in the yielding of pear trees and an improvement in their health after using biochar in combination with organic fertilization. The use of biochar in perennial fruit crops can significantly reduce the effects of soil fatigue [Atucha and Litus 2015]. The most susceptible to replant disease (soil fatigue) are apple, sour cherry, sweet cherry, and peach trees, and, to a lesser extent, pear trees and strawberry plants [Rebandel 1987, Pacholak et al. 1996, Sienkiewicz 2006]. The main objective of the study was to determine the effect of biochar on the growth and yielding of young peach trees grown in open-field conditions.

MATERIALS AND METHODS

The experiment was established in 2014 in the Experimental Orchard of the National Institute of Horticultural Research in Dąbrowice (51°54'51.5"N 20°06'29.8"E). The objects of the study were peach trees of the cultivar Meredith planted in the spring of 2013 at a spacing of 4 × 2 m. The experiment was designed in a random block arrangement, in four replicates with three trees per plot. The peach trees that were the objects of the study were planted on a sandy-loam podzolic soil of quality class III b, used for many years for fruit growing. The soil pH was slightly acidic at pH 6.2, and the average soil humus content was 1.4%.

The experiment involved the use of biochar produced by the Polish company Fluid S.A., with the composition shown in Tables 1 and 2. In the spring of 2014, the following combinations of plant fertilization treatments were applied:

1) control without fertilization (K);

2) microorganisms (M) – strains of bacteria belonging to the species *Pseudomonas fluorescens* (Ps1/2) and to the genus *Pantoea* (N52AD). Each strain was applied in a single treatment in the form of an aqueous suspension in the amount of 200 ml. The concentration of the bacteria in the suspension was 2×10^9 cfu·ml^{-1} for strain Ps1/2, and 1.5×10^9 cfu·ml^{-1} for strain N52AD. Arbuscular mycorrhizal fungi were applied in compost with the composition given in Table 3, at a dose of 0.3 kg of compost per tree. The mycorrhizal substrate contained *Glomus caledonium*, *G. intraradices*, and *G. coronatum*.

3) organic fertilizer (O) produced by Grupa Inco – Florovit NPK (N – 5%, P_2O_5 – 3%, K_2O – 2%, organic matter – 30%), applied at a dose of 0.2 kg/tree;

4) microorganisms plus organic fertilizer (M + O) – a strain of the species *Pseudomonas fluorescens* (Ps1/2) and a strain belonging to the genus *Pantoea* sp. (N52AD), and also arbuscular mycorrhizal fungi in compost were applied at a dose of 0.3 kg of compost

Table 1. pH and mineral content of the biochar used in the experiment

pH	P	K	Mg	B	Cu	Fe	Mn	Na	Zn	N tot.	C	SO
KCl	mg/100 g			mg/kg						%		
6.05	85.7	58.3	22.9	14.9	6.19	219	97.2	76.3	81.3	0.96	75.9	100

Table 2. Concentration of heavy metals in the biochar used in the experiment

Cd	Pb	As	Hg
mg/kg			
0.25	0.64	1.63	0.03

Table 3. pH and mineral composition of the compost used in the experiment

pH	P	K	Mg	B	Cu	Fe	Mn	Na	Zn	N tot.	C	SO
KCl	mg/100 g			mg/kg						%		
6.37	10.3	21.5	11.9	1.93	3.13	1064	53.9	57.5	6.51	0.18	2.05	3.5

per tree together with the organic fertilizer Florovit NPK at a dose of 0.2 kg/tree;

5) biochar (B) – produced by rapid pyrolysis at 280°C for 5 minutes from coniferous wood chips containing 80% organic matter and 20% organic carbon, applied at a dose of 1.6 kg/tree;

6) biochar, with the composition as described above, at a dose of 1.6 kg/tree applied together with microorganisms (B + M) including a strain of the species *Pseudomonas fluorescens* (Ps1/2) and a strain belonging to the genus *Pantoea* sp. (N52AD), and also arbuscular mycorrhizal fungi in compost applied at a dose of 0.3 kg of compost per tree;

7) biochar, with the composition as above, at a dose of 1.6 kg/tree applied together with the organic fertilizer Florovit NPK at a dose of 0.2 kg/tree (B + O).

All of the products were applied in May 2014 by sprinkling them around tree trunks in the form of a 0.5 m diameter ring, and then mixing them with topsoil to a depth of 20 cm. Application of microorganisms and organic fertilization were repeated in the spring of 2015 and are to be carried out in the subsequent years of the study.

After planting, the young peach trees were pruned to ensure proper rooting. During the growing season, plant care treatments consisted of shortening and bending back the shoots to ensure proper formation of the crown. The trees in the experimental orchard were drip-irrigated during dry spells. Plant protection treatments against diseases and pests were carried out in accordance with the existing recommendations for commercial peach orchards.

Peach fruitlets, at the size of a hazelnut, were thinned by hand in late May. On shoots, they were left at a distance of about 20 cm from each other. During harvest, fruit yield and the number and average weight of the fruits were assessed. Leaf surface area and leaf fresh weight were determined with a sample of 50 randomly picked leaves from each treatment, in four replicates. Leaf surface area was measured using an image analysis system with WinDias 2.0 software (Delta-T Devices UK) [Jonckheere et al. 2003]. A laboratory balance was used to measure leaf fresh weight. Tree trunk diameter was measured with an electronic vernier calliper gauge, 30 cm above the graft union. The obtained results were statistically analyzed with Statictica 10.

One-way analysis of variance was carried out using the Tukey test at a significance level of α = 0.05. The results not significantly different from each other were marked with the same letters.

RESULTS

During the research period, the climatic conditions were favourable to the growth and yielding of peach trees. There was no evidence of frost damage to the trees, buds or flowers. The average temperatures for the months May–August were higher and the rainfall lower than the long-term averages for central Poland.

There was no measurable effect of the preparations on the number and yield of fruits in the first year after their application, i.e. in 2014. The treatment combinations used in the experiment modified the yields obtained in 2015 and 2016. The highest number and yield of fruits in 2015 were obtained from the trees treated with microbiologically enriched compost, and the lowest in the combination where the trees were treated with biochar together with the organic fertilizer. Good productivity was shown by the peach trees when they were treated with microorganisms, organic fertilizer, microorganisms + organic fertilizer, biochar alone, and biochar + microorganisms. In 2016, the largest number of fruits and the highest weight of fruits were obtained from the trees treated with biochar + organic fertilizer. The control trees produced the lowest yields. Considering the cumulative yields for the three years of fruiting, it should be stated that, except for the use of biochar + organic fertilizer, all the experimental treatments had a positive effect on the yielding of peach trees (Tabs. 4 and 5).

In 2014 and 2015, the average fruit weight ranged from 65.2 g to 85.5 g. The lowest value was for the control combination, and the highest for the trees treated with biochar + organic fertilizer. In 2016, no

Table 4. Number of fruits harvested from 'Meredith' peach trees, depending on tree fertilization

Treatment	Number of fruits (per tree)			
	2014	2015	2016	Total 2014–2016
Control	46.3 a*	212.0 ab	182.9 a	441.2 a
Microorganisms 300 g/tree	60.6 a	285.8 b	220.9 a-c	567.3 b
Florovit NPK organic fertilizer 200 g/tree	60.4 a	251.3 b	245.0 bc	556.7 b
Microorganisms + organic fertilizer	64.4 a	277.7 b	218.1 ab	560.2 b
Biochar 1.6 kg/tree	60.1 a	266.7 b	220.8 a-c	547.6 b
Biochar + microorganisms	49.8 a	259.3 b	222.2 a-c	531.3 b
Biochar + organic fertilizer	58.5 a	156.7 a	264.4 c	479.6 a

*Means followed by the same letter do not differ at $p = 0.05$

Table 5. Peach fruit yield in the first three years of biochar application and different tree fertilization treatments

Treatment	Fruit yield (kg/tree)			
	2014	2015	2016	Total 2014–2016
Control	5.1 a*	14.1 ab	21.5 a	40.7 a
Microorganisms 300 g/tree	6.3 a	20.7 b	23.7 ab	50.7 bc
Florovit NPK organic fertilizer 200 g/tree	6.4 a	17.2 ab	25.7 ab	49.3 bc
Microorganisms + organic fertilizer	7.1 a	19.7 ab	25.7 ab	52.5 c
Biochar 1.6 kg/tree	6.1 a	18.8 ab	25.3 ab	50.2 bc
Biochar + microorganisms	5.4 a	17.5 ab	24.6 ab	47.5 b
Biochar + organic fertilizer	5.3 a	13.1 a	26.7 b	45.1 ab

*Means followed by the same letter do not differ at $p = 0.05$

significant effect of the experimental combinations on the average weight of peach fruit was found. The average results from the three years of the study indicate that, compared with the control trees, the trees treated with microorganisms + organic fertilizer, biochar only, and biochar + organic fertilizer produced larger fruits (Tab. 6). However, fruit weight should be considered in relation to tree growth vigour and tree productivity.

Measurements of leaf fresh weight and leaf surface area made in 2015 and 2016 showed that the leaves of the trees treated with biochar + microorganisms and also biochar + organic fertilizer were larger than those of the control trees (Tab. 7). Better tree growth vigour after the application of biochar + microorganisms and biochar + organic fertilizer, as compared with the control trees, was also found when tree trunk diameter was taken as a measure of growth vigour. During the three years of the study, those trees had the largest increase in trunk thickness (Fig. 1).

Table 6. Average weight of fruits harvested from peach trees after applying biochar and organic fertilization in the first three years

Treatment	Fruit weight (g)			
	2014	2015	2016	Mean 2014–2016
Control	65.4 a*	65.2 a	119.2 a	83.3 a
Microorganisms 300 g/tree	74.2 ab	74.3 ab	109.6 a	86.0 ab
Florovit NPK organic fertilizer 200 g/tree	71.1 ab	71.2 ab	105.4 a	82.6 a
Microorganisms + organic fertilizer	70.0 a	70.5 a	120.3 a	86.9 b
Biochar 1.6 kg/tree	70.6 a	70.8 a	117.8 a	86.4 b
Biochar + microorganisms	67.6 a	67.3 a	113.8 a	82.9 a
Biochar + organic fertilizer	85.1 b	85.5 b	102.9 a	91.2 c

*Means followed by the same letter do not differ at $p = 0.05$

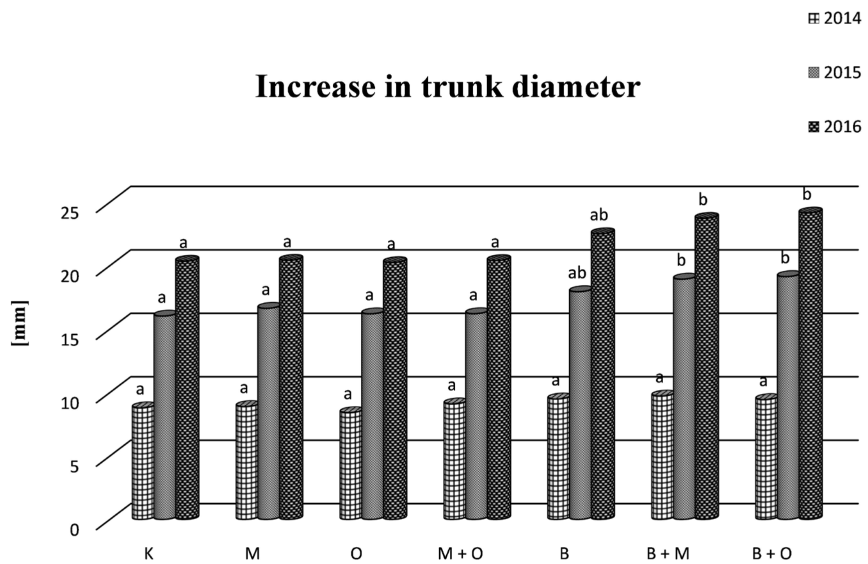

Fig. 1. Increase in trunk diameter of peach trees resulting from treatments with biochar, microorganisms, and organic fertilization (2014–2016)

Table 7. Effect of different fertilization treatments and biochar on the surface area and fresh weight of peach tree leaves

Treatment	Leaf fresh weight (g)			Leaf surface area (cm²)		
	2015	2016	mean 2015–2016	2015	2016	mean 2015–2016
Control	0.67 a*	0.79 a	0.73 a	50.1 a	51.3 ab	50.7 a
Microorganisms 300 g/tree	0.70 ab	0.74 a	0.72 a	51.2 ab	46.1 a	48.7 a
Florovit NPK organic fertilizer 200 g/tree	0.74 b	0.83 ab	0.79 b	52.4 ab	47.1 a	49.8 a
Microorganisms + organic fertilizer	0.70 ab	0.82 ab	0.76 ab	51.9 ab	50.2 a	51.1 a
Biochar 1.6 kg/tree	0.72 ab	0.80 a	0.76 ab	50.9 a	51.4 a	51.2 a
Biochar + microorganisms	0.74 b	0.91 b	0.83 c	56.3 b	61.2 b	58.8 b
Biochar + organic fertilizer	0.76 b	0.93 b	0.85 c	58.4 c	60.3 b	59.4 b

*Means followed by the same letter do not differ at $p = 0.05$

DISCUSSION

Soil microorganisms play a very important role in the mineralization processes of organic matter. Application of biochar can be an effective method of increasing the carbon (C) content in orchard soils, as confirmed by Street et al. [2014]. Literature data indicate that NPK fertilization combined with biochar has a more favourable effect on plant growth and yielding than NPK without biochar [Steiner et al. 2007]. That experiment had been carried out on sorghum and rice plants, growing on very poor soils.

Schaffert and Percival [2016], investigating the effects of organic fertilization, molasses, and biochar on the yielding and growth of 'Bonkreta Williamsa' (*Pyrus communis* 'Williams') pear trees demonstrated that the use of biochar in combination with organic fertilization, and biochar with molasses pellets significantly improved the growth and yielding of the trees (by 24% and 20%, compared with control tree yields). The use of molasses alone did not give an increase in yield, whereas organic fertilization increased fruit yield by 1 kg per tree, compared with non-fertilized control. This yield was lower by 0.4 kg per tree than the yield obtained from the trees fertilized with biochar + organic fertilizer. The authors of this study also observed a positive effect of the combined use of biochar and organic fertilization, but only in the third year of the study. The yield of trees treated with biochar varied greatly depending on whether biochar was used alone or in combination with other products. The total yields for the period of three years of fruiting allow us to state that, except for the use of biochar with organic fertilizer, all experimental combinations had a positive effect on the yield of peach trees.

The authors of this study, analyzing the dynamics of tree growth, observed that over the course of 3 years each year, the diameter of the trunk of trees treated with biochar was greater than the diameter of trees where biochar was not used. The benefits of applying biochar to the soil were more and more visible in the following years. Schaffer and Percival [2016] obtained similar dependencies. In their research, the volume of the crown was taken as the measure of tree growth vigour. Biochar used in this experiment significantly increased the volume of the crown of the studied trees compared to the volume of the crown of trees where it was not used.

The use of biochar in the experiments conducted by Gale and Thomas [2019] at doses of 8 and 30 t/ha had resulted in an increase in leaf surface area of velvetleaf (*Abutilon theophrasti*) by 30% and 33%, respectively, in comparison with the plants growing in a substrate without the addition of biochar. A similar effect of the use of biochar + organic fertilization and biochar + microbiologically enriched compost was observed in our study. Leaf surface area of the peach trees treated with biochar increased by 15% relative to the size of the leaves of control plants in both 2015 and 2016.

Studies conducted by Atucha and Litus [2015] confirm the beneficial effect of biochar addition to the soil in significantly reducing the adverse effects of replant disease. Elmer and Pignatello [2011] indicate that the use of biochar can be a beneficial factor in helping to counter the harmful effects of allelopathic residues in replanted soils in asparagus cultivation.

Many researchers have observed a very low level of mineral leaching from the Amazonian *Terra preta* (black earth) soils after biomass carbonification, which without biochar application occurs very quickly in the natural conditions of the Amazon basin. Confirmation of the high effectiveness of biochar has been looked for in those soils in which organic matter from charcoal has been accumulating for hundreds or even thousands of years [Atkinson et al. 2010, after Lehmann et al. 2003a, b].

The very large variations in the results of research on biochar effectiveness may result from the differences in the pyrolysis process during biochar production and the type of raw material that is used to produce biochar. These differences also result from and depend on the type of crop and soil to which biochar is applied, and also on the type of substrates of which it is a component. In general, biochar, by effecting bio-physico-chemical changes in the soil or growth substrate, exerts a positive influence on the growth and yielding of plants, and also on their resistance/tolerance to diseases and abiotic stress. The field experiment carried out by the authors of this study with peach trees showed a positive effect of the use of biochar. Better fruiting of trees where biochar was applied to the soil were most visible in the third year after application. It was probably because of the fact that the biomass subjected to pyrolysis in the high-temperature process needs time to properly integrate with the soil.

CONCLUSIONS

The effectiveness of the use of biochar in peach orchard begins to be visible in the second and third growing seasons. In the experiment, very good effects of improving the growth and fruiting of peach trees were obtained after the combined use of biochar and organic fertilization. Biochar can be recommended for improving the growth and yielding of fruit trees, especially those growing in soils that are not rich in organic matter.

SOURCE OF FUNDING

This publication is funded by research commissioned by the private sector.

REFERENCES

Abujabhah, I.S., Bound, S.A., Doyle, R., Bowman, J.P. (2016). Effects of biochar and compost amendments on soil physico-chemical properties and the total community within a temperate agricultural soil. Appl. Soil Ecol., 98, 243–253. https://doi.org/10.1016/j.apsoil.2015.10.021

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., Wessolek, G. (2013). Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. Geoderma, 202–203, 183–191. https://doi.org/10.1016/j.geoderma.2013.03.003

Ahmed, A., Gariepy, Y., Raghavan, V. (2017). Influence of wood-derived biochar on the compactibility and strength of silt loam soil. Int. Agrophys., 31, 149–155. http://dx.doi.org/10.1515/intag-2016-0044

Andrenelli, M.C., Maienza, A., Genesio, L., Miglietta, F., Pellegrini, S., Vaccari F.P., Vignozzi N. (2016). Field application of pelletized biochar: short term effect on the hydrological properties of a silty clay loam soil. Agric. Water Manag., 163, 190–196. https://doi.org/10.1016/j.agwat.2015.09.017

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

Atucha, A., Litus, G. (2015). Effect of biochar amendments on peach replant disease. HortScience, 50(6), 863–868. https://doi.org/10.21273/HORTSCI.50.6.863

Bayabil, H.K., Stoof, C.R., Lehmann, J.C., Yitaferu, B., Steenhuis, T.S. (2015). Assessing the potential of biochar and charcoal to improve soil hydraulic properties in the humid Ethiopian Highlands: The Anjeni watershed. Geoderma, 243–244, 115–123. https://doi.org/10.1016/j.geoderma.2014.12.015

Blanco-Canqui, H. (2017). Biochar and soil physical properties. Soil Sci. Soc. Am. J., 81, 687–711. https://doi.org/10.2136/sssaj2017.01.0017

Bridgwater, A.V. (2003). Renewable fuels and chemicals by thermal processing of biomass.

Chem. Eng. J., 91, 87–102. https://doi.org/10.1016/S1385-8947(02)00142-0

Castellini, M., Giglio, L., Niedda, M., Palumbo, A.D., Ventrella, D. (2015). Impact of biochar addition on the physical and hydraulic properties of a clay soil. Soil Till. Res., 154, 1–13. https://doi.org/10.1016/j.still.2015.06.016

Chan, K.Y., Van Zwieten, L., Meszaros, I., Downie, A., Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. Austral. J. Soil Res., 45, 629–634. https://doi.org/10.1071/SR07109

Elmer W.H., Pignatello J.J., (2011). Effect of biochar amendments on mycorrhizal associations and Fusarium crown and root rot of asparagus in replant soils. Plant Dis., 95, 960–966. https://doi.org/10.1094/PDIS-10-10-0741

Farrell, M., Kuhn, T.K., Macdonald, L.M., Maddern, T.M., Murphy, D.V., Hall, P.A., Singh, B.P., Baumann, K., Krull, E.S., Baldock, J.A. (2013). Microbial utilisation of biochar-derived carbon. Sci. Total Environ., 465, 288–297. https://doi.org/10.1016/j.scitotenv.2013.03.090

Gale, N.V., Thomas, S.C. (2019). Dose-dependence of growth and ecophysiological responses of plant to biochar. Sci. Total Environ., 658, 1344–1354. https://doi.org/10.1016/j.scitotenv.2018.12.239

Glaser, B., Lehmann, J., Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal. A review. Biol. Fertil. Soils, 35, 219–230.

Głuszek, S., Sas-Paszt, L., Sumorok, B., Kozera, R. (2017). Biochar-rhizosphere interactions – a review. Pol. J. Microbiol., 66(2), 151–161.

Gonzaga, M.I.S., Mackowiak, C., Quinatao de Almeida, A., Tinel de Carvalho, J.I., Jr., Andrade, K.R., (2018). Positive and negative effects of biochar from coconut husks, orange bagasse and pine wood chips on maize (*Zea mays* L.) growth and nutrition. Catena, 162, 414–420. https://doi.org/10.1016/j.catena.2017.10.018

Hansen, V., Nielsen, H.H., Petersen, C.T., Mikkelsen, T.N., Stover, D.M., (2016). Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types. Soil Tillage Res., 161, 1–9. https://doi.org/10.1016/j.still.2016.03.002

Hosseini Bai, S., Xu, C.Y., Xu, Z., Blumfield, T., Zhao, H., Wallace, H., Reverchom, F., Van Zwieten, L. (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. Available: https://link.springer.com/article/10.1007/s11356-014-3649-2

Jones, D.L., Murphy, D.V., Khalid, M., Ahmad, W., Edward-Jones, G., DeLuca, T.H. (2011). Short-term biochar-induced increase in soil CO_2 release is both biotically and abiotically mediated. Soil Biol. Biochem., 43, 1723–1731. https://doi.org/10.1016/j.soilbio.2011.04.018

Jonckheere, I., Fleck, S., Nackaerts, K., Muys, B., Coppin, P., Weiss, M., Baret, F. (2003). Review of methods for in situ leaf area index determination. Part I. Theories, sensors and hemispherical photography. Agric. Forest Meteor., 121, 19–35. https://doi.org/10.1016/j.agrformet.2003.08.027

Kraska, P., Oleszczuk, P., Andruszczak, S., Kiecińska-Poppe, E., Różyło, K., Pałys, E., Gierasimiuk, P., Michałojć, Z. (2016). Effect of various biochar rates on winter rye yield and the concentration of available nutrients in the soil. Plant Soil Environ., 62(11), 483–489. Available: https://www.agriculturejournals.cz/publicFiles/94_2016-PSE.pdf

Lehmann, J., da Silva Junior, J.P., Steiner, C., Nehls, T., Zech, W., Glaser, B. (2003a). Nutrient availability and leaching in an archaeological Anthrosol and Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil, 249, 343–357. http://www.css.cornell.edu/faculty/lehmann/publ/PlantSoil%20249,%20343-357,%202003%20Lehmann.pdf

Lehmann, J., Kern, D., German, L., McCann, J., Martins, G.C., Moreira, L., (2003b). Soil fertility and production potential. Chapter 6. In: Amazonian dark earths: origin, properties, management, Lehmann, J., Kern, D.C., Glaser, B., Woods, W.I. (eds.). Kluwer Academic, Dordrecht, 105–124. Available: https://link.springer.com/chapter/10.1007/1-4020-2597-1_6

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D. (2011). Biochar effects on soil biota – a review. Soil Biol. Biochem. 43, 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Liu, Z., Dugan, B., Masiello, C.A., Barnes, R.T., Gallagher, M.E., Gonnermann, H. (2016). Impacts of biochar concentration and particle size on hydraulic conductivity and DOC leaching of biochar-sand mixtures. J. Hydrol., 533, 461–472. https://doi.org/10.1016/j.jhydrol.2015.12.007

Majeed, A.J., Dikici, H., Demir, Ö.F. (2018). Effect of biochar and nitrogen applications on growth of corn (*Zea mays* L.) plants. Turk. J. Agric. – Food Sci. Technol., 6(3), 346–351. https://doi.org/10.24925/turjaf.v6i3.346-351.1746

Marks, E.A.N., Mattana, S., Alcañiz, J.M., Domene, X. (2014). Biochars provoke diverse soil mesofauna reproductive responses in laboratory bioassays. Europ. J. Soil Biol., 60, 104–111. https://doi.org/10.1016/j.ejsobi.2013.12.002

Masek, O., Brownsort, P., Cross, A., Sohi, S. (2013). Influence of production conditions on
the yield and environmental stability of biochar. Fuel 103, 151–155. https://doi.org/10.1016/j.fuel.2011.08.044

Matsubara, Y.-I., Hasegawa, N., Fukui, H. (2002). Incidence of Fusarium root rot in asparagus seedlings infected with arbuscular mycorrhizal fungus as affected by several soil amendments. Jpn. Soc. Hortic. Sci., 71, 370–374. https://doi.org/10.2503/jjshs.71.370

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., Borresen, T. (2016). In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. Soil Till. Res., 155, 35–44. https://doi.org/10.1016/j.still.2015.08.002

Omondi, M.O., Xia, X., Nahayo, A., Liu, X., Korai, P.K., Pan, G., (2016). Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. Geoderma, 274, 28–34. https://doi.org/10.1016/j.geoderma.2016.03.029

Pacholak, E., Cwynar, M., Zydlik, Z. (1996). Wpływ siedemnastoletniego nawożenia i nawadniania na wzrost jabłoni odmiany 'Šampion' na podkładce P 60 w drugim roku po replantacji [Effect of 17-year fertilization and irrigation on the growth of 'Šampion' apple trees on P 60 rootstock in the second year after replantation]. 34. Ogólnopolska Naukowa Konferencja Sadownicza, Skierniewice, 96–99.

Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A.R., Lehmann, J. (2012). Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biol. Fertil Soils, 48, 271–284. Available: https://link.springer.com/article/10.1007/s00374-011-0624-7

Rebandel, Z. (1987). Problem zmęczenia gleby w sadownictwie. Sadownictwo w Wielkopolsce [The problem of soil fatigue in fruit farming. Fruit growing in Wielkopolska]. PWRiL, Warszawa.

Schaffer, E., Percival, G. (2016). The influence of biochar, slow-release molasses, and an organic N : P : K fertilizer on transplant survival of *Pyrus communis* 'Williams' Bon Chrétien'. Arboricult. Urban For. 42(2), 102–110. Available: http://joa.isa-arbor.com/request.asp?JournalID=1&ArticleID=3385&Type=2

Scheer, C., Grace, P.R., Rowlings, D.W., Kimber, S., Van Zwieten, L. (2011). Effect of biochar amendment on the soil-atmosphere exchange of greenhouse gases from an intensive subtropical pasture in northern New South Wales, Australia. Plant Soil, 345, 47–58. Available: https://link.springer.com/article/10.1007/s11104-011-0759-1

Sienkiewicz, P. (2006). Wpływ głęboszowania i nawożenia na wzrost jabłoni i grusz posadzonych po zlikwidowanym sadzie jabłoniowym [The effect of subsoiling and fertilization on the growth of apple and pear trees planted in a liquidated apple orchard]. Acta Agrophys., 8(4), 949–961.

Sohi, S.P., Krull, E., Lopez-Capel, E., Bol, R. (2010). A review of biochar and its use and function in soil. Adv. Agron., 105, 47–82. https://doi.org/10.1016/S0065-2113(10)05002-9

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macedo, J.L.C., Blum, W.E.H., Zech, W. (2007). Long-term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291(1–2), 275–290. Available: https://link.springer.com/article/10.1007/s11104-007-9193-9

Street, T.A., Doyle, R.B., Close, D.C. (2014). Biochar media addition impacts apple Rootstock growth and nutrition. HortScience, 49(9), 1188–1193. https://doi.org/10.21273/HORTSCI.49.9.1188

Tammeorg, P., Bastos, A.C., Jeffery, S., Rees, F., Kern, J., Graber, E.R., Ventura, M., Kibblewhite, M., Amaro, A., Budai, A., Cordovil, C.M.d.S., Domene, X., Gardi, C., Gasco, G., Horak, J., Kammann, C., Kondrlova, E., Laird, D., Loureiro, S., Martins, M.A.S., Panzacchi, P., Prasad, M., Prodana, M., Puga, A.P., Ruysschaert, G., Sas Paszt, L., Silva, F.C., Teixeira, W.G., Tonon, G., Vedove, G,D., Zavalloni, C., Glaser, B., Verheijen, F.A.G., (2016). Biochars in soils: towards the required level of scientific understanding. J. Environment. Engineer. Landscape Manag., 25(2) 1–16. https://doi.org/10.3846/16486897.2016.1239582

Tan, Z., Linb, C.S.K., Jic, X., Raineyd, T.J. (2017). Returning biochar to fields: a review. Appl. Soil Ecol., 116, 1–11. https://doi.org/10.1016/j.apsoil.2017.03.017

Thomas, S.C., Frye, S., Gale, N., Garmon, M., Launchbury, R., Machado, N., Melamed, S., Murray, J., Petroff, A., Winsborough, C. (2013). Biochar mitigates negative effects of salt additions on two herbaceous plant species. J. Environment. Manag., 129, 62–68. https://doi.org/10.1016/j.jenvman.2013.05.057

Uzoma, K.C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., Nishihara, E. (2011). Effect of cow manure biochar on maize productivity under sandy soil condition. Soil Use Manag., 27, 205–212. Available: https://onlinelibrary.wiley.com/doi/full/10.1111/j.1475-2743.2011.00340.x

Verheijen, F.G.A., Jeffery, S., Bastos, A.C., van der Velde, M., Diafas, I. (2010). Biochar application to soils – a critical scientific review of effects on soil properties, processes and functions. EUR 24099 EN. Office for the Official Publications of the European Communities, Luxembourg.