Biochar Effect on Nutrients Availability to Barley

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Biochar can serve as a soil ameliorant preventing nutrient leaching. Due to its porous structure and chemical composition, it can also adsorb elements on its surface. However, various biochars have different sorption ability, and the mechanistic understanding of nutrient storage in biochar is missing. It is not clear if nutrients adsorbed by biochar will be available for plants. Therefore, it is necessary to investigate biochar efficacy in pure substrates to characterise its specific influence on plants. In this study, the sorption capacity and ability of the wood-based biochar to provide barley plants with nutrients was investigated. The sorption capacity of biochar was investigated by saturating it with Gelrigel nutrient solution. Then nutrient-enriched biochar was tested for its effect on barley growth in comparison with non-enriched biochar. The results of the sorption experiment showed that the wood-based biochar could adsorb high amounts of nutrients such as ammonium (NH_4^+), potassium, calcium and phosphate (PO_4^{3-}), but not nitrate (NO_3^-). Nutrient-enriched biochar showed an ability to support 46% higher dry biomass of barley than non-enriched biochar. These results suggest a potential of nutrient-enriched biochar for recovering essential nutrients for plants.

Keywords: nutrient-enriched biochar, sorption, barley, ammonium, nitrate, phosphate.

Introduction

Growing rates of mineral fertiliser production and application to agricultural soils lead to harmful effects to the environment. Production of mineral fertilisers causes air pollution with aerosols and greenhouse gases, contamination of soils and water bodies with heavy metals. Meanwhile, the use of these fertilisers in agriculture also has tremendous negative effects such as soil acidification, heavy metal pollution, and

increased greenhouse gas (GHG) emissions from soil (Laird et al., 2010; Savci, 2012). Moreover, approximately 2–10% of nutrients from mineral fertilisers leach from the soil to water bodies causing eutrophication (Savci, 2012). Losses of nutrients through leaching and GHG emissions considerably decrease the efficiency of mineral fertilisers. Improving of nutrient use efficiency is required to decrease production and use of fertilisers. Researchers propose amendment of soils with biochar as a solution to retain nutrients and decrease their leaching from agricultural soils.

Biochar is produced by pyrolysis of organic waste (residues from agriculture and forestry, sewage sludge, etc.) and is characterised by a high content of stable carbon (C) compounds. Its application to soil as an amendment leads to carbon sequestration (Lehmann, 2007) and thus can help to decrease carbon dioxide (CO_2) concentration in the atmosphere. Biochar amendment enhances such soil properties as soil aeration, aggregation, pH, cation-exchange capacity, water-holding capacity and availability of nutrients to plants (Van Zwieten et al., 2009; Major et al., 2010; Glaser et al., 2002; Lehmann et al., 2003). All these properties will modulate changes in activity, abundance and diversity of microbiota as well as plant growth (Rondon et al., 2007). But there is still no consensus on the net absolute benefits of applying pure biochar for nutrient recovery. The reason is that pure biochar addition to soils does not always give consistent yield increases, and the plant responses to biochar addition vary widely (Jeffery et al., 2011; Cornelissen et al., 2013; Bonanomi et al., 2017). Thereby, the improvements of crop production and plant growth may be dependent on the mechanisms behind the capture, and subsequent release of organic or inorganic mineral nutrients by different types of biochar. Biochar has the ability to adsorb cations, anions and non-polar organic compounds (Fujita et al., 1991; Sander and Pignatello, 2005), thereby reducing leaching of nutrients (mineral nitrogen: ammonium (NH_4^+) and nitrate (NO_3^-); phosphates (PO_4^{3-}) and others) from soils (Zhang et al., 2015; Shepherd et al., 2016). Moreno-Castilla (2004) determines pore texture, surface chemistry and mineral matter content as the main characteristics which influence carbon sorption capacity. Sorption capacity, porosity and

other biochar physical properties vary with the pyrolysis temperature and the type of biomass used as raw material (Lehmann, 2007; Downie et al., 2009). Patra et al. (2016) distinguished the following mechanisms responsible for the sorption: precipitation, complexation, ion exchange, chemisorption, and physical sorption. The sorption capacity of biochar could lead to lower nutrient leaching from soils and higher nutrient use efficiency, thus, reducing the need in fertilisers (Gronwald et al., 2015).

However, the availability of the adsorbed nutrients for plants is uncertain and depends on soil type, feedstock for biochar production and pyrolysis conditions. Several studies have shown that nutrients retained by biochar slowly become available to plants as a result of decomposition of char and changes in soil properties (Spokas et al., 2012; Biederman and Harpole, 2013). Investigations of plant uptake of nutrients adsorbed by biochar are crucial for understanding of the biochar application effect on nutrient retention in soils and their availability to plants. Therefore, investigations of the amendment efficacy require the study of pure components to characterise their specific behaviour in soil. Thus, this study was aimed to analyse sorption ability of biochar and its influence on plant growth in pure sand.

It was hypothesised that biochar will adsorb a significant amount of nutrients from the nutrient solution, which will improve barley growth.

Materials and methods

Materials

The sorption ability of biochar was examined in a pure sand substrate using a modified Gelrigel mixture as a nutrient solution. Treatment with bidistilled water was chosen as a control as it was characterised by the absence of any dissolved components. The nutrient retention capacity of biochar was studied in the experiment. Comparison of biochar properties in bidistilled water and nutritive solution would help to understand how biochar elemental composition changes in bidistilled water and how nutrients are adsorbed by biochar from Gelrigel solution. Concentrations of

the target nutrients (NH_4^+, NO_3^-, P^{3+}, and K^+) and trace elements (Ca^{2+}, and Mg^{2+}) in biochar were determined before and after the sorption period. Subsequently, the amounts of nutrients adsorbed onto biochar were calculated based on their initial and final concentrations in the solutions and the biochar.

The sand was chosen as a pure substrate for the experiment. Sand is commonly used as a substrate in hydroponics. Assimilation of nutrients by plants from solutions in sands is more favourable than in soils due to the fact that the distribution of nutrients in sand is more even than it can be in soils. Proper washing of the sand was conducted to remove any nutrients from it, thus avoiding influence of the substrate on the results of the experiment. The sand was placed in 20%-HCl for 7–10 days. Then it was washed with a large amount of water and placed into the acid again. This operation was repeated 4–5 times until hydrochloric acid became transparent. After that, the sand was washed with distilled water until its pH value became constant. As the final step, the sand was heated at 800°C for 24 hours.

Biochar was produced from wooden residues (birch, aspen, alder) by fast pyrolysis under the temperature of 550 °C. Biochar obtained from wooden residues was chosen for the study since it is the main type of biochar produced in Russia. C, N and H contents in biochar were determined using elemental analyser Leco CHN-628 (USA). Ammonium (NH^{4+}) was determined by the colorimetric method in the extraction of 2% KCl with Nessler reagent (K_2Hg_{I4}.KOH) (Lenreactiv, Russia) (Arinushkina, 1970). Nitrates (NO_3^-) were determined in the aqueous extract by the disulfophenol method (Arinushkina, 1970). The method of Kirsanov was used to determine P and K concentrations (0.2 normal solution of HCl $5H_2O$ soil extract) (Arinushkina, 1970). Phosphorus was determined by the colorimetric method with the addition of the Truog`s reagent (0.002 normal solution of H_2SO_4 ($NH_4)_2SO_4$) (Lenreactiv, Russia) and $SnCl_2$ as a reducing agent (Arinushkina, 1970). The determination of potassium was carried out by a flame-photometric method (Arinushkina, 1970). The determination of Ca and Mg was carried out in an extract with ammonium acetate (CH_3COOHN_4) by the Schollenberger titrimetric method (Arinushkina,

1970). Heavy metals were determined using an atom absorption spectrometer (Shimadzu AA-300, Japan). Benzo[a]pyrene concentration in biochar was determined by HPLC (Lumachrome, Russia) after extraction with acetone-cyclohexane.

Porosity of biochar was determined using equation:

$$\text{Porosity} = 1 - Db/Dp \qquad (1)$$

Where: Db is bulk density (g $cm^{-3)}$;

Dp is specific bulk density (g cm^{-3}).

Specific bulk density was determined using the pycnometer method (ASTM 9854 - 14). Bulk density was studied by EN ISO 60 (DIN 53468), by apparatus HLL Landgraf Laborsysteme (Germany). The bulk material was poured through a standardised funnel into a collecting vessel with a defined volume. By means of differential weighing, the mass bulk density was calculated.

In the laboratory experiment, barley (*Hordeum distichon* L.) was used to study the uptake of nutrients from biochar.

Experiment 1: *Nutrient sorption capacity of biochar*

For the experiment, biochar was ground with a mortar and pestle and 1–2-mm size fraction was used in the experiment. A modified aqueous mixture of Gelrigel (Prusakova et al., 2008), which is commonly recommended for sands in hydroponics and sandy soils, was used as a nutrient solution. All nutrients of the Gelrigel mixture were dissolved in 1 litre of bidistilled water to make an aqueous solution. Its composition is presented in Table 1. Using bidistilled water as a control to the nutrient solution allowed to analyse nutrient leaching from biochar in aqueous solutions.

Table 1. *Composition of the Gelrigel nutrient solution*

Component	Value
Ca($NO_3)_2$, g l^{-1}	0.49
KCl, g l^{-1}	0.075
($NH_4)_2SO_4$, g l^{-1}	4
KH_2PO_4, g l^{-1}	0.14
$MgSO_4·7H_2O$, g l^{-1}	0.12

Concentrations of the investigated nutrients in the Gelrigel solution were calculated (Table 2).

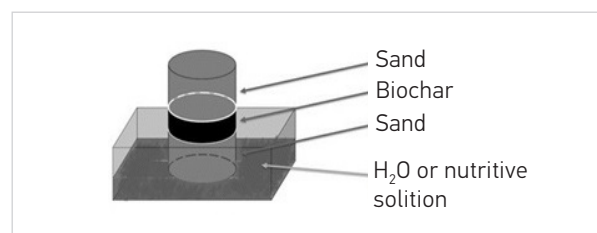**Table 2.** *Concentration of nutrients in the Gelrigel solution*

Substance	Concentration
NO_3^-, mg kg^{-1}	294.0
NH_4^+, mg kg^{-1}	1090.2
P, mg kg^{-1}	31.9
K, mg kg^{-1}	39.3
Ca, mg kg^{-1}	196.0
Mg, mg kg^{-1}	23.8

Sand and biochar were placed in glass columns 5 cm in diameter and 10 cm high (Fig. 1). The columns were fastened together in the following order: the bottom tube was filled with sand, with 2-cm layer of biochar on the top, and the upper tube was filled with sand. Filter paper was put between the layers of sand and biochar. The amount of biochar represented a 25-tonnes ha^{-1} application rate or 10% of the total mass in the column. Such a high amendment rate was chosen to ensure that it would allow detecting any changes in the studied properties happening during the experiment.

The columns, 5 replicates for each treatment, were inserted in two containers: one with bidistilled water (BC) as a control, and another with nutritive solution (EB). The layer of the liquids was constantly maintained 5-mm deep during the experiment. Water and the nutrient solution filled the columns and reached the tops of the columns in 2 minutes after the columns were placed into the solutions. The columns were kept in the containers under laboratory temperature 18°C and relative air humidity approximately 60%. The majority of research experiments have shown that biochars could have a highly variable water-holding capacity, depending on whether they are freshly made or were aged for some time, as it was in our experiment. Some biochars, especially those made of wood, are able to hold an amount of water more than 10 times of their own weight (Kinney et al., 2012). Moving water into small pores requires exceeding the capillary pressure of the narrowest part of the pore. Since capillary pressure is inversely

proportional to the pore radius, it creates a soil water potential. The weight of the columns in water and the Gelrigel solution was measured until, on day 14 of the experiment, it became constant. After that, each layer was analysed for the content of nutrients.

Fig. 1. *The sorption experiment with biochar*

By the difference in the biochar nutrient concentration between BC and EB treatments, the amount of nutrients adsorbed by the biochar from the nutrient solution was calculated. The control treatment with water was necessary for the assessment of the biochar nutrient retention ability.

The coefficient of sorption intensity was determined as the ratio of concentration of the nutrient adsorbed by the biochar to concentration of the same nutrient in the solution.

Experiment 2: *Nutrient uptake from biochar*

160 g of biochar saturated with bidistilled water or the Gelrigel solution (BC and EB, respectively) was introduced into the vessels with 0.5 kg of the sand. The sand-biochar mixture was moistured to reach 60% of the field capacity (or 15% of soil water content). In each pot, 10 grains of barley were sown. The experiment was performed in 5 replicates at a constant air temperature of 18°C (average air temperature during the growing season in St. Petersburg area).

After the emergence of sprouting, at the stage of the second leaf, 5 healthy plants of the same height and size were left in each pot. The initial moisture content in the vessels was maintained during the experiment. When the plants reached the boot stage, they were taken out of the vessel and cleaned from sand. The roots were separated from the sprouts and weighed to find out the wet mass of the roots and the sprouts. Then the plant material was fixed in the Binder drying

and heating chamber FD115 (Germany) at a temperature of 120°C for 10 minutes to stop the activity of enzymes (fermentation) and after that was dried at a temperature of 60°C. The wet and dry mass of the roots and the sprouts was measured.

Statistical analyses

Statistical analyses were performed using R 3.1.2 (R Development Core Team, 2013). One-factorial ANOVA ($p < 0.05$) was used to assess the sorption capacity of biochar and its influence on barley growth and plants' nutrient uptake.

Results and Discussion

Characteristics of biochar

The main characteristics of the biochar are presented in Table 3. The biochar studied in the experiment is an alkaline product and that is common for biochars produced at high temperatures. The alkaline nature of biochar makes it a good ameliorant with liming properties for application to acidic soils (Berek et al., 2018). The investigated biochar has high porosity which is supposed to contribute to nutrient adsorption from the solution by capillary forces. High porosity of biochars determines their effect on soil properties, such as water-holding capacity, aeration, bulk density, nutrient leaching, etc.

Elemental composition analysis showed that biochar is a carbon rich material. However, biochar is a stable carbonaceous material and only little part of this carbon is in the labile form available for soil microorganisms and plants. Labile carbon in biochar represents a small proportion of the total content, less than 0.01–0.07 % (Lin et al., 2012; Uchimiya et al., 2013), and its content and composition are dependent on both the biochar feedstock material and biochar pyrolysis conditions. Biochar has a low concentration of the main macronutrients: ammonium and phosphorus. Therefore, the use of biochar as a fertiliser is not enough to support the plant growth. However, a sufficient amount of basic elements such as calcium, potassium and magnesium in biochar can contribute to the plant growth.

Table 3. *Properties and elemental composition of biochar*

Parameter	Value
C, %	87.4
N, %	0.4
H, %	2.8
N-NO$_3$, mg kg^{-1}	1.2
N-NH$_4$, mg kg^{-1}	7.3
P, mg kg^{-1}	10.7
K, mg kg^{-1}	74
Ca, mg kg^{-1}	3655
Mg, mg kg^{-1}	958
Fe, mg kg^{-1}	50
Hg, mg kg^{-1}	0.049
As, mg kg^{-1}	2.6
Cd, mg kg^{-1}	0.59
Cu, mg kg^{-1}	16.8
Ni, mg kg^{-1}	12.9
Pb, mg kg^{-1}	< 0.1
Zn, mg kg^{-1}	116.4
Benzopyrene, mg kg^{-1}	< 0.005
pH	8.34
Porosity, %	81

Biochar was analysed for concentrations of heavy metals and benzopyrene to determine the presence of harmful elements in the material. The results of the analysis did not show critical concentrations of these substances in the studied biochar with an exception of zinc.

Nutrient sorption capacity of biochar

After two weeks of the sorption experiment, BC and EB biochars were analysed for concentrations of nutrients (Table 4). Biochar saturated with distilled water did not lose a significant amount of nutrients during the experiment. Concentrations of nitrate, calcium and magnesium in BC biochar did not change. Cations Ca and Mg are divalent (2$^+$) and can act as an ionic "glue" with negatively charged biochar particles (electrostatic attraction) (Droge and Goss, 2012). At the same time, BC biochar released 18% of its

ammonium, 6% of phosphorus and 5% of potassium to the water ($p > 0.05$). The reason for that could be the increase of the water pH due to biochar alkaline nature, which promoted some leaching of the cations (NH_4^+, P_3^+ and K^+), while nitrate leaching could be suppressed. Therefore, it can be concluded that macronutrients in biochar cannot easily be dissolved by water. However, their insignificant amount can be dissolved and then used by plants.

Table 4. *Amounts of nutrients in biochar after the saturation experiment*

Substance	BC, mg kg^{-1}	EB, mg kg^{-1}	Adsorbed nutrients, mg kg^{-1}	Coefficient of sorption intensity
NO_3^-	1.2 ± 0.1	1.2 ± 0.2	0	0
NH_4^+	6 ± 1.3	114 ± 11.2	108	0.1
P	10 ± 0.1	35 ± 4.5	25	0.8
K	71 ± 4.3	274 ± 27.6	200	5.09
Ca	$3{,}650 \pm 10$	$4{,}120 \pm 89$	470	2.4
Mg	954 ± 60	$1{,}000 \pm 68$	46	1.9

The biochar saturated with the solution (EB) had a significantly ($p < 0.05$) higher concentration of the nutrients, excluding nitrate and magnesium than the biochar saturated with bidistilled water.

Biochar showed the ability to adsorb a significant amount of ammonium. Its concentration increased 18 times by the end of the experiment whereas the concentration of nitrates did not change. The concentration of phosphorus in EB biochar increased 3.5 times with the coefficient of sorption intensity being 0.8. Similar results for NO_3^-, NH_4^+ and PO_4^{3+} sorption by biochar were found in the experiment of Yao et al. (2012). They investigated biochars produced from different feedstock and at different temperatures (300–650 °C). Little or no nitrate and phosphate sorption ability but significant ammonium removal was found.

Earlier studies pointed out that the ability of biochar to adsorb NO_3^- and NH_4^+ is highly dependent on the biochar production temperature (Yao et al., 2011; Mizuta et al., 2004). Based on earlier studies, Clough et al. (2013) determined pyrolysis temperature of 600°C as a minimum for biochar to have NO_3^- adsorption

potential. Nitrate adsorption could be a result of base functional groups with content higher in biochars produced at high pyrolysis temperatures (due to a high pH value caused by an increase in ash content) (Banno et al., 2009; Kameyama et al., 2012). Conversely, biochar produced at lower temperatures could have a higher ammonium sorption capacity (Zheng et al., 2013). The biochar studied in this experiment was produced at 550°C and it could be the reason for no NO_3N and considerably high NH_4-N sorption. Besides, the temperature of biochar production could be the reason of low NO_3^- anion sorption. Cheng et al. (2008) after 12 months of biochar incubation found disappearance of surface positive charge and an increase of surface negative charge due to the oxidation process.

The influence of the chemical composition of biochar on the PO_4P sorption capacity was found in some experiments (Takaya et al., 2016; Wang et al., 2015). Yao et al. (2012) and Zheng et al. (2013) noticed in their experiments that biochar with a high Mg content (above 3 g kg^{-1}) could have a sufficient PO_4-P sorption capacity. Probably, a low Mg content in the investigated biochar (0.96 g kg^{-1}) caused such a little sorption intensity of PO_4-P by biochar.

EB biochar also had a high sorption intensity to potassium, calcium and magnesium. It adsorbed a significant ($p < 0.05$) amount of potassium and calcium and not a significant ($p > 0.05$) amount of magnesium. Their concentration increased 3.9, 1.1 and 1.04 times for K, Ca and Mg, respectively. A high sorption intensity of these nutrients by biochar can be related to negatively charged particles on the char surface, which increase in aged biochars. A low sorption intensity of Mg by the studied biochar could be partly attributed to the increased Ca concentration, the adsorption of which would be favoured onto the substrate exchange sites compared with Mg (Jalali and Ranjbar, 2009). Low Mg concentrations are considered to be good with respect to the soil structure, as some studies have shown that elevated soluble or exchangeable Mg^{2+} could be deleterious in maintaining the soil permeability (Mahmoodabadi et al., 2013). The studied biochar was produced one year before the experiment and probably had a high amount of negatively charged functional groups on its surface. It could facilitate the attraction of cations to the biochar surface.

A high sorption capacity of biochar resulted in its enrichment with nutrients and that can have an effect on plant growth.

Nutrients uptake from biochar

In the BC treatment, the deficiency in the main macronutrients such as N, P and K and a significant amount of Ca and Mg introduced to the sand with biochar were observed, which could contribute to the pool of plant available nutrients upon incorporation to the soil (Table 5).

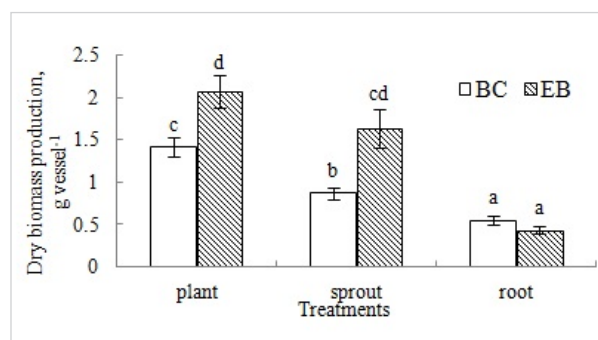**Table 5.** *Amounts of nutrients inserted to the vessels (BC and EB) and adsorbed by biochar*

Element	BC	EB	Nutrients adsorbed by biochar
N, mg vessel⁻¹	0.9 ± 0.06	18.2 ± 1.27	17.3 ± 1.21
P, mg vessel⁻¹	1.6 ± 0.11	5.6 ± 0.39	4.0 ± 0.28
K, mg vessel⁻¹	11.8 ± 0.81	43.8 ± 3.04	32.0 ± 2.22
Ca, mg vessel⁻¹	584.0 ± 40.86	659.2 ± 46.12	75.2 ± 5.31
Mg, mg vessel⁻¹	153.0 ± 10.41	160.4 ± 11.45	7.4 ± 0.55

When biochar was saturated with the nutrient solution (EB treatment), the amount of nutrients in biochar increased significantly, except for the amount of magnesium.

The results showed that the BC biochar was capable of supporting plant biomass production (Fig. 2). Dry biomass of barley plants in BC treatment reached 1.4 g vessel⁻¹. It can be concluded that some nutrients from biochar were available for plants. Based on the results of the sorption experiment, part of ammonia, phosphorus and potassium from biochar could be dissolved by water and subsequently used by plants.

Nutrients adsorbed by biochar had a positive effect on the plant biomass growth. Barley dry biomass was 46% higher in EB treatment in comparison with BC treatment. Similar results with nutrient enriched biochars were found in some experiments (Kamman et al., 2015; Brantley et al., 2015; Schmidt et al., 2015). Brantley et al. (2015) in their study with pine wood-chip biochar found a significant increase of corn yield when biochar was applied together with a nitrogen

Fig. 2. *Dry biomass production of barley plants at the end of the experiment*

fertiliser while biochar alone caused a significant yield decrease in comparison with no biochar treatment. Biochar enriched with mineral nitrogen (NH_4^+ and NO_3^-) and phosphate could work as a fertiliser slowly providing nutrients and, thus, improving plant growth (Kammann et al., 2015; Schmidt et al., 2015).

Dry biomass of barley sprouts in EB treatment was significantly ($p < 0.05$) higher than in BC treatment. The difference reached 90%. Release of the nutrients adsorbed by biochar could be the reason of a higher dry biomass yield in EB treatment. For example, Liu et al. (2019) in their experiment with urea-enriched biochar found a 61–98% release of nitrogen from biochar to the soil through dissolution and diffusion processes.

The influence of biochar on the root growth and the allocation of resources to roots could be a major factor to emphasise nutrient acquisition and, consequently, higher plant growth. Dry biomass of the roots in EB treatment was insignificantly lower than in BC treatment. This can be explained by the physiology of root systems growth, which is dependent on nutrient content. In poor substrates, root growth is more intensive as they search for nutrients. With an optimal soil nutrient composition, the main function of roots is to transport nutrients to sprouts, so the roots form smaller biomass.

Concentration and removal of nutrients by plants

Biochar can increase plant nutrient uptake serving as a source of nutrients and improving the sorption of nutrients from soil (Lehmann et al., 2003). Since biochars are produced from organic materials, they

inherently contain nutrients that are found in minerals. Therefore, the addition of biochar to soil adds free exchangeable bases such as K, Ca, and Mg to occupy soil-exchange sites, thus resulting in an increase in nutrients supplying plant growth (Glaser et al., 2002). Sandy textured soils also give biochar the potential to ameliorate P leaching in soils (Gronwald et al., 2015); therefore, P content should increase with increasing levels of biochar additions (Novak et al., 2009).

Concentrations of nutrients in sprouts and roots of barley plants varied between the treatments (Table 6). N and K concentrations in barley roots were significantly higher ($p < 0.05$) in EB than in BC; while concentrations of Ca and Mg in EB were lower ($p < 0.05$) than in BC treatment. The concentration of P between these treatments was without a significant difference. Barley sprouts in EB treatment showed significantly lower ($p < 0.05$) concentrations of N, P, K and Ca than in BC treatment.

Concentrations of N and K in barley plants were without a significant difference between the treatments (Table 6). However, concentrations of Ca and Mg in BC treatment were significantly ($p < 0.05$) higher than in EB treatment (1.6 and 1.4 times higher, respectively). Probably, lower concentrations of nutrients in plants in this treatment in comparison with BC are connected with higher dry biomass yields of barley in EB treatment and dilution of the nutrients' contents in the plants. Another hypothesis is that nutrients from EB treatment could have a short-term effect due to a flush release of nutrients.

Probably, lower concentrations of nutrients in plants in EB treatment in comparison with BC treatment are connected with higher yields of barley in EB treatment and dilution of nutrients' content in the plants. The total nutrient content in barley plants was compared to test this hypothesis (Table 7).

Table 6. *Concentration of nutrients in barley*

Treatment		N, %	P, %	K, %	Ca, %	Mg, %
Plant	BC	1.75 c	0.74 c	4.99 e	12.52 e	6.14 d
	EB	1.77 c	0.45 ab	4.93 e	7.75 cd	4.32 bc
Sprouts	BC	1.25 b	0.57 b	4.41 d	6.03 c	2.39 ab
	EB	1.15 b	0.29 ab	4.23 c	4.83 b	2.43 ab
Roots	BC	0.50 a	0.17 a	0.59 a	6.49 c	3.75 b
	EB	0.622 a	0.16 a	0.73 b	2.92 a	1.89 a

Data are means of n = 5. Different letters in the same column indicate significant differences between the treatments. (p < 0.05) (ANOVA)

Table 7. *The total content of nutrients in barley plants*

Treatment		N, mg	P, mg	K, mg	Ca, mg	Mg, mg
Sprouts	BC	10.88 ± 0.85c	4.96 ± 0.40c	38.37 ± 2.51c	52.46 ± 4.40c	20.79 ± 1.63c
	EB	18.86 ± 2.67e	4.76 ± 0.68c	69.37 ± 9.81d	79.21 ± 11.3d	39.85 ± 5.57d
Roots	BC	2.15 ± 0.3a	0.73 ± 0.076a	2.54 ± 0.25a	27.91 ± 2.91b	16.13 ± 2.17b
	EB	3.42 ± 0.29b	0.88 ± 0.070b	4.02 ± 0.32b	16.06 ± 1.35a	10.40 ± 0.84a
Plants	BC	13.03 ± 1.15d	5.69 ± 0.47d	40.91 ± 2.76c	80.37 ± 7.31d	36.92 ± 3.8d
	EB	22.28 ± 2.96e	5.64 ± 0.75d	73.39 ± 10.13d	95.27 ± 12.65d	50.25 ± 6.41e

Data are means of n = 5. Different letters in the same column indicate significant differences between the treatments. (p < 0.05) (ANOVA)

N, K and Mg contents in barley plants were significantly higher in EB treatment than in BC treatment, while there was no significant difference in P and Ca contents between these treatments. These results confirm the hypothesis of nutrient dilution in barley plants in EB.

Nutrient-enriched biochar (EB) increased the nitrogen content in barley plants up to 71%, the potassium content up to 79% and the magnesium content up to 36% in comparison with BC treatment. Similar results were found in a study of Morandi et al. (2019). In their experiment with biochar enriched by rock phosphate and cow manure, an increase in N, P and K in saline soil was observed. In an experiment of Kizito et al. (2019), digestate-enriched biochar improved maize growth and increased the content of soil organic matter and macronutrients in clay loam soil. The relationship between dry matter and nutrient content in barley plants suggested that biochar enriched with nutrients could slowly release them and provide to the plants, thus improving their growth.

N and P content in roots and sprouts of barley under BC and EB treatments were not significantly different ($p > 0.05$). The concentration of K in barley roots in EB treatment increased by 24% ($p < 0.05$) under the influence of potassium adsorbed by biochar from the nutrient solution. Conversely, the concentration of K in barley sprouts in EB treatment was 4% lower ($p < 0.05$) than in BC treatment. The lower concentration of potassium in EB barley sprouts can be connected with significantly higher dry biomass of EB sprouts in comparison with BC and dilution of this element in sprouts. Some experiments showed an increase in K uptake by plants after biochar application and availability of K from biochar to plants (Lehmann et al., 2003; Chan et el., 2008). However, Widowati and Asnah (2014) in their experiment noticed a decrease in the potassium uptake for the treatment of joint application of biochar with a K fertiliser compared with the treatment with a K fertiliser only while yields in biochar treatments were higher.

Conclusions

It was demonstrated that the biochar made of wood had high porosity and sorption capacity. It adsorbed such cations as ammonium, calcium, phosphorus and potassium. The biochar saturated with the Gelrigel solution showed the ability to adsorb a significant ($p < 0.05$) amount of ammonium, phosphorus and potassium by 18, 3.5 and 3.9 times higher, respectively, compared with control. The sorption capacity of biochar can be an option for nutrient leaching mitigation. However, there is a need in further investigations of factors which influence biochar sorption capacity and its effect on nutrient leaching.

The current results indicate that a single BC application of 25 t ha^{-1} can also increase plant biomass at least over the first cropping season. But the nutrient-enriched biochar showed the ability to support significantly ($p < 0.05$) higher dry biomass of barley plants, which was by 46% higher of what was achieved using non-enriched biochar. Further research will be important to validate these results for soils in field experiments.

Acknowledgements

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