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Research Article

Exploring Biochar with N-Fertilizer Effects on Soil CO_2 Emissions and Physical-Chemical Properties as a Climate Change Mitigation Tool

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The global agriculture industry is facing never before faced issues in the form of soil degradation, water scarcity, rising greenhouse gas emissions, and climate change. Among the possible remedies, applying biochar to the soil has drawn interest as a viable strategy. Although a great deal of literature has been written about the benefits and drawbacks of applying biochar initially, there is still a significant amount of research on the effects of using biochar repeatedly. This study seeks to address this gap by examining the varied effects of both the initial application (at rates of 0 t.ha^{-1}, 10 t.ha^{-1}, and 20 t.ha^{-1}) and the reapplication of biochar (at rates of 0, 10, and 20 t.ha^{-1}), especially when combined with different levels of nitrogen fertilizer (0, 108, and 162 kg.ha^{-1}). The investigation focuses on soil properties and CO_2 emissions from Haplic Luvisol in the temperate climate zone (Slovakia). The results showed that biochar generally improved soil properties, such as soil pH (KCl) (p <0.05), shifting it from acidic towards moderately acidic, and generally led to a decrease in ammonium (NH_4^+) and nitrate (NO_3^-) content. The second level of fertilization, combined with different biochar treatments, yielded the most efficient results in physical properties such as soil temperature, bulk density (BD), and soil water content (SWC) compared to control treatments without biochar. Biochar application contributed to the reduction of both average daily CO_2 emissions and cumulative CO_2 emissions during the study period (April – October) in 2022 compared to the control without biochar application.

Keywords: biochar, nitrogen fertilization, soil chemical properties, soil physical properties, CO_2

1 Introduction

These days, global climate change is a significant issue. It causes the planet's average yearly temperature to gradually rise, a trend that started with the start of the industrial revolution at the turn of the millennium. The current spate of extreme weather events has intensified discussions on Earth's temperature rise (Albergel et al., 2010). Human activity has had a substantial impact on climate change. First and foremost, this is caused by changes in the amount and quantity of greenhouse gases (CO_2, N_2O, CH_4) in the atmosphere (Mikhaylov et al., 2020). Between the start of industrialization and 2018, the atmospheric concentration of CO_2 rose from 280 to 408 parts per million (Shafawi et al., 2021). Significant effects of the steadily growing CO_2 in the atmosphere include severe droughts, extreme weather, glacier melting, and increasing sea levels in the telluric environment (Cao et al., 2022). Soil respiration, or the flow of CO_2 from the soil, is a significant factor in the global carbon balance. It contributes between 20 and 40% of the overall flow of CO_2 into the atmosphere. Capturing CO_2 before it leaves the emission sources and enters the atmosphere is one of the practical ways to lower CO_2 emissions (Shafawi et al., 2021). The emission rate of soil CO_2 is closely linked to the quantity and composition of organic materials present or added into the soil. This intricate relationship involves the interplay of soil physical, chemical, and biological processes, in addition to environmental factors such as temperature, precipitation, etc. Some studies show that production CO_2 is higher in fertilized soils compared to their non-fertilized counterparts. Moreover, findings indicate that following a period of dryness, soils, upon receiving increased moisture (post-rain), release more CO_2 than soils that have not experienced prolonged

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dry conditions. Notably, more productive soils exhibit a lower CO_2 release compared to less productive ones (Horák et al., 2020). It is ideal to create economically feasible, effective CO_2 absorbent materials. Biochar has been identified as one of the most promising CO_2 sorptive materials (Jung et al., 2019). The solid byproduct of heating biomass at zero or extremely low oxygen levels is called biochar. It is a black, porous, carbon-rich substance that offers significant potential advantages for soil and plant growth (Shackley et al., 2016). With the expected increase in CO_2 emissions in the atmosphere there is a growing focus among environmentalists on mitigating CO_2 emissions from soils and increasing soil carbon (C) reserves. This emphasis arises from the recognition that soil organic carbon (SOC) plays a crucial role in influencing soil fertility. The SOC content in arable soils is influenced not only by soil genesis but also by the intensity and depth of plowing. In Slovakia, the average values of SOC content in arable soils typically range from 1% to 2.5%. An innovative and viable solution to increase SOC content involves the application of biochar to the soil (Horák et al., 2020). The kind of feedstock and temperature of pyrolysis affect the physical and chemical characteristics of biochar (Kotuš et al., 2022). The specific surface area (SSA), chemical content, and pore structure of biochar all affect how well it adsorbs CO_2 (Cao et al., 2022). Furthermore, biochar has been regarded as a potentially effective environmental media for soil amendment. In specifics, adding biochar to soil offers an excellent opportunity to raise soil fertility (Jung et al., 2019).

This study aimed to assess the impact of applied and reaplied biochar, either alone or in combination with an N-fertilizer in 2022 on soil CO_2 emissions and soil chemical (pH, NH_4^+, NO_3^-, SOC) and physical (SWC, soil T, BD) properties. Specifically, we aimed to investigate the hypothesis (H1) that adding biochar lowers CO_2 emissions from arable soils and improves soil chemical and physical properties.

2 Material and methods

2.1 Field site

The field experiment was set up in 2014 at the Slovak University of Agriculture's experimental site at Dolná Malanta, which is located close to Nitra in Slovakia (48° 19´ N, 18° 09´ W). The site is in the temperate climate zone, with a mean annual air temperature of 9.8 °C and mean annual rainfall of 539 mm (30-year climate normal, 1961–1990). Mean air temperature and rainfall in 2022 were 11.05 °C and 551.6 mm during the studied year. The agricultural crop output at the experimental location was managed conventionally for several decades prior to the field experiment's implementation. According to the soil taxonomy, the soil with contents of 15.2%, 59.9%, and 24.9% of sand, silt, and clay was categorized as a silt loam Haplic Luvisol. The average pH of the soil was 5.71 and its SOC content was 9.13 g.kg^{-1}.

2.2 Experimental design

This field experiment started in March 2014 at that time was biochar applied at doses 0, 10 and 20 t.ha^{-1} (B0, B10, B20) and that was followed by three application levels (N0, N1 and N2) of calcium ammonium nitrate (LAD 27) as a mineral nitrogen fertilizer. There was no N-fertilizer at the N0 fertilization level. The N1 fertilization level was determined using the balancing approach based on each crop's requirements. The N2 fertilization level comprised 50% more than the N1 fertilization level. Corn (*Zea mays* L.) variety KWS ALMANZO was planted in 2022 at the beginning of April and harvested at the end of October. In 2022 (studied year), N-fertilizer was applied at rates of 0, 108 and 162 kg N.ha^{-1}. The original plots that had previously been treated with biochar were split into two sections in 2018 (two 4 × 3 m subplots), and the biochar was reapplied

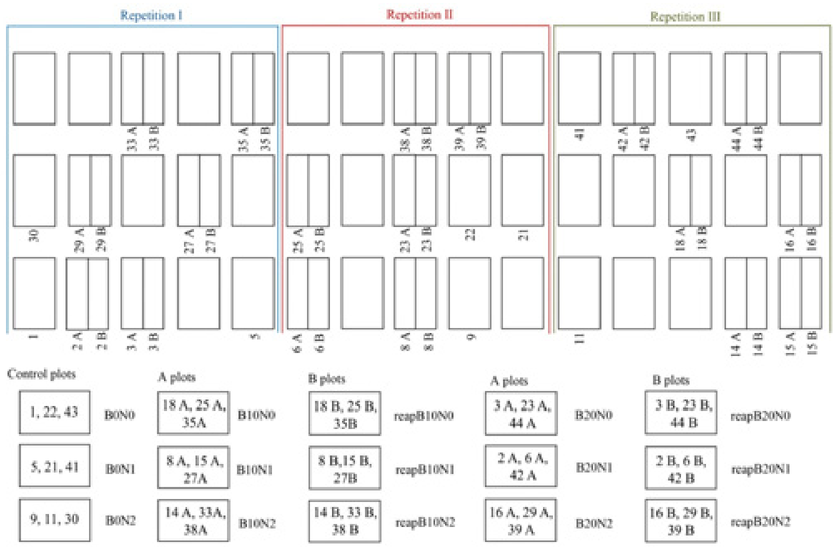

Figure 1 Schematic arrangement of the experimental field with 27 highlighted plots which were used in this experiment
A – subplots with the biochar applied only in 2014; B – subplots with the biochar reapplication in 2018; and control plots without biochar but with different rates of the mineral N-feritilizer

at the same rates as in 2014. As a result, there were 15 treatments with three replicates during the 2018 study period (27 previous plots plus 18 reapplication subplots for a total of 45 plots) which is showed in Fig. 1. The field experiment included the following 15 treatments in three replications (Table 1).

The 27 test plots (4 × 6 m) were placed in a random pattern with 1.2 m wide access pathways in the intermediate rows and 0.5 m wide protection strips between them. Before the experiment began, the entire field was ploughed. The plots with varying treatments were then localized, and biochar was applied, with the material being immediately incorporated into the soil (0–0.1 m). Paper fiber sludge and grain husks (1 : 1, Sonnenerde, Austria) were pyrolyzed at 550 ºC for 30 minutes in a Pyreg reactor (Pyreg GmbH, Dörth, Germany) to create the biochar utilized in the experiment. The biochar's fundamental physical and chemical characteristics are as follows: pH 8.8, bulk density 0.21 g.cm^{-3}, surface area 21.7 m^2.g^{-1}, ash content 38.3%, and C content 53.1%.

2.3 Measurement of CO_2 emission from soil

Air samples were collected between April and October in 2022 using the closed chamber method (Elder & Lal, 2008). In every treatment plot, a metal collar frame (galvanized sheet) was placed 0.1 m deep in the ground and kept undisturbed in between soil management activities. The collars were taken off for management operations and then put back in their proper places. The removable cover PVC chambers, which were 0.25 m in height and 0.3 m in diameter, were water-sealed onto the bottom collars at each sampling event. Two-week intervals were used to collect gas samples. Gas samples were collected using a 60 mL plastic syringe to collect from 20 mL tube fittings that were sealed with a septum at 0, 30 and 60 minutes after chamber deployment. The collected gas was then transferred to pre-evacuated 12 mL glass vials (Labco Exetainer). A gas chromatograph (GC-2010 Plus Shimadzu) fitted with a thermal conductivity detector (TCD) was used to test gas samples for CO_2. CO_2 emissions on a daily average are expressed in kg.ha^{-1}.day^{-1}. The emissions between each sample day was interpolated to get the cumulative CO_2 fluxes (April through October), which are expressed in t.ha^{-1}.

2.4 Measurements of the chemical and physical soil properties

Soil samples were taken biweekly between April and October (2022) in order to measure the pH of the soil (potentiometrically in 1 M KCl at KCl:soil ratio of 1 : 2.5) and the amount of inorganic nitrogen forms (N-NH_4^+ and

Table 1 Overview of the treatments and specific amount of applied biochar and inorganic mineral nitrogen fertilizer in the field experiment

Treatments	Biochar application in 2014 (t.ha^{-1})	Biochar reapplication in 2018 (t.ha^{-1})	N-fertilization application in 2022 (kg.N.ha^{-1})
N0 level – unfertilized treatments			
B0N0	0	0 0	
B10N0	10	0	0
B20N0	20	0	0
reapB10N0	10	10	0
reapB20N0	20	20	0
N1 level – fertilized treatments			
B0N1	0	0	108
B10N1	10	0	108
B20N1	20	0	108
reapB10N1	10	10	108
reapB20N1	20	20	108
N2 level – fertilized treatments			
B0N2	0	0	162
B10N2	10	0	162
B20N2	20	0	162
reapB10N2	10	10	162
reapB20N2	20	20	162

$N-NO_3^-$). Using the calorimetric approach, a spectrometer (WTW SPECTROFLEX 6100, Weilheim, Germany) was used to measure the quantity of soil $N-NH_4^+$ and $N-NO_3^-$ in soil filtrates (Yuen & Pollard, 1954). Three disturbed, randomly spaced soil samples were taken for each plot at a depth of 0–0.1 m once a month from April to October. After mixing, representative soil samples were created for each plot. C_{org} content in samples collected in April and October was measured with the Tyurin wet oxidation method (Dziadowiec & Gonet, 1999). Every time there was a gas sampling event, disturbed soil samples were taken at a depth of 0–0.1 m to estimate the soil water content (SWC) with using the gravimetric method. A Volcraft DET3R thermometer was used to measure the temperature of the soil at a depth of 0.05 m twice a month. The bulk density (BD) of the undisturbed soil was measured twice a year (in June and November 2022) using steel cores with a volume of 100 cm^3. The 3 samples were taken randomly from each individual plot at a depth of 0.02–0.07 m. This makes 9 representative soil samples per treatment (a grand total of 135 soil samples per sampling event). Gravimetric water content and soil BD data were used to compute the volumetric soil water content.

2.5 Statistical analyses

The study evaluated the effects of biochar to CO_2 emissions, and certain chemical and physical soil properties by a one-way analysis of variance (ANOVA) using the Statgraphics Centurion program (XV v. 15.1.2) and the LSD test (p <0.05).

3 Results and discussion

3.1 Soil chemical properties

The pH of the soil was 5.6 before the experiment establishment in 2014 was a bit acidic. Generally, biochar applied either with or without N-fertilizer, increased the pH of the soil in all treatments compared to the control treatments that did not include biochar. More pronounce positive effect was found in reaplied biochar treatments. Statistically significant increase (p <0.05) was found in most fertilized treatments. The soil pH increased by 0.03–0.16, 0.18–0.26 and 0.29–0.53 pH units for N0, N1, and N2 fertilizer levels, respectively. A similar results were found on the same Haplic Luvisol by Kubaczyński et al. (2023) using dosages of biochar at 0, 1, 5, 10, 20, 30, 40, 50, 60, 80, and 100 $t.ha^{-1}$. This study found that introduction of biochar significantly increased the soil pH from its initial value without biochar (5.04 ±0.08) for almost all doses, excluding 1 $t.ha^{-1}$, with improvements ranging from 0.24 to 1.71 units. Since the biochar is alkaline (in our case, with a pH of 8.8), it has the potential to increase soil pH, but this effect could be softened by adding nitrogen fertilization (Kotuš et al., 2022). Yu et al. (2018) for instance, examined the impacts of nitrogen ammonium fertilizer applied alone at a rate of 30 $kg.N^{-1}$ ha^{-1}, as well as the effects of applying it in conjunction with 19.5 $t.ha^{-1}$ of biochar. The pH of the soil was 5.3 following the addition of nitrogen fertilizer alone, and it increase to 6.0 following the application of biochar containing nitrogen fertilizer. The ammonium form of nitrogen fertilizers used over a long period of time may be the cause of soil acidity (Kotuš et al., 2022). In this study, the effect of acidification with N fertilization was eliminated by using calcium-ammonium nitrate, and the maximum increase in soil pH (Table 2) was noted in the treatments with applied and reapplied biochar at both rates (B10 and B20), combined with second level of N-fertilizer. The biochar acid/base characteristics are determined by the oxygen-containing functional groups on its surface. The primary process behind biochar's ability to buffer the pH of soil is thought to be the interaction between the oxygen-containing groups on its surface and their dissociation (Cybulak et al., 2019). Consequently, it serves as a liming agent, enhancing conditions in acidic soils by promoting greater nutrient accessibility and improving overall soil structure (Shackley et al., 2016). The soluble ash alkalinity found in biochar can quickly be released into the soil and percolate down the soil profile, leading to a modification in soil pH. Consequently, biochar can serve as a viable alternative amendment for neutralizing soil acidity (Kotuš et al., 2022).

Generally, throughout the 2022 growing season, the application of nitrogen fertilizer led to an increase in the average NH_4^+ content within the examined soil. Specifically, the NH_4^+ levels increased from 13.69 ±2.3 $mg.kg^{-1}$ in the B0N0 treatment to 43.16 ±10.5 $mg.kg^{-1}$ and 65.07 ±15.6 $mg.kg^{-1}$ in the B0N1 and B0N2 treatments, respectively (Table 2). Generally, the biochar application to soil decreased the NH_4^+ contents in all treatments except B20N0 treatment, however without any statistical significance (p <0.05). There was also found that all reapplication biochar treatments showed more stronger decreasing effect on NH_4^+ in both fertilized levels (N1 and N2). At the first level of fertilization biochar decreased NH_4^+ content in treatment reapB10N1 by 33.04% and in reapB20N1 by 46.59% compared to the control (B0N1), while in the second level of fertilization, biochar decreased the NH_4^+ content in reapB10N2 and reapB20N2 by 40.57% and 26.71% respectively compared to control (B0N2).These results align with findings from Hailegnaw et al. (2019), indicating that in soils with relatively high NH_4^+ contents, biochar demonstrated the ability to reduce ammonium content. In the study by Li et al. (2019), compared with B0N2 (without biochar and 240 $kg.N.ha^{-1}$

fertilization), B2N2 (40 t.ha^{-1} biochar and 240 kg.N.ha^{-1} fertilization) significantly reduced the NH_4^+ stock in the plow layer soil (depth 0.0–0.2 m) by 24.4%.In studies by Takaya et al. (2016) and Wang et al. (2015), they suggest that biochars with large surface areas may not always have better NH_4^+ adsorption capacities when considering cations. This implies that surface area might not be the main factor influencing NH_4^+ adsorption. The improvement in NH_4^+ adsorption is likely connected to the existence of acidic functional groups, particularly phenolic OH and carboxyl C=O. In case of NO_3^- content the application of nitrogen fertilizer led to an increase in the average NO_3^- content. Specifically, NO_3^- levels increased by 7.36–9.93% in the B0N0 treatment to 10.74–32.23% and 14.33–23.17% in the B0N1 and B0N2 treatments, respectively (Table 2). Overall, biochar application to the soil decreased NO_3^- contents in all treatments except B10N0, B20N0, and reapB10N0 treatments when compared to its individual control treatments. However, these differences were not statistically significant (p <0.05). In the study by Li et al. (2019), concentrations and stocks of NO_3^- decreased with the application of biochar under N1 (120 kg.ha^{-1} N) and N2 (240 kg.ha^{-1} N) conditions. When compared to the application of N fertilizer alone (without biochar) in N1 and N2 treatments, the B1 (20 t.ha^{-1}) treatment resulted in a reduction of NO_3^- stocks in the subsoil (depth 0.2–0.6 m) by 13.2% and 74.7%, respectively. According to Kameyama et al. (2012), biochar exhibits low affinity for NO_3^- adsorption due to the prevalence of negative surface charges over positive ones. In the study by Montes-Morán et al. (2004), Amonette and Joseph (2012) assert that the presence of basic functional groups such as chromenes, ketones, and pyrones on biochar can enhance the adsorption of NO_3^- to biochar. According to Mukherjee et al. (2011), Lawrinenko and Laird (2015), and Kammann et al. (2015), the adsorption of NO_3^- is attainable through unconventional hydrogen bonding interactions between NO_3^- ions and the surface of biochar.

In both sampling times (spring and autumn), the C_{org} content varied in treatments without fertilization and in the first level of fertilization during autumn sampling (Table 2). The highest C_{org} content was observed in the B20N0 (increased by 0.83% and 9.24% compared to B0N0) and reapB20N0 (1.66% and 17.97%) treatments during spring and autumn sampling, respectively. In the spring samples, biochar increased C_{org} content in all treatments at the first level of fertilization (15.22–37.44%)

Table 2 Selected chemical properties (soil pH, NH_4^+, NO_3^-, SOC) of the soil with different treatments in 2022 (means ±standard errors). Different letters (a, b) within columns for each fertilized group show that the means are significantly different at p <0.0

Treatments	$pH_{(KCl)}$	NH_4^+ (mg.kg^{-1})	NO_3^- (mg.kg^{-1})	C_{org} (spring) (g.kg^{-1})	C_{org} (autumn) (g.kg^{-1})
	n = 3	n = 3	n = 3	n = 3	n = 3
not fertilized group – N0 level (0 kg.N.ha^{-1})					
B0N0	5.15 ±0.2^a	13.69 ±2.3^a	11.28 ±1.3^a	13.25 ±1.2^a	13.86 ±4.7^a
B10N0	5.18 ±0.2^a	12.43 ±1.6^a	12.11 ±1.5^a	12.55 ±1.8^a	11.04 ±0.6^a
B20N0	5.22 ±0.1^a	14.04 ±1.6^a	11.51 ±1.4^a	13.36 ±1.1^a	15.14 ±3.8^a
reapB10N0	5.20 ±0.1^a	13.17 ±2.1^a	12.40 ±1.3^a	11.70 ±0.9^a	11.95 ±0.6^a
reapB20N0	5.31 ±0.1^a	13.19 ±2.3^a	10.19 ±0.9^a	13.47 ±1.6^a	16.35 ±5.0^a
fertilized group – N1 level (108 kg.N.ha^{-1})					
B0N1	4.90 ±0.2^a	43.16 ±10.5^a	28.67 ±4.3^a	14.13 ±2.0^a	13.18 ±2.8^a
B10N1	5.16 ±0.2^b	36.44 ±14.5^a	25.59 ±2.4^a	18.65 ±4.1^a	11.13 ±0.9^a
B20N1	5.08 ±0.2^{ab}	35.60 ±15.4^a	25.11 ±4.7^a	16.28 ±2.4^a	14.54 ±3.5^a
reapB10N1	5.14 ±0.4^b	28.90 ±12.5^a	19.43 ±3.6^a	19.42 ±3.6^a	12.44 ±2.3^a
reapB20N1	5.12 ±0.1^{ab}	23.05 ±4.3^a	24.89 ±4.1^a	18.33 ±3.4^a	16.92 ±4.5^a
fertilized group – N2 level (162 kg.N.ha^{-1})					
B0N2	4.46 ±0.1^a	65.07 ±15.6^a	34.75 ±4.8^a	21.47 ±4.7^a	10.55 ±0.3^a
B10N2	4.75 ±0.2^b	48.97 ±14.4^a	28.51 ±4.3^a	18.35 ±5.8^a	14.30 ±1.5^a
B20N2	4.99 ±0.4^b	62.30 ±24.2^a	26.70 ±3.4^a	17.13 ±4.5^a	14.68 ±2.9^a
reapB10N2	4.92 ±0.3^b	38.67 ±16.7^a	29.77 ±5.0^a	17.73 ±5.0^a	14.64 ±0.9^a
reapB20N2	4.99 ±0.3^b	47.69 ±14.6^a	29.21 ±3.8^a	17.60 ±5.3^a	17.69 ±4.1^a

compared to the control (B0N1), while in the second level of fertilization, biochar decreased the C_{org} content (14.53–20.21%) in all treatments compared to control (B0N2). In autumn samples, the organic carbon (C_{org}) content increased in the first level of fertilization treatments, B20N1 and reapB20N1 (10.32–28.38%), and decreased in B10N1 and reapB10N1 (5.61–15.55%) compared to the control treatment (B0N1). Autumn samples showed a highest C_{org} increase due to biochar in the second level of fertilization (35.55–67.68%) compared to control treatment (B0N2). In the study conducted by Amoakwah et al. (2017), among the various biochar treatments, only the application of 20 t.ha^{-1} resulted in a noteworthy increase of 66% in soil organic carbon (SOC) in the treated soils, as compared to the control plots. The results of Dong et al. (2022) showed that adding biochar to the soil increased the amount of soil organic carbon (SOC), with increases in the surface layer (0.0–0.1 cm) ranging from 26.9% to 65.3% and in the subsurface layer (0.1–0.2 m) from 30.3% to 63.0%. Over the past decade, research indicates that incorporating biochar into soil affects the mineralization of soil organic carbon (SOC). This impact is attributed to diverse mechanisms, such as biochar supplying energy-rich organic compounds that stimulate microbial growth. The microbial activity, in turn, accelerates the degradation of various organic matter types, including soil organic matter. Notably, biochars rich in labile compounds show increased mineralization of native SOC, suggesting that the most labile organic fraction of biochar may temporarily replace native soil organic carbon, reducing its mineralization (Lehmann & Joseph, 2015).

3.2 *Soil physical properties*

Table 3 presents the impact of both the initial application and subsequent reapplication of biochar on physical soil parameters, including soil water content (SWC), water-filled pore space (WFPS), soil temperature (soil T), and bulk density (BD). Generally, application of biochar with or without N-fertilizer (both fertilization levels) increased SWC. SWC varied in the treatment without nitrogen fertilization, increased (from 0.79% to 4.47%) and decreased (from 1.95% to 4.47%) compared to the control (B0N0). In case of the first level of nitrogen fertilization (N1), biochar increased SWC by 0.61% to 4.30% compared to the control (B0N1). In the second level of nitrogen fertilization, biochar increased SWC from 4.94% to 9.33% compared to the control (B0N2). Similar results were found in the study of Yeboah et al.

Table 3 Selected physical properties (SWC, soil T, BD) of the soil with different treatments in 2022 (means ± standard errors). Different letters (a, b) within columns for each fertilized group show that the means are significantly different at $p < 0.05$

Treatments	**SWC (% mass)**	**Soil T (°C)**	**BD (spring) (g.cm^{-3})**	**BD (autumn) (g.cm^{-3})**
	n = 3	*n* = 3	*n* = 3	*n* = 3
not fertilized group – N0 level (0 kg.N.ha^{-1})				
B0N0	13.87 ±0.8^{a}	18.58 ±0.6^{a}	1.43 ±0.02^{a}	1.43 ±0.03^{a}
B10N0	13.25 ±0.6^{a}	18.51 ±0.4^{a}	1.53 ±0.03^{a}	1.50 ±0.03^{a}
B20N0	13.98 ±0.7^{a}	18.39 ±0.5^{a}	1.43 ±0.05^{a}	1.43 ±0.03^{a}
reapB10N0	14.49 ±2.1^{a}	18.81 ±0.4^{a}	1.43 ±0.04^{a}	1.50 ±0.02^{a}
reapB20N0	13.60 ±0.7^{a}	18.82 ±0.5^{a}	1.47 ±0.04^{a}	1.47 ±0.02^{a}
fertilized group – N1 level (108 kg.N.ha^{-1})				
B0N1	13.02 ±0.7^{a}	18.51 ±0.5^{a}	1.42 ±0.03^{ab}	1.46 ±0.03^{a}
B10N1	13.14 ±0.7^{a}	18.21 ±0.3^{a}	1.50 ±0.04^{bc}	1.43 ±0.03^{a}
B20N1	13.47 ±0.7^{a}	18.30 ±0.5^{a}	1.37 ±0.02^{a}	1.44 ±0.05^{a}
reapB10N1	13.10 ±0.8^{a}	18.35 ±0.4^{a}	1.54 ±0.02^{c}	1.55 ±0.06^{a}
reapB20N1	13.58 ±0.7^{a}	18.34 ±0.6^{a}	1.40 ±0.04^{ab}	1.45 ±0.05^{a}
fertilized group – N2 level (162 kg.N.ha^{-1})				
B0N2	12.54 ±0.7^{a}	18.19 ±0.3^{a}	1.47 ±0.01^{ab}	1.41 ±0.03^{a}
B10N2	13.43 ±0.7^{a}	18.56 ±0.5^{a}	1.45 ±0.04^{ab}	1.46 ±0.02^{ab}
B20N2	13.71 ±0.9^{a}	18.47 ±0.4^{a}	1.41 ±0.02^{ab}	1.47 ±0.04^{ab}
reapB10N2	13.16 ±0.7^{a}	18.70 ±0.5^{a}	1.52 ±0.06^{b}	1.51 ±0.00^{b}
reapB20N2	13.46 ±0.7^{a}	18.84 ±0.4^{a}	1.40 ±0.03^{a}	1.42 ±0.04^{ab}

(2017), where in a field trial, the application of 15 $t.ha^{-1}$ biochar with nitrogen fertilizer at a rate of 50 $kg.ha^{-1}$ of N (BN50) consistently exhibited higher soil water contents compared to other treatments at various depths and throughout all stages of crop development. The results indicated that the BN50 treatment increased soil water content in the 0.0–0.3 m depth range by approximately 40%, 32%, and 53% on average at different stages of crop development, respectively, compared with the zero-amendment (CN0) treatment. The same was also found by Huang et al. (2022), where the addition of biochar increased soil water content (SWC) in the 0.0–0.6 m layer during the growing seasons. This potential of biochar to increase SWC may be attributed to the elevated specific surface area, porosity, and water-binding capabilities of biochar particles (Blanco-Canqui, 2017, Jačka et al., 2018, Zhang et al., 2019). The addition of biochar has the potential to modify soil pore systems, achieved through the intrinsic porosity of biochar, reconfiguration of soil and biochar particles, and the improved stability of aggregation, as discussed by Ajayi et al. (2016).

Soil temperature in the treatment without fertilization showed a decrease in B10N0 and B20N0 treatments, with temperature decreases by 0.07 °C and 0.19 °C, respectively, compared to the control (B0N0). On the other hand, reapB10N0 and reapB20N0 showed an increase in temperature from 0.23 °C to 0.24 °C compared to the control B0N0. In the first level of fertilization, there was a decrease by 0.30 °C to 0.16 °C compared to the control (B0N1). In the second level of fertilization, there was an increase in all treatments compared to the control (B0N2), ranging from 0.28 °C to 0.65 °C. In the experiment conducted by Yan et al. (2019), biochar was applied at rates of 0 $t.ha^{-1}$, 20 $t.ha^{-1}$, 40 $t.ha^{-1}$, and 60 $t.ha^{-1}$ in field plots. The results indicated an increase in soil temperature corresponding to the increasing rate of biochar application when compared to the control plot without biochar. In a field experiment conducted by Feng et al. (2021), the findings revealed that the application of 10 $t.ha^{-1}$ of biochar (-0.13–0.51 °C) and 20 $t.ha^{-1}$ of biochar (-0.03–0.69 °C) resulted in slightly higher temperatures than those in the control treatment. Because of its black appearance and high heat conductivity, biochar is expected to have a similar effect on soil temperature (Shackley et al., 2016). Additionally, the application of biochar changed the color of the soil and had an impact on its temperature (Crutzen, 2006). There wasn´t found any effect of biochar applicaton with or without N-fertilizer on soil bulk density (BD) decrease. Bulk density varied a lot in all treatments. A positive effect of biochar amendment on bulk density (BD) reduction was observed in the following treatments: B10N0 and reapB20N0 in spring samples, and B10N0, reapB10N0, and reapB20N0 in autumn samples, compared to the control (B0N0). In spring samples, BD reduction was observed in the first level of N-fertilization in treatments B20N1 and reapB20N1, compared to the control (B0N1). In the second level of N-fertilization in spring samples, BD reduction occurred in B10N2, B20N2, and reapB20N2 treatments, compared to the control (B0N2). In autumn samples at the first level of N-fertilization, BD reduction was observed in B10N1, B20N1, and reapB20N1 treatments, compared to the control (B0N1). In the study by Guo et al. (2022), in comparison with the treatment without straw incorporation, the mean soil bulk density under straw incorporation and straw-derived biochar application treatments decreased by 3.1% and 4.2% at 0.0–0.1 m, 4.2% and 6.0% at 0.1–0.2 m, 7.0% and 8.3% at 0.2–0.4 m, and 2.3% and 4.8% at 0.4–0.6 m depth, respectively. A lower mean soil bulk density was observed with nitrogen fertilizer application in the soil profile of 0.0–0.6 m (soil tilth) compared to no nitrogen application. In this investigation, a significant decrease in bulk density and an increase in porosity were noted with nitrogen fertilizer application, with no significant difference observed among various nitrogen application rates. Numerous studies have demonstrated that the addition of biochar has a propensity to reduce bulk density in various soils, primarily attributed to its lower specific gravity in comparison to the native soil (Shackley et al., 2016).

3.3 Carbon dioxide emissions

The impact of the initial application and reapplication of biochar, at various rates, on average daily carbon dioxide (CO_2) emissions and cumulative emissions of CO_2 measured from April to October under three different nitrogen fertilizer rates (N0, N1, N2) is illustrated in Table 4. Generally, application of biochar with or without N-fertilizer decreased the average daily CO_2 compared to its individual controls (B0N0, B0N1 and B0N2). The average daily emissions of CO_2 in the treatments without nitrogen fertilization decreased ranging from 10.72% to 41.01%, compared to the control (B0N0). For treatments with the N1 fertilization, biochar reduced CO_2 emissions by 0.80% to 20.28% compared to the control (B0N1). In N2 level of fertilization, biochar reduced CO_2 emissions by 6.73% to 25.50% compared to the control (B0N2). The higher reduction potential of biochar was observed in treatments with biochar reapplications compared to its individual controls at all fertilization levels. When looking at cumulative CO_2 emissions across different nitrogen fertilization levels (B0N0, B0N1, and B0N2), treatments with biochar application showed comparatively lower cumulative CO_2 emissions than control treatments without biochar (except for B20N1 and B10N2).

Table 4 Average daily and cumulative CO_2 emissions (± standard error) monitored in the silty loam Haplic Luvisol throughout the study period of 2022

Treatments	Average daily emissions of CO_2 (kg CO_2-C.ha^{-1}.day^{-1})	Cumulative emissions of CO_2 (t CO_2–C.ha^{-1})
not fertilized group – N0 level (0 kg.N.ha^{-1})		
B0N0	76.84 ±12.3^{b}	7.98 ±1.3^{c}
B10N0	62.56 ±11.4^{ab}	6.06 ±1.1^{abc}
B20N0	68.60 ±10.0^{b}	6.86 ±1.0^{abc}
reapB10N0	59.49 ±15.8^{ab}	5.64 ±1.5^{abc}
reapB20N0	45.33 ±8.6^{a}	3.99 ±0.8^{a}
fertilized group – N1 level (108 kg.N.ha^{-1})		
B0N1	64.11 ±7.5^{a}	6.11 ±0.6^{abc}
B10N1	62.76 ±10.6^{a}	6.00 ±0.9^{abc}
B20N1	63.60 ±11.7^{a}	6.13 ±1.1^{abc}
reapB10N1	51.38 ±9.5^{a}	4.55 ±0.8^{ab}
reapB20N1	51.11 ±8.3^{a}	4.44 ±0.6^{ab}
fertilized group – N2 level (162 kg.N.ha^{-1})		
B0N2	74.24 ±8.9^{bc}	7.10 ±0.7^{abc}
B10N2	79.24 ±9.7^{c}	7.77 ±0.9^{bc}
B20N2	68.24 ±9.1^{abc}	6.62 ±0.8^{abc}
reapB10N2	59.44 ±8.6^{ab}	5.18 ±0.7^{abc}
reapB20N2	55.31 ±6.7^{a}	4.95 ±0.5^{abc}

Cumulative CO_2 emissions decreased from 14.04% to 50.00% in the treatment without nitrogen fertilization compared to the control (B0N0). Biochar, in N1 treatments reduced CO_2 emissions by 0.33% to 27.33% compared to the control (B0N1). In N2 fertilization treatments, biochar reduced CO_2 emissions by 6.76% to 30.28% compared to the control (B0N2). Remarkably, treatments with biochar reapplication showed the most significant reductions in cumulative emissions compared to controls. In general, biochar's regulatory mechanisms on CO_2 emissions across diverse environments, encompassing both abiotic and biotic factors, can be succinctly outlined as follows: 1. elevated soil pH and the presence of alkaline metals on biochar surfaces facilitate CO_2 precipitation into carbonates; 2. biochar's adsorption of organic matter may shield it from further mineralization, reducing CO_2 production; 3. reduction in the abundance of two carbohydrate-mineralizing enzymes (glucosidase and cellobiosidase) contributes to decreased CO_2 emissions; and 4. enhanced plant growth and biomass resulting from biochar addition intensify the net exchange of CO_2 between the atmosphere and soil (Guo et al., 2020).

4 Conclusions

In summary, this study highlights the positive impact of both initial and reapplication of biochar, in conjunction with varying nitrogen fertilizer levels, on key soil properties. Notably, the interventions showcased a notable improvement in soil pH with increase in range of 0.58–11.88%, highlighting biochar's role in increasing soil alkalinity of a bit acid studied soil. The results revealed a consistent reduction in ammonium (NH_4^+) levels, decrease from 3.66% to 46.59%, across most treatments. Nitrate (NO_3^-) levels exhibited a substantial decrease in the range of 9.66–32.23%, with exceptions noted in B10N0, B20N0, and reapB10N0, where marginal increases ranging from 2.04% to 9.93% were recorded. These results highlight the complex and treatment-specific reactions in the dynamics of nutrients impacted by the use of biochar. Biochar applications demonstrated a dual impact on soil organic carbon (C_{org}) content, with increases observed during spring samples, especially at the first level of nitrogen fertilization. However, a contrasting trend emerged at the second level, suggesting intricate interactions between biochar and nitrogen availability. This aligns with current literature indicating the complex nature of biochar-soil interactions and highlights the need for tailored approaches based on nitrogen levels. Biochar application positively influenced soil water content (SWC), indicating its potential to improve water retention and accessibility for crops. Differential responses to the application of biochar were found by analysis of soil temperature fluctuations. The study explored the impact of biochar on average daily CO_2 emissions, revealing the potential to mitigate CO_2 emissions, particularly evident in reapplication treatments. These findings contribute to the growing body of evidence supporting biochar's role in carbon sequestration and emission reduction.

As agriculture faces the challenges of environmental sustainability, adopting tailored biochar applications presents a promising avenue for resilient and eco-friendly soil management.

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