

The Effectiveness of Biochar on Soil pH and Sorption Capacity of Luvisol after the 1st and 9th Year of Application

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Recent research indicates that biochar applied to soil brings several positive benefits for farmers. However, there is still lack of data on how biochar behaves in the soil environment over extended periods, beyond just a few years. This study evaluated the effectiveness of two biochar rates (B0 – control; B10 – 10 t.ha⁻¹; and B20 – 20 t.ha⁻¹) on changes in soil pH and soil sorption capacity after 1st and 9th year of application to silt loam Haplic Luvisol (experimental base of SUA in Nitra, Dolná Malanta, Slovakia). The results indicate a decreasing effect on soil pH over time since the application of biochar. However, the higher rate significantly increased soil pH even after 9th year of application. Similarly, the effectiveness of biochar on soil sorption capacity decreased over time.

Keywords: basic cations, base saturation, biochar, cation exchange capacity, soil pH

1 Introduction

Biochar has recently garnered significant attention from the scientific community, as evidenced by 33,499 records in the Scopus database for the period 2001–2024. In 2001, the database recorded only 2 original scientific papers on this topic, while in 2008 there were 12 studies for that year, and by 2010, there were 101 per year. In 2016, the number of scientific papers on biochar increased tenfold (1,048 studies per year), and by 2020, there were 3,062 papers per year related to this topic. As of 2024, the Scopus database records 7,074 studies. It is evident that the topic has received increased attention, showing an exponential growth rate in recent years.

The published studies report positive, negative, and neutral effects of biochar on a wide range of soil properties, the environment, crop yields, etc. However, most studies indicate the positive effects of biochar on soil environment changes. For example, its incorporation into the soil increases soil pH, especially in acidic soils (Blanco-Canqui et al., 2024). One of the most significant properties of biochar is its large surface area and

the presence of micropores. Liang et al. (2006) reported that after incorporating biochar into the soil, the total surface area of the soil increased 4.8 times compared to soil without biochar, suggesting its positive impact on soil sorption capacity. The porous structure of biochar provides a habitat for soil microorganisms (Lehmann et al., 2011). Biochar applications can immobilize heavy metals such as Cu, Pb, and Cd in acidic soils, reducing their availability and phytotoxicity to plants (Li et al., 2017). Many scientific studies highlight the positive impact of biochar applied to soil on increasing carbon sequestration in the soil and reducing CO₂ and N₂O emissions from the soil into the atmosphere (Horák & Šimanský, 2017; Horák et al., 2021). Biochar improves the aggregation process (Šimanský, 2016), and the physical and hydro-physical properties of the soil (Igaz et al., 2018).

The effect of biochar on changes in soil properties, including soil pH and sorption capacity, primarily depends on its characteristics. The properties of biochar incorporated into the soil change due to chemical,

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physical, and biological processes occurring in the soil, with the aging process of biochar accelerating in acidic soils (Rechberger et al., 2017). During the aging process, the mechanical properties of biochar improve, the release of labile fractions decreases, which, in addition to increasing carbon sequestration, can improve processes such as nitrification inhibition and ammonia oxidation, leading to reduced CO₂ and N₂O emissions (Wang et al., 2021). For various stakeholders (farmers, biochar producers, environmentalists, and the scientific community), the effectiveness of biochar in soil due to aging is crucial. Therefore, this issue must be given increased attention. From a farmers' perspective, it is extremely important to apply biochar to the soil that is not an environmental burden while improving soil properties in the long term, resulting in benefits such as safe production. Based on the above context, the effect of applying two rates of biochar after 1 and 9 years on changes in soil pH and soil sorption capacity was evaluated.

2 Material and Methods

2.1 Site Description

The experimental base of Slovak University of Agriculture (in Dolná Malanta) is situated in the northeastern part of the Danubian Lowland (lat. 48° 19' 00"; lon. 18° 09' 00"), in the western part of the Žitava Upland, at the lower basin of the Selenec stream. It is located 4 km east of the city of Nitra, in a maize production area. The experimental plot has a flat character with a slight southwest slope, at an altitude of 170–180 m above sea level. From a geological point of view, the experimental base is in the area of the geological interface between the Crystalline-Mesozoic massif of the Tribeč Mountains and the Žitava Upland. The geological substrate is mainly composed of eluvial-deluvial sediments of the Tribeč Mountains, which in some local enclaves mix with loess sediments of the Žitava Upland. The soil type is Haplic Luvisol (IUSS Working Group WRB, 2015). Before the experiment, the soil was on average composed of 15.2% of sand, 59.9% of silt, and 24.9% of clay (silt loam in soil texture). The soil pH was slightly acidic (5.71). Soil organic carbon content was low (9.13%), and soil had soil sorption complex saturated to 85% with cation exchange

capacity 142 mmol (p)⁺.kg⁻¹. The area belongs to a very warm and very dry agro-climatic region with an average annual precipitation of 559 mm and an average annual air temperature of 10.8 °C (based on long-term averages in 1991–2020).

2.2 Experimental Setup

The experiment is designed with two study factors (biochar and N fertilizer application). Biochar was applied once at 0, 10, and 20 t.ha⁻¹ in 2014. Three levels of N fertilization (0, 1st and 2nd N levels) were combined with biochar. Detailed information about treatments is published in Horák et al. (2021). The experiment was managed under no till. The characteristics of the biochar used in this study are reported in Table 1. Biochar was acquired from Pyreg GmbH, Dörth, Germany. The pyrolysis temperature of the biochar was 550 °C for 30 min. The crop rotation was based on alternating four crops: wheat, barley, maize, and peas. In 2015, at the time of soil sampling, maize was grown here, and in 2023, spring barley was grown.

2.3 Soil Sampling and Analysis

Soil samples were taken at monthly intervals during the growing season of both crops. In 2015, sampling was conducted monthly from April to September, and in 2023 from April to July, which corresponds to the 1st and 9th year after the initial and repeated application of biochar to the soil. Soil samples were taken only from biochar treatments (B0 – control, B10 – 10 t.ha⁻¹ of biochar, and B20 – 20 t.ha⁻¹ of biochar). The soil samples were analysed for soil pH and soil sorption capacity using standard methods (Hrivňáková et al., 2011).

2.4 Statistical analysis

All statistical analyses were conducted with Statgraphics Centurion XV. I (Statpoint Technologies, Inc., Warrenton, VA). All results are reported as means with a standard deviation. The differences between all treatments were evaluated using one-way analysis of variance (ANOVA), the Tuckey test ($P < 0.05$). In all treatments, dependencies between the soil pH and sorption capacity were evaluated using simple correlations and were expressed by the Pearson's correlation coefficient at different probability levels.

Table 1 The physical and chemical properties of applied biochar

pH	Particle-size	Organic C	Total N	C : N	Bulk density	Specific surface area	Ca	Mg	K	Ash
	(mm)	(%)	(g.cm ⁻³)		(m ² .g ⁻¹)	(g.kg ⁻¹)				
8.8	1-5	53.1	1.4	37.9	0.21	21.7	57	3.9	15	38.3

3 Results and Discussion

3.1 Effect of Biochar on Soil pH

Alkaline biochar (pH of biochar in this study 8.8) has a liming effect, acting more intensively in acidic than in neutral soils (Blanco-Canqui et al., 2024). However, its effectiveness is highest in the 1st year after application, as documented by the findings in this study (Fig. 1). The application of biochar had a statistically significant effect ($P = 0.000$) on increasing soil pH values one year after its incorporation into the soil. The higher the rate of biochar, the greater the increase. Compared to the control (B0), soil pH values increased by 3% and 9% in the B10 and B20 treatments, respectively, one year after application. In 2023, i.e., nine years after the incorporation of biochar into the soil, soil pH values were still statistically altered ($P = 0.000$) depending on the biochar application rate. However, while the lower application rate (10 t.ha⁻¹) showed no effect on changes in soil pH, the higher rate (20 t.ha⁻¹) maintained soil pH values 0.22 pH units higher compared to the control. Thus, the significant factor influencing soil pH was the biochar application rate. Several studies (Jin et al., 2019; Juriga & Šimanský, 2019; Blanco-Canqui et al., 2024) have also indicated that the higher the biochar rate, the greater the increase in soil pH. In addition to being alkaline, the applied

biochar contained basic cations (Table 1), which can react with H⁺, increasing pH, especially in acidic soils, as noted in the study by Novak et al. (2009). Comparing the differences between 2015 and 2023 within individual treatments, decreases in soil pH were observed in all treatments, indicating acidification and the need to lime the soil. In B0, a statistically significant decrease in soil pH from 5.63 to 5.52 ($P = 0.0003$) was observed. A similar trend was found in the B10 treatment (from 5.77 to 5.45; $P = 0.0000$) and B20 (from 6.11 to 5.74; $P = 0.0149$), with the higher the rate of biochar, the greater the difference between the years. Overall, while a higher rate of biochar increased pH in acidic soil more rapidly, the liming effect of biochar in the soil decreased more intensively with higher rates (Fig. 1).

3.2 Effect of Biochar on Soil Sorption Capacity

One year after the application of biochar, there were statistically significant changes in hydrolytic acidity (Ha) and the base saturation (Bs). The higher the rate of biochar, the more intense the changes (Fig. 2). Compared to B0, Ha content decreased by 1.56 and 2.67 mmol (p)⁺ kg⁻¹ in B10 and B20, respectively. Despite the sorption complex being fully saturated in the control, its saturation values significantly increased ($P = 0.0218$) after the application of both biochar rates (Fig. 2). On the other hand, there was a tendency to increase in the sum of basic cations (SBC) ($P = 0.7297$) and cation exchange capacity (CEC) ($P = 0.7701$) after the application of both biochar rates, although without statistical significance. Depending on its production conditions, biochar contains basic cations (Rajkovich et al., 2012), which enter the soil upon application. Ding et al. (2016) reported that the higher the rate of biochar incorporated into the soil, the greater the volume of basic cations that can be extracted into the soil. The applied biochar contained 15 g.kg⁻¹ K, 57 g.kg⁻¹ Ca, and 3.9 g.kg⁻¹ Mg, but their presence in the biochar did not significantly affect the change in SBC and CEC in this study. Only a tendency to increase in SBC and CEC after biochar incorporation was found, without statistical significance in 2015. The explanation lies in the fact that the sorption complex was fully saturated, making further saturation more difficult, which could have resulted in the non-significant increase in SBC and CEC after biochar application. However, the overall situation changed over the observed period. Ha significantly increased from 1st to 9th year. Ha significantly increased, while Bs decreased across all treatments. There was also a non-significant tendency for a decrease in SBC and CEC over the period from 1st to 9th year after application (Fig. 2). Nine years after biochar application to the soil, no effect on Ha and Bs was observed across all treatments. On the other hand, surprisingly, the higher

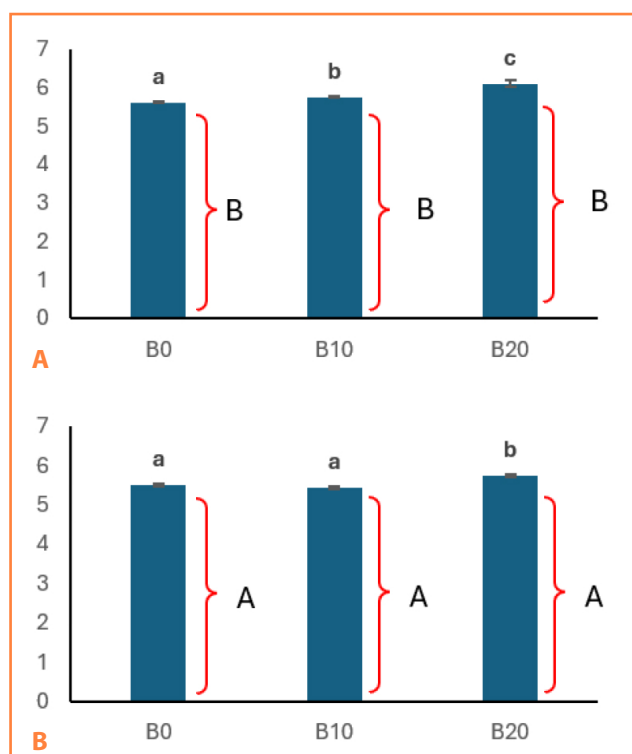


Figure 1 Soil pH after
A – 1st year in 2015, B – 9th year of biochar in 2023
Different letters between treatments (a, b, c), and years (A, B) indicate homogeneous groups of the means based on Tukey's test at 0.05 significance level

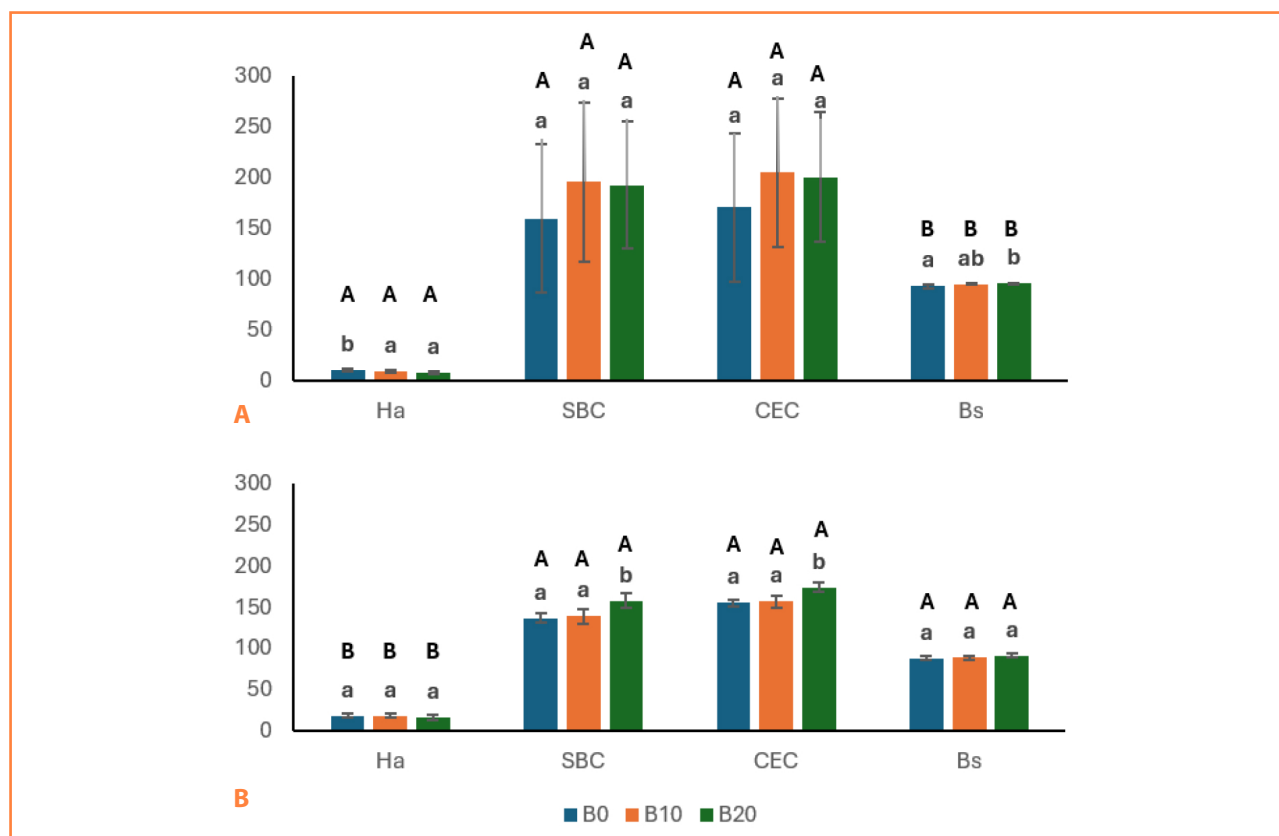


Figure 2 Soil sorption capacity
Ha – hydrolytic acidity, SBC – sum of basic cations, CEC – cation exchange capacity, Bs – base saturation after A – 1st year in 2015, B – 9th year of biochar in 2023
Different letters between treatments (a, b, c), and years (A, B) indicate homogeneous groups of the means based on Tukey's test at 0.05 significance level

rate of biochar (B20) still significantly increased SBC and CEC values compared to B10 and B0 treatments in 2023. These findings indicate that biochar applied to the soil gradually reduces its effectiveness in improving soil sorption capacity. After biochar is incorporated into the soil, it undergoes gradual aging (Rechberger et al., 2017; Wang et al., 2021). The pores in biochar gradually become clogged with fine soil particles (content of clay 24.9% in the soil) (Blanco-Canqui, 2017) or obstructed by earthworm activity (Šimanský et al., 2022), smaller biochar particles (biochar size particle 1–5 mm) become occluded within stable aggregates (Juriga & Šimanský, 2018), and become inactive, ultimately reducing the effectiveness of biochar over time after its incorporation into the soil. The results of this study indicated that the 20 t.ha⁻¹ rate was more effective on sorption capacity than the 10 t.ha⁻¹ rate.

3.3 Correlations Between Soil pH and Soil Sorption Capacity

The correlation coefficients between soil pH and soil sorption capacity depending on the treatments are shown in Table 2. Soil pH negatively correlated with Ha

in all treatments, with the strongest negative correlation coefficient found in B10 >B20 >B0. Increasing soil pH as a result of biochar application positively affected the increase in Bs values. However, in this case, it did not mean that the higher the rate of biochar, the higher the saturation in the sorption complex of basic cations. The explanation, as mentioned above, may lie in the fact that if the soil is saturated with bases, as was the case in this study, a higher rate does not significantly saturate the sorption complex. Carter et al. (2013) stated that higher pH as a result of biochar application also increases CEC in the soil. They explain this by the higher input of organic matter from biochar, which contains functional groups on its surface (Ding et al., 2016), and in this way, biochar can increase CEC in the soil. However, the effectiveness of biochar on CEC in soils depends on several factors. In this study, soil pH did not correlate with CEC. Similar results were published by Mikajlo et al. (2024), who explained it by the different properties of biochar, especially its feedstock. Other results of this study indicated statistically significant negative and positive correlations between Ha and Bs, as well as SBC and Bs, respectively, across all treatments (Table 2).

Table 2 Correlation coefficients between soil pH and sorption capacity

	Soil pH	Ha	SBC	CEC	Bs
B0					
Soil pH	1	-0.664*	0.189	0.138	0.594
Ha		1	-0.228	-0.152	-0.912***
SBC			1	0.997***	0.600
CEC				1	0,537
Bs					1
B10					
Soil pH	1	-0.882**	0.503	0.435	0.895***
Ha		1	-0.354	-0.271	-0.953***
SBC			1	0.996***	0.612
CEC				1	0.541
Bs					1
B20					
Soil pH	1	-0.783**	0.172	0.103	0.719*
Ha		1	-0.341	-0.258	-0.969***
SBC			1	0.996***	0.559
CEC				1	0.485
Bs					1

Ha – hydrolytic acidity, SBC – sum of basic cations, CEC – cation exchange capacity, Bs – base saturation, B0 – no biochar, B10 – 10 t.ha⁻¹ of biochar, B20 – 20 t.ha⁻¹ of biochar

4 Conclusion

The results of this study indicate that biochar applied to soil gradually reduces its effectiveness in increasing soil pH and improving soil sorption capacity in acidic Luvisol. In terms of soil pH and sorption capacity, the 20 t.ha⁻¹ rate of biochar was more effective than the 10 t.ha⁻¹ rate. Overall, while a higher rate of biochar increased pH in acidic soil more rapidly, the liming effect of biochar in the soil decreased more intensively nine years after its application. Since the sorption complex of the Luvisol was fully saturated before the experiment began, further saturation was less effective. Overall, the relationships between soil pH and soil sorption capacity, in addition to the rate, will also result from the properties of biochar and its aging in the soil.

Based on the results obtained, it is evident that the Luvisol in the experiment requires farmers' attention. The more intensive the intervention (higher rate of biochar, fertilization), the more care this soil will require in the future.

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