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Research article

Interactive effects of biochar and ammonium fertilizer on wheat yield, soil acidity and their residual effect on soybean under no-tillage conditions

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Abstract: Reductions in soil organic matter (SOM) affect soil quality and fertility in tropical agricultural soils. Due to its recalcitrant nature, biochar persists longer in soils. A greenhouse experiment was conducted to assess the effect of biochar, locally produced from animal manures (poultry litter, swine, and cattle manures) and crop residues (rice, soybean, and corn straws) on soil pH, aluminum (Al) concentration, and yields of wheat, as well as its residual effects on soybean under a no-tillage planting system. Undisturbed soil was collected at a 25 cm depth in polyvinyl tubes (PVC) from a long-term no-tillage site. The experiment included six biochar types and two rates of each biochar type, with and without N fertilizer, leading to 26 treatment combinations including 2 controls. Two control treatments were used, one without biochar and N (control –N-B) and the other without biochar but with N (control +N-B). The treatments were replicated three times and laid out in a complete randomized design (CRD). Biochar was applied at rates of 10 Mg ha^{-1} (33.5 g $column^{-1}$) and 20 Mg ha^{-1} (67 g $column^{-1}$) and ammonium sulfate at 0 and 110 kg ha^{-1} (1.6 g ammonium sulfate $column^{-1}$). The study showed that applying N along with biochar increased wheat and soybean growth and growth attributes. Additionally, applying biochar influenced the soil pH and exchangeable Al effectively in the topsoil. However, its impact decreased with increasing depth under the no-tillage planting system. These findings suggest that biochar, especially when applied with nitrogen fertilizer could improve plant performance and ameliorate soil acidity in no-tillage planting systems due to its recalcitrant nature.

Keywords: biochar; nitrogen; wheat; soybean; soil pH; no-tillage; residual effect

1. Introduction

Soil organic matter (SOM) plays an essential role in retaining nutrients and water in the soil. Low SOM is one of the primary contributors to several soil fertility constraints in tropical agricultural soils. The reduction in SOM and its effects on soil fertility are among the most significant environmental problems for agricultural production in tropical soils [1–3]. Unlike the conventional organic materials used for soil amendments, biochar is a recalcitrant material that can keep soils amended for a longer time [4]. Biochar enhances soil fertility by increasing nutrient adsorption capacity and crop yields [5,6]. Recently, numerous studies have focused on climate change, carbon (C) sequestration, soil amendments, and crop production using biochar prepared from a wide variety of feedstocks, as they are varied in their characteristics and functions [7,8].

Usually, biochars prepared at 400 °C or higher temperatures are alkaline with a high pH [9]. When applied to soils, they increase soil pH and cation exchange capacity (CEC) while decreasing exchangeable aluminum (Al), depending upon the exchangeable base cations [10]. Biochar's high adsorptive capacity results in immobilization of ammonium nitrogen (NH_4^+-N) or inhibition of nitrification and releases H^+ into the soil [11]. Moreover, the soil's physical and chemical properties and the agricultural management practices play a crucial role in the effectiveness of soil amendment using biochar to mitigate N_2O emissions and increase carbon sequestration [12].

In Southern Brazil, a no-tillage farming system has been adopted for many years on acidic soil [13]. Several studies have reported its effects on C sequestration, alterations in soil conditions, nitrogen (N) dynamics in the soil, and crop production [13]. These studies were conducted under incubation, greenhouse, or field conditions, with biochar incorporated into the topsoil. However, limited research has examined the application of biochar in the no-tillage system and its effects on soil properties, crop growth, and production.

Initially, given the biochar’s properties and the soil conditions, it was hypothesized that different types of biochar would influence wheat growth depending on the CEC and N application. The second hypothesis was that biochar would enhance soybean growth due to the residual effects of earlier biochar application. Thirdly, it was hypothesized that biochar would increase soil pH to a certain extent, avoiding the application of lime to increase the soil pH.

Bearing biochar's properties and relevant soil management practices in mind, a further study was proposed with the following objectives: (1) To evaluate the influence of different rates of biochar with and without N application on wheat cultivation under no-tillage soil conditions; (2) to evaluate the residual effect of biochar on soybean as the subsequent crop; and (3) to evaluate the impact of different biochar types on soil pH and exchangeable Al in different soil layers after harvesting the crops.

2. Material and methods

For preparing the biochar, all feedstocks were collected from the experimental areas of the Federal University of Santa Maria, Rio Grande do Sul (RS) (29°43'14.4"S and 53°43'31.2"W), except for corn straw, which was collected nearby from Paraíso do Sul, RS (29°35'10.3"S and 53°07'26.3"W).

2.1. Preparation and analysis of biochar

Stones were removed from animal manure and grasses from straw samples before pyrolysis of the feedstock. Six different biochars were produced from swine manure (SMB), poultry litter (PLB), cattle manure (CMB), rice (*Oryza sativa*) straw (RSB), soybean (*Glycine max*) straw (SSB), and corn (*Zea mays*) straw (CSB). Each feedstock was pyrolyzed at 450 °C for 1.0 h in a muffle furnace, with the temperature increased gradually at a rate of 10 °C per minute. The furnace was turned off and cooled to room temperature upon reaching the required temperature and time. All biochars were analyzed for pH (1:10 w/v of water, pH_{H2O}) and electrical conductivity (EC) (1:10 w/v of water) by the method used by Tedesco et al. [14] with alterations because of the large volume of biochar involved. Total C and total N were analyzed by the dry combustion method using a Thermo Scientific Flash EA 1112. Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and micronutrients (Mn and Fe) were extracted using 0.1M HNO_3 [15]. Phosphorus was measured using the method of Murphy and Riley [16], and the K content was measured using a flame photometer. The cations Mn and Fe were measured with an atomic absorption spectrophotometer (AAS).

2.2. Soil collection and analysis

Polyvinyl tubes (PVC) (0.29 m height × 0.20 m diameter) were used to collect undisturbed layers of Typic Hapludult (US Soil Taxonomy) at a depth of 0.25 m from experimental areas of the Department of Soil Science (29°43'14.2"S and 53°42'15.0"W) of the Federal University of Santa Maria. Separate soil samples were collected at 0.20 m for pre-sowing analysis.

2.3. Greenhouse experiment

Undisturbed soil samples were taken to the greenhouse to conduct wheat experiments by applying different types of biochar and ammonium fertilizer (ammonium sulfate). The experiment consisted of six main biochar treatments (six biochar types), two rates of each biochar type, and two N fertilizer rates (see Table 1 for the treatment combinations). Biochar was applied at 10 Mg ha^{-1} (33.5 g $column^{-1}$) and 20 Mg ha^{-1} (67 g $column^{-1}$), while ammonium sulfate was applied at rates of 0 and 110 kg ha^{-1}

(1.6 g ammonium sulfate column^{-1}). The treatments were replicated three times, and the experiment was arranged in a complete randomized design (CRD). Two control treatments were used, one without biochar and N (control –N-B) and the other without biochar but with N (control +N-B).

Due to the large volume of straw-derived biochar, it was mixed with the soil to a depth of 2.5–3.0 cm to enhance seed contact with the soil. Basal nutrients were applied to all treatments at 170 kg P_2O_5 ha^{-1} (1.3 g triple superphosphate column^{-1}) and 120 kg K_2O ha^{-1} (0.65 g potassium chloride column^{-1}). Eight wheat seeds (variety Sinuelo) were then sown into the PVC columns, thinned to four healthy seedlings after germination, and grown for 93 days in a glasshouse. The wheat shoots were then harvested, dried in an oven at 60°C, and stored for further analysis.

Table 1. Treatment combinations for the greenhouse experiment under a no-tillage planting system. (Swine manure biochar, SMB; poultry litter biochar, PLB; cattle manure biochar, CMB; rice straw biochar, RSB; soybean straw biochar, SSB; corn straw biochar, CSB)

Treatment	Combination	Treatment	Combination
T_1	Soil + N_0	T_{14}	Soil + N_{110}
T_2	Soil + N_0 + SMB_{10}	T_{15}	Soil + N_{110} + SMB_{10}
T_3	Soil + N_0 + SMB_{20}	T_{16}	Soil + N_{110} + SMB_{20}
T_4	Soil + N_0 + PLB_{10}	T_{17}	Soil + N_{110} + PLB_{10}
T_5	Soil + N_0 + PLB_{20}	T_{18}	Soil + N_{110} + PLB_{20}
T_6	Soil + N_0 + CMB_{10}	T_{19}	Soil + N_{110} + CMB_{10}
T_7	Soil + N_0 + CMB_{20}	T_{20}	Soil + N_{110} + CMB_{20}
T_8	Soil + N_0 + RSB_{10}	T_{21}	Soil + N_{110} + RSB_{10}
T_9	Soil + N_0 + RSB_{20}	T_{22}	Soil + N_{110} + RSB_{20}
T_{10}	Soil + N_0 + SSB_{10}	T_{23}	Soil + N_{110} + SSB_{10}
T_{11}	Soil + N_0 + SSB_{20}	T_{24}	Soil + N_{110} + SSB_{20}
T_{12}	Soil + N_0 + CSB_{10}	T_{25}	Soil + N_{110} + CSB_{10}
T_{13}	Soil + N_0 + CSB_{20}	T_{26}	Soil + N_{110} + CSB_{20}

After harvesting the wheat, soybean (variety 5958 RSF IPRO) was sown in the same PVC column with no additional biochar or N fertilizer application to estimate the residual effect of the biochar. Equivalents to 90 kg P_2O_5 ha^{-1} (0.69 g triple superphosphate column^{-1}) and 120 kg K_2O ha^{-1} (0.65 g potassium chloride column^{-1}) were applied to all treatments with no N application. Three out of six seedlings were grown for 66 days with the plant tops harvested, oven-dried, and measured for dry mass (DM) yield. The samples were then stored for further analysis. The dried samples were milled and analyzed for total carbon (TC), and samples were digested using HNO_3-$HClO_4$ to measure P, K, Ca, Mg, Mn, and Fe [15]. Exchangeable cations were determined by atomic absorption spectrophotometry (AAS) and P by colorimetry [16]. Total N was measured using the dry combustion method in an elemental analyzer (Thermo Scientific, Flash EA 1112, Milan, Italy). After the soybean harvest, stratified soil samples were collected at 0–5, 5–10, 10–15 and 15–25 cm layers to evaluate the influence of different biochars on soil pH and exchangeable Al across the whole 0–25 cm profile. Stratified soil samples were air-dried and prepared by passing the samples through a 2 mm sieve. Soil pH and exchangeable Al were measured.

2.4. Statistics

Analysis of variance (ANOVA) was performed using R3.5.1 statistical software with the assistance of R Studio to evaluate the main effects and interaction effects among different factors (biochar type × nitrogen × biochar rates) and to determine significant treatment effects. Tukey's test was performed to estimate the mean differences among the different biochars and their levels with and without N application. The figures used to differentiate the means between various factors were created using SigmaPlot 12.3.

3. Results

The soil collected for the whole experiment contained 1.2 of C%, 0.8 of N%, 4.8 mg P kg^{-1}, 28 mg K kg^{-1}, 15.5 $cmol_c$ Ca dm^{-3}, 9.3 $cmol_c$ Mg dm^{-3} and 16.89 Al $cmol_c$ dm^{-3} determined using the methods of Mehmood et al. [35] and Tedesco et al. [14]. Soil $pH_{(H20)}$ was measured to be 4.8.

Table 2. Chemical characteristics of the six different biochars, prepared and applied under a no-tillage planting system [40]. (Swine manure biochar, SMB; poultry litter biochar, PLB; cattle manure biochar, CMB; rice straw biochar, RSB; soybean straw biochar, SSB; corn straw biochar, CSB)

Nutrient	Animal manures			Crop straws			LSD
	SMB	PLB	CMB	RSB	SSB	CSB	
TC (%)	38.27 c	22.11 d	16.42 e	43.95 b	69.17 a	67.78 a	2.42
N (%)	3.00 a	1.82 b	0.95 c	0.87 c	2.13 b	0.79 c	0.33
P (%)	4.88 a	3.33 b	0.94 c	0.60 c	0.83 c	0.45 c	0.54
K (%)	3.67 c	5.60 b	2.66 d	5.97 a	0.69 f	2.23 e	0.27
Ca (%)	7.02 b	23.89 a	1.36 e	1.53 e	2.65 c	0.61 e	0.77
Mg (%)	5.84 a	2.79 b	0.07 c	0.05 c	0.13 c	0.04 c	0.2
Cu (mg kg^{-1})	20.7 b	7.7 d	31.2 a	17.6 c	20.5 b	18.4 c	1.9
Mn (mg kg^{-1})	462.6 b	262.7 c	476.6 b	1041.7 a	97.9 e	159.8 d	18.7
Zn (mg kg^{-1})	508.6 a	35.9 e	75.3 b	67.6 c	48.0 d	66.6 c	7.2
Fe (mg kg^{-1})	282.8 b	28.8 e	855.4 a	118.9 c	41.5 d	33.1 e	7.9

3.1. Wheat and soybean production

Plant height of wheat, spikelet length, and DM were greater for the treatment with N than for the non-N treatment (Tables 3 and 4). The data show that the application of N increased plant height, spikelet length, and DM in the wheat crop and the subsequent soybean crop, without any positive impact from the combination of N-B and N-R, except on DM in soybean. Biochar types increased plant height only at 10 Mg ha^{-1} of poultry and corn biochar and 20 Mg ha^{-1} of cattle, soybean, and corn biochar without N. Maximum heights of 98.4 and 97.9 cm were obtained when N was applied with poultry biochar at 10 Mg ha^{-1} and corn biochar at 20 Mg ha^{-1}, respectively. Wheat DM yield did not differ among the biochar treatments, but all biochar types produced higher DM yields than the control, and this effect was observed only in the absence of N addition (Tables 3 and 4). Application of N fertilizer increased DM for swine, cattle, soybean, and corn biochar. Nonetheless, a significant increase was observed in treatments without and with N, but no significant difference was observed among biochar rates. The control treatment showed an increase of more than 100% in DM with the application of N. Maximum wheat DM (15.2 Mg ha^{-1}) was observed with the addition of 20 Mg ha^{-1} of cattle manure biochar applied with N, while the minimum (4.5 Mg ha^{-1}) was observed in the control (no biochar, no N) treatment.

The biochar had no residual effect on soybean plant height at both the 10 and 20 Mg ha^{-1} rates. As with the other treatments, the control +N-B treatment also showed an increase in soybean plant height compared with the control –N-B. Biochar applied to wheat influenced soybean DM across treatments compared with the control –N-B treatment. Maximum soybean DM (17.3 and 17.9 Mg ha^{-1}) was observed with poultry litter biochar at 10 and 20 Mg ha^{-1} (no N), respectively, with no significant improvement at higher biochar rates. Treatments with N application showed a difference only between the control treatment and all other treatments that received biochar. In the comparison on N-added treatments with those with no N, there was a significant increment under all treatments except poultry biochar applied at 10 and 20 Mg ha^{-1} and cattle biochar applied at 20 Mg ha^{-1}.

3.2. Nutrient concentration in wheat and soybean tissues

Biochar type did not affect the N contents for wheat and soybean crops at 10 Mg ha^{-1}, while application at 20 Mg ha^{-1} significantly altered the N contents in the straws (Table 5). Conversely, a 100% increase in the control and a 50% increase under the other treatments were observed with higher biochar doses. Compared with the control (4.3 g kg^{-1}), the maximum N content was noted at 14.7 g kg^{-1} and 11.1 g kg^{-1} under the application of swine and poultry biochar at 10 Mg ha^{-1}, respectively. Using N with biochar increased the N content in wheat straw under the swine and poultry biochar treatments at 10 Mg ha^{-1}. Conversely, the application of 20 Mg ha^{-1} swine and poultry biochar decreased the wheat's N content.

Table 3. Wheat and soybean plant height (PH, cm), spikelet length (SL, cm), and dry matter (DM, Mg ha^{-1}) analysis of variance (ANOVA) summary of the main and interactive effects. (Control, C; nitrogen, N; biochar type, B; rate, R)

Crop	Nutrient	C	N	B	R	C × N	N × B	N × R	B × R	N × B × R
Wheat	PH	ns	***	ns	ns	*	ns	ns	–	ns
	SL	ns	***	ns	ns	ns	ns	–	ns	ns
	DM	*	***	ns	ns	ns	ns	ns	ns	ns
Soybean	PH	***	***	ns	ns	ns	ns	ns	ns	ns
	DM	***	***	***	*	ns	**	**	ns	ns

*** $P < 0.001$; ** $P < 0.01$; * $P < 0.5$; – $P < 0.1$; ns, nonsignificant.

Table 4. Wheat and soybean plant height (PH, cm), spikelet length (SL, cm), and dry matter (DM, Mg ha^{-1}) as affected by biochar type (swine manure biochar, SMB; poultry litter biochar, PLB; cattle manure biochar, CMB; rice straw biochar, RSB; soybean straw biochar, SSB; corn straw biochar, CSB) and rate (10 and 20 Mg ha^{-1}), and N application (0 and 110 kg ha^{-1}).

Crop	Measuremeant	N rate (kg ha^{-1})	Biochar rate (mg ha^{-1})	Control	SMB	PLB	CMB	RSB	SSB	CSB
Wheat	PH	0	10	65.0bBα	72.2aAα	76.3aBα	80.3aAα	82.0aAα	78.5aAα	71.7aBα
		110	20		80.8aAα	78.0aAα	72.3aBα	79.6aAα	74.7aBα	77.7aBα
		0	10	91.2aAα	81.7aAα	98.4aAα	88.7aAα	86.0aAα	95.0aAα	83.7aAα
		110	20		86.1aAα	84.7aAα	81.7aAα	87.8aAα	97.9aAα	89.0aAα
			LSD			16.04				
Wheat	SL	0	10	7.0aBα	6.8aBα	7.1aBα	7.3aAα	7.6aAα	6.7aBα	7.0aBα
		110	20		7.6aBα	8.4aAα	7.0aBα	8.3aAα	7.0aAα	7.3aBα
		0	10	9.0aAα	8.7aAα	9.2aAα	7.9aAα	8.7aAα	9.1aAα	8.6aAα
		110	20		9.3aAα	8.9aAα	8.4aAα	8.5aAα	8.1aAα	8.7aAα
			LSD			1.82				
Wheat	DM	0	10	4.5aBß	5.7aBα	5.9aBα	5.02aBα	7.6aBα	7.2aBα	6.5aAα
		110	20		5.9aBα	8.0aAα	7.4aBα	9.1aAα	7.0aBα	7.6aBα
		0	10	10.0aAα	11.7aAα	10.7aAα	12.5aAα	15.1aAα	11.6aAα	11.0aBα
		110	20		12.9aAα	11.7aAα	15.2aAα	11.7aAα	12.2aAα	12.8aAα
			LSD			5.55				
Soybean	PH	0	10	72.0aAα	77.7aAα	81.3aAα	80.7aAα	85.3aAα	81.7aAα	82.3aAα
		110	20		87.7aAα	84.3aAα	83.0aAα	79.3aAα	84.3aAα	86.3aAα
		0	10	78.0aAα	90.3aAα	89.0aAα	92.0aAα	91.3aAα	86.3aAα	86.7aAα
		110	20		92.7aAα	92.0aAα	94.0aAα	85.3aAα	87.3aAα	78.0aAα
			LSD			15.76				
Soybean	DM	0	10	7.9cBß	15.5aBα	17.3aAα	12.1bBα	12.0bBα	11.8bBα	9.9cBα
		110	20		17.4aBα	17.9aAα	15.7aAα	14.2bBα	13.8bBα	11.8cBα
		0	10	11.1bAß	18.1aAα	17.1aAα	16.9aAα	16.6aAα	16.4aAα	16.3aAα
		110	20		18.3aAα	17.4aAα	15.2aAα	16.6aAα	17.7aAα	15.2aAα
			LSD			3.79				

Lower case letters within rows show the differences among different biochars, uppercase letters within the columns indicate the effect of nitrogen application, α and ß within rows indicate the effect of different rates of biochar. The least significant difference (LSD) test was performed to distinguish the differences among different treatments.

Table 5. Wheat and soybean straw nutrient (TC, TN, P, K, Ca, Mg, Mn, and Fe) content: ANOVA summary of main and interactive effects, control (C), nitrogen (N), biochar type (B), and biochar rate (R).

Nutrient	C	N	B	R	C × N	N × B	N × R	B × R	N × B × R
Wheat									
TC	***	***	***	-	**	*	ns	-	**
TN	**	**	**	ns	**	***	***	*	***
P	***	ns	***	*	ns	**	ns	*	ns
K	***	***	***	***	ns	**	ns	**	*
Ca	ns	*	ns	ns	ns	ns	ns	ns	ns
Mg	ns	***	***	ns	ns	ns	ns	ns	ns
Mn	***	**	-	ns	**	ns	ns	ns	ns
Fe	ns	***	**	ns	ns	ns	ns	ns	ns
Soybeans									
TC	ns	***	ns	ns	ns	***	ns	*	*
TN	ns	***	ns	ns	ns	***	ns	ns	ns
P	***	***	***	-	-	ns	ns	ns	ns
K	***	***	***	***	ns	ns	ns	ns	ns
Ca	*	***	**	ns	-	ns	ns	ns	ns
Mg	-	-	***	ns	ns	ns	ns	ns	ns
Mn	*	***	***	ns	**	*	ns	ns	ns
Fe	ns	ns	ns	ns	ns	ns	ns	ns	ns

*** $P < 0.001$; ** $P < 0.01$; * $P < 0.5$; – $P < 0.1$; ns, nonsignificant.

In wheat straw, P content in the control (1.3 g kg^{-1}) was lower compared with biochar, demonstrating differences in P content among the different types at application rates of 10 and 20 Mg ha^{-1}. An increase in the biochar rate increased P content in plant tissues except for cattle biochar, where P content decreased with an increase in the rate (20 Mg ha^{-1}) for the no-N treatment. Adding N fertilizer and different biochar types did not increase P in plant tissues except for the swine biochar (33% increase) at the 20 Mg ha^{-1} rate. With other biochars, the P content in plant tissues decreased to some extent but remained close to the contents observed without N application.

In wheat straw, K content was influenced by the biochar type and was increased by the biochar rate and N application (Table 5 shows the interaction of B × R × N). The K contents in plant tissues increased by approximately 25 % with an increase in the biochar rate, except for soybean at 20 Mg ha^{-1}. In addition, N decreased the K content in wheat tissues with a biochar application rate of 10 Mg ha^{-1}, while at 20 Mg ha^{-1}, no significant change was observed.

Similar outcomes were observed when comparing Ca, Mg, and micronutrients (Mn and Fe), with no significant differences among biochar types or rates. Calcium and Mg contents increased with an increase in the rate of biochar, but no significant difference was noticed. No changes in micronutrient (Mn and Fe) concentrations were observed across biochar types, although higher concentrations were observed with the application of N.

Table 6. Wheat straw nutrient concentrations (N, P, K, Ca, and Mg in g kg^{-1}; Mn and Fe in mg kg^{-1}) as affected by biochar type (swine manure, SMB; poultry litter, PLB; cattle manure, CMB; rice straw, RSB; soybean straw, SSB; corn straw, CSB) and rate (10 and 20 Mg ha^{-1}) and N application (0 and 110 kg ha^{-1}).

Nutrient	N rate (kg ha^{-1})	Rate (mg ha^{-1})	Control	SMB	PLB	CMB	RSB	SSB	CSB
N	0	10	4.3b	4.5b	8.3a	8.2a	8.2a	8.2a	4.2b
		20		9.4a	9.6a	6.7c	7.7b	8.4a	9.9a
N	110	10	8.3a	14.7a	11.1b	8.4b	8.8b	7.4c	6.8c
		20		8.4a	7.6a	8.0a	6.9a	7.3a	6.6a
		LSD				0.33			
P	0	10	1.3c	2.8a	1.9a	2.8a	1.9a	2.1a	2.2a
		20		3.3a	2.5a	1.7b	2.9a	2.2a	2.4a
P	110	10	1.8a	3.1b	2.3a	1.8a	1.7a	1.9a	1.6a
		20		4.5a	2.9a	1.9a	1.9a	2.0A	1.7a
		LSD				1.23			
K	0	10	9.1b	16.3a	18.8a	13.4a	17.9a	11.2b	15.4a
		20		20.5a	21.8a	18.1a	21.4a	13.9a	19.5a
K	110	10	8.8b	13.2b	17.6b	10.9b	18.5a	7.5a	12.8b
		20		20.1a	24.0a	14.7a	19.2a	7.7a	19.4a
		LSD				4.00			
Ca	0	10	9.1a	8.9a	8.8aAα	9.9aAα	10.7aAα	10.9aAα	9.4bAα
		20		9.1aAα	10.9aAα	9.7aAα	10.8aAα	11.9aAα	14.6aAα
Ca	110	10	12.1aAα	10.1aAα	10.9aAα	12.0aAα	10.9aAα	13.2aAα	9.8aAα
		20		11.7aAα	12.3aAα	11.2aAα	12.0aAα	13.4aAα	10.1aBα
		LSD				4.77			
Mg	0	10	4.0aAα	3.9aBα	3.9aAα	3.7aAα	3.4aBα	3.9aBα	3.5aAα
		20		4.2aAα	4.4bAα	3.7bAα	3.2bAα	4.2bAα	3.5bAα
Mg	110	10	4.1aAα	5.4aAα	4.3bAα	4.3bAα	4.0bAα	4.6bAα	3.9bAα
		20		4.2aAα	4.4bAα	3.7bAα	3.2bAα	4.2bAα	3.5bAα
		LSD				0.78			
Mn	0	10	220.9aAα	170.2aAα	171.4aAα	232.1bAα	223.9aAα	141.6aAα	155.0aAα
		20		199.2aAα	208.8aAα	399.9aAα	126.9aAα	111.4aAα	116.7aAα
Mn	110	10	498.1aAα	197.4aAα	247.9aAα	275.5aBα	250.2aAα	261.4aAα	269.9aAα
		20		168.7aAα	272.4aAα	205.9aAα	216.9aAα	189.8aAα	201.3aAα
		LSD				205.72			
Fe	0	10	109.8aAα	100.2aAα	114.5aAα	107.3aAα	94.7aAα	117.9aAα	107.1aAα
		20		88.3aAα	111.0aAα	103.7aAα	119.4aAα	100.6aAα	100.0aAα
Fe	110	10	100.2aAα	114.5aAα	107.3aAα	94.7aAα	117.9aAα	107.1aAα	100.2aAα
		20		88.3aAα	111.0aAα	103.7aAα	119.4aAα	100.6aAα	100.0aAα
		LSD				31.51			

For the same nutrient group, lowercase letters within rows show the difference among different biochars, uppercase letters within columns indicate the effect of nitrogen application, and α and ß within rows indicate the effect of different rates of biochars. The least significant difference (LSD) test was performed to distinguish the differences among different treatments.

In soybean straw, N concentration was not affected by the biochar type or the N rate applied to wheat (Table 7). A slight increase in N content was observed with an increase in the biochar rate from 10 Mg ha^{-1} to 20 Mg ha^{-1}. Treatments with N applied to the previous crop exhibited a 25–33% increase compared with those without N application, although there were no significant increases among biochars and rates of biochar. Compared with N, P was affected by the biochar type (2.1 and 2.0 g kg^{-1}), with the level under swine and poultry biochar at 10 Mg ha^{-1} remaining unchanged at 20 Mg ha^{-1}. The application of N decreased the P content by up to 16% in soybean straw under treatments with 10 Mg ha^{-1}, while poultry and soybean biochar at 20 Mg ha^{-1} showed no difference between treatments with N and without N. Biochar type and rate had no impact on the K content in soybean tissue. The addition of N to previous wheat crops had no effect with or without N application, whereas only a significant increase was observed at a biochar application rate of 20 Mg ha–1, which increased K content by up to 22%.

Table 7. Soybean straw nutrient concentrations (N, P, K, Ca, and Mg in g kg^{-1}; Mn and Fe in mg kg^{-1}) as affected by biochar type (swine manure biochar, SMB; poultry litter biochar, PLB; cattle manure biochar, CMB; rice straw biochar, RSB; soybean straw biochar, SSB; corn straw biochar, CSB), biochar rate (10 and 20 Mg ha^{-1}), and N application (0 and 110 kg ha^{-1}).

Nutrient	N rate (kg ha^{-1})	Rate (mg ha^{-1})	Control	SMB	PLB	CMB	RSB	SSB	CSB
N	0	10	19.0aBα	19.0aBα	26.0aAα	18.0aBα	20.0aBα	18.0aBα	19.0aBα
	0	20		21.0aAα	27.0aAα	20.0aBα	19.0aBα	21.0aBα	18.0aBα
N	110	10	28.0aAα	30.0aAα	23.0aAα	26.0aAα	28.0aAα	29.0aAα	30.0aAα
	110	20		26.0aAα	28.0aAα	27.0aAα	27.0aAα	29.0aAα	31.0aAα
		LSD				0.66			
P	0	10	1.1cAß	2.1aAα	2.0aAα	1.8bAα	1.6bAα	1.6bAα	2.0aAα
		20		2.1aAα	2.0aAα	1.7aAα	1.8aAα	1.7aAα	1.9aAα
P	110	10	1.1bcAß	1.8aBα	1.4aBß	1.2bBα	1.3aBα	1.3aBα	1.2bBα
		20		1.8aBα	1.9aAα	1.5aBα	1.4aBα	1.5aAα	1.2bBα
		LSD				0.49			
K	0	10	7.8bBß	12.6aAα	13.9aAα	10.9aBα	14.2aBα	13.1aAα	13.2aBα
		20		14.0aAα	17.4aAα	12.2aBα	16.3aAα	12.7aAα	14.4aBα
K	110	10	12.6aAα	14.8aAß	16.4aAß	15.5aAα	17.4aAα	13.4aAα	14.3aAα
		20		18.0aAα	19.5aAα	15.4aAα	18.1aAα	13.2aAα	18.7aAα
		LSD				4.07			
Ca	0	10	14.9aAα	12.8aAα	15.9aAα	13.5aBα	12.1aBα	16.6aBα	14.7aAα
		20		11.0aBα	19.1aAα	14.1aAα	11.0aAα	14.7aBα	14.4aBα
Ca	110	10	27.7aAα	15.6aAα	19.0aAα	22.2aAα	19.6aAα	26.1aAα	16.7aAα
		20		17.8aAα	21.9aAα	17.4aAα	16.3aAα	22.6aAα	22.2aAα
		LSD				10.13			
Mg	0	10	1.8aAα	1.8aAα	1.8aAα	1.6aAα	1.2aAα	1.8aAα	1.6aAα
		20		1.7aAα	1.8aAα	1.6aAα	1.0aAα	1.9aAα	1.4aAα

Continued on the next page

Nutrient	N rate (kg ha^{-1})	Rate (mg ha^{-1})	Control	SMB	PLB	CMB	RSB	SSB	CSB
Mg	110	10	1.8aAα	1.8aAα	1.7aAα	1.9aAα	1.4aAα	2.0aAα	1.6aAα
		20		2.2aAα	1.8aAα	1.7aAα	1.1aAα	2.0aAα	1.6aAα
		LSD				0.59			
Mn	0	10	126aBα	127aAα	222aAα	137aBα	128aAα	118aAα	130aBα
		20		121bAα	262aAα	154bAα	135bAα	87bAα	97bBα
Mn	110	10	280aAα	169aAα	170aAα	225aAα	188aAα	175aAα	207aAα
		20		146aAα	255aAα	165aAα	166aAα	135aAα	201aAα
		LSD				101.58			
Fe	0	10	44.5aAα	45.5aAα	52.3aAα	50.5aAα	37.5aAα	63.9aAα	53.6aAα
		20		89.4aAα	67.0aAα	66.9aAα	54.5aAα	39.0aAα	54.4aAα
Fe	110	10	57.2aAα	42.6aAα	49.6aAα	61.4aAα	53.4aAα	52.5aAα	56.1aAα
		20		52.3aAα	59.4aAα	66.4aAα	48.8aAα	43.8aAα	51.3aAα
		LSD				43.35			

For the same nutrient group, lowercase letters indicate differences among biochars, uppercase letters within columns indicate the effect of nitrogen application, and α and β within rows indicate the effect of different biochar rates. The least significant difference (LSD) test was performed to distinguish the differences among the different treatments.

Calcium, Mg, and micronutrients showed no influence of biochar type and application rate with N and without N. Maximum Ca (22.2 g kg^{-1}) and Mg (2.2 g kg^{-1}) were observed for cattle biochar at 10 Mg ha^{-1} and swine biochar at 20 Mg ha^{-1}, respectively, both combined with N application. Micronutrients (Mn, Fe) had nonsignificant changes across different biochars, application rates, and with and without N. However, a slight increase was observed in treatments that included N fertilizer.

3.3. Soil pH and Al alteration

The results showed an increase in soil pH with the addition of biochar (Figure 1). The maximum change in soil pH was noticed at 0–5 cm depth. The effect on soil pH decreased with depth, as the 15–25 cm depth was the least affected by the addition of biochar and other amendments. No significant differences were noted in deeper soil layers, but the pH decreased with increased soil depth. The addition of N (as NH_4SO_4) decreased the soil pH, but pH slightly increased without N application. The effect of biochar addition on soil pH was noticed. Maximum pH values were noticed with poultry biochar followed by the sequence corn > rice > cattle > soybean > swine. The biochar application rate influenced soil pH (Figure 1D), with higher rates increasing soil pH. However, the increase in soil pH was not significantly different at the double biochar rate, but the increase was noticeable enough to indicate a change.

A significant gradient can be observed when different biochars were added to soil compared with undisturbed soil (no-tillage system). The minimum exchangeable Al was observed at 0–5 cm depth (Figure 2) and increased with depth. The amendment applications affected the exchangeable Al content at 0–5 cm and 5–10 cm depths, but no change was noticed at 15–25 cm depth. The addition of N fertilizer increased exchangeable Al content, showing nearly double the amount compared with soil samples with no N application.

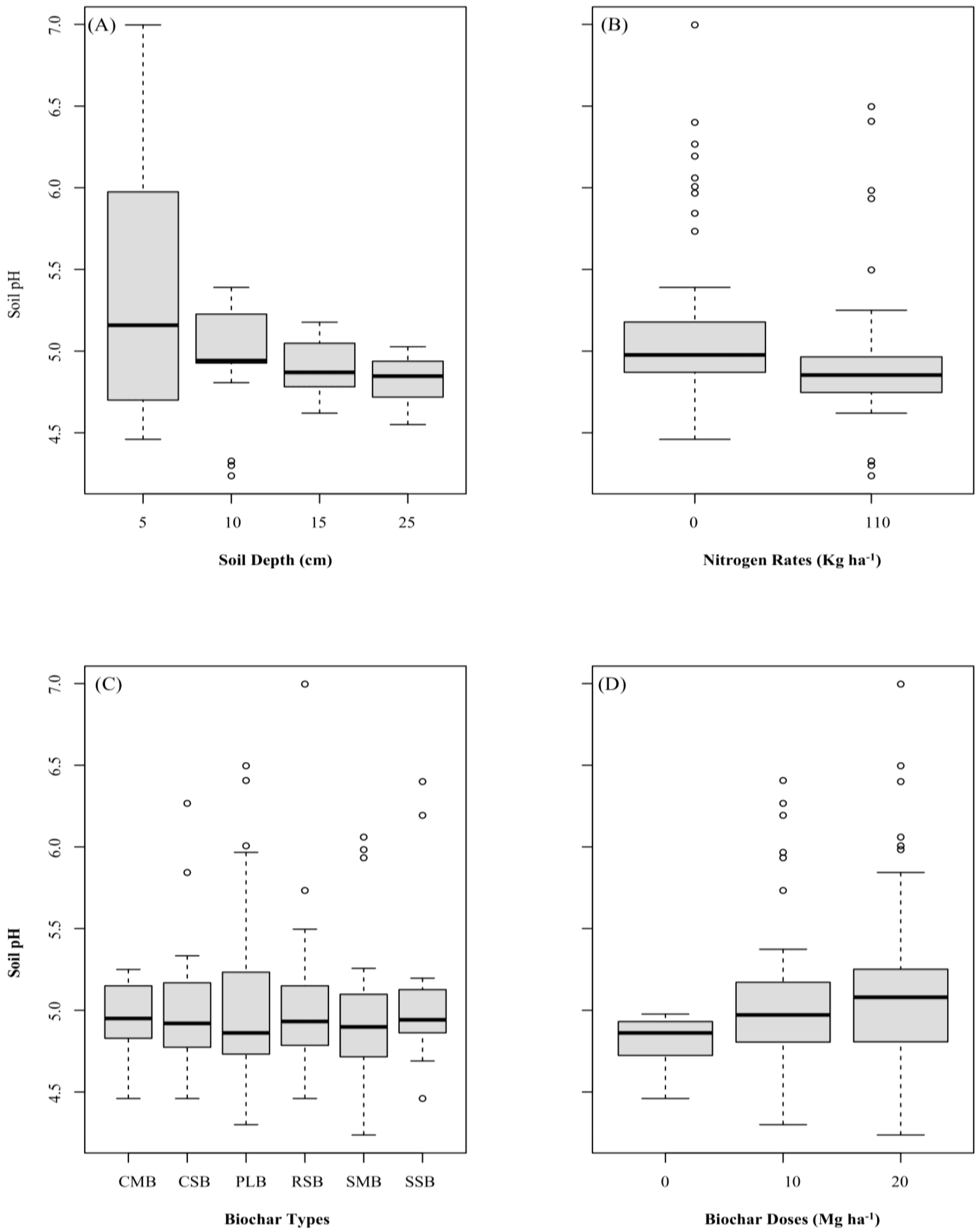

Figure 1. Changes in soil pH with surface application of cattle manure biochar (CMB), corn straw biochar (CSB), poultry litter biochar (PLB), rice straw biochar (RSB), swine manure biochar (SMB), and soybean straw biochar (SSB). (A) Effect of soil depth on soil pH, (B) effect of nitrogen rates on soil pH, (C) effect of biochar types on soil pH, and (D) effect of biochar rates (doses) on soil pH.

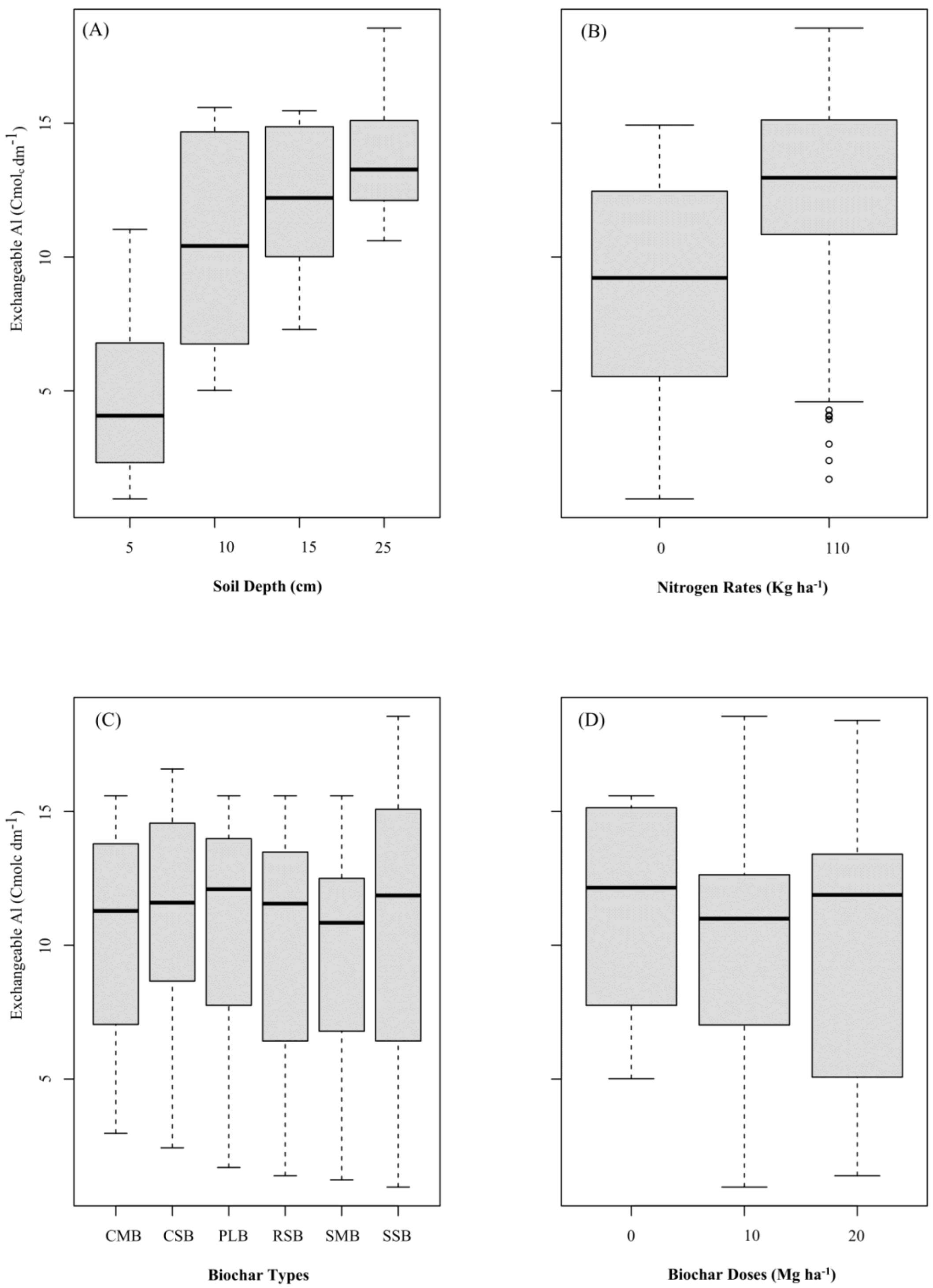

Figure 2. Soil exchangeable Al with surface application of cattle manure biochar (CMB), corn straw biochar (CSB), poultry litter biochar (PLB), rice straw biochar (RSB), swine manure biochar (SMB), and soybean straw biochar (SSB). (A) Effect of soil depth on exchangeable Al, (B) effect of nitrogen rates on exchangeable Al, (C) effect of biochar types on exchangeable Al, and (D) effect of biochar rates (doses) on exchangeable Al.

Different biochar types showed variable effects on the soil's exchangeable Al content (Figure 2C). The sequence of effects was rice < swine < soybean < cattle < poultry < corn. Soybean biochar showed the largest variation in exchangeable Al contents in the soil, while the variation in exchangeable Al content was the least when swine biochar was applied to undisturbed soil. Biochar application rates also showed variable results compared with the control, with a decrease in exchangeable Al with the application of biochar. Figure 2 shows a decrease in exchangeable Al with increasing application rates. The maximum influence was observed at the 20 Mg ha^{-1} application rate compared with 10 Mg ha^{-1}.

4. Discussion

4.1. Wheat and soybean production

The results showed that biochar significantly affected agronomic parameters and wheat DM. However, no significant difference was observed between different application rates of biochar. A slight increase in plant height and DM yield could be related to the application of 20 Mg ha^{-1} and N, as well as a slight increase in wheat plant height and DM yield. Biochar alone did not have a promising effect on wheat DM, which may be attributed to the low N content and elevated C:N ratio of the biochar [9], which may prevent N supply to crop plants and crop yield. High ratios immobilize N, while low ratios release it. Biochar's high C:N ratio may restrict N initially, but it enhances the soil's structure, pH, and nutrient retention. Combined with N sources, biochar improves soil fertility and crop productivity. Therefore, adding NH_4^+ fertilizer ensured that the N concentration in biochar + soil mix was sufficient for wheat growth. The addition of N fertilizer increased the wheat DM under the no-tillage system. In the experiment, the lesser impact of biochar alone can be attributed to the lower N content in swine, cattle, and rice biochar, which contained 1.8, 3.0, and 2.1% N, respectively. It is possible that the N present in biochar was leached from the PVC columns. The addition of N in the presence of biochar favored N uptake by plants as well as retaining N in the soil–biochar mixtures for a longer time. The results align with the findings of Chan et al. [4], who reported that greenwaste biochar did not affect radish biomass yield even at 100 t ha^{-1}, while the addition of N fertilizer increased yield significantly. The improved radish yield was attributed to the soil's physical condition, especially the reduction in tensile strength and higher field capacity water, both of which favor root growth and the soil's increased ability to absorb N. Maduabuchi et al. [38] reported that the addition of N increased paddy rice yield regardless of the biochar type, supporting our findings that the application of N with biochar increased wheat biomass without any effect of biochar type. Likewise, in their findings from their field experiment, Maduabuchi et al. [39] reported an increase in rice yield of up to 9% for the application of N with biochars under a no-tillage planting system.

The same pattern was observed in the residual effect of biochar on soybean plant height and DM, where the addition of N in combination with biochar favored plant growth and DM. High DM can be associated with the positive changes in soil quality induced by biochar, which enhances nutrient use efficiency. However, biochar alone did not affect wheat DM, which may be attributed to its low N content and elevated C:N ratio, which may prevent N supply to crop plants and reduce crop yield. The results confirmed the findings of Solaiman et al. [17], who found that oil mallee biochar increased wheat yield when applied with mineral fertilizer. Furthermore, biochar increased cassava and chili yield when applied with N over four years [18].

Generally, increased growth and yield were observed when biochar was added or mixed with different fertilizers. Abbasi and Anwar [24] reported that poultry litter biochar increased corn DM in combination with N fertilizer by up to 26% compared with the control. They applied compound poultry manure (CPM) and nitrophos (NP) along with biochar to investigate the impact of biochar on CPM and NP on cucumber growth and yield. The application of CPM and NP reduced the impact of nutrient deficiency on cucumber growth when biochar was applied [19]. On the other hand, Bista et al. [20] conducted an experiment using wood biochar (Douglas fir) and concluded that the application of biochar at 11.2 and 22.4 Mg ha^{-1} increased wheat shoot biomass by 15–20% without the addition of fertilizers. Long-term benefits may include SOM retention for a longer period, elevated nutrient-holding capacity, and slow nutrient release due to the biochar's high CEC [21]. Rice straw biochar increases crop growth and yield by enhancing NO_3^- retention in the soil [22]. A similar effect has been reported by Prommer et al. [23], who noticed that the addition of biochar enhances the ammonia oxidizer populations and accelerates the net nitrification rates that may retain NO_3^-. However, in this study, ammonium sulfate was used as an N source, and hence, due to the increase in the CEC of soil through the addition of biochar, the soil could retain NH_4^+, and nitrification may occur when needed. Our results align with those of Steiner et al. [21], who reported that biochar increased soil CEC and sustained nutrient absorption for extended periods.

4.2. Nutrient concentration, soil pH, and Al concentration

Nutrient concentrations in wheat and soybean shoots demonstrate that the addition of biochar to soil enhanced nutrient concentrations in plant tissues, directly affecting wheat crops and exerting a residual effect on soybeans. The nutrient concentration in plant tissues observed in this study is similar to the findings of [4] and [24], which stated that the increased nutrient uptake with biochar use could be related to greater nutrient use efficiency. Organic waste biochar can enhance corn yield by up to 6.24 Mg ha^{-1} [25]. Widowati and Ashah observed that a dual application of biochar and a lower KCl rate enhanced corn yield by up to 26% [25].

Incorporating animal manure and crop straw-derived biochar increased soil pH and decreased exchangeable Al. In this study, the crop straw-derived biochar presented a consistent increase in soil pH and a decrease in exchangeable Al compared with the animal waste-derived biochar, where the response was more varied. Overall, in the greenhouse experiment, the addition of N to different biochars greatly affected the agronomic parameters of wheat (direct effect) and soybean (residual effects). The nutrient concentration in plant tissue was affected by the addition of N fertilizer in combination with biochar compared with biochar application alone, which can be related to the presence of less N in the biochar applied to the soil, as well as plants absorbing nutrients such as P and K.

Biochar's pH ranges from 5.5 to 10.5, depending on the mineral fractions' content and composition, which vary with the feedstock and pyrolysis conditions [26]. Biochar can alter the NH^{4+} and NO^{3-} dynamics in soils by impacting adsorptive properties and pH [27]. The addition of biochar alone greatly influenced soil pH, along with NH^{4+} fertilizer (Figure 1). The increase in pH in the soil surface layer can be related to the presence of biochar's negatively charged phenolic, carboxyl, and hydroxyl groups on the surface of biochar, which tends to bind H^+ from the soil solution by reducing soil H^+ and hence causing an increase in pH [28]. The higher pH increases CEC by reducing leaching of base cations in competition with H^+ ions [29]. In this study, the biochar affected only the surface layer, while the layers underneath were not directly affected by the addition of biochar, even at 20 Mg ha^{-1}. Adding NH^{4+} as fertilizer in soil decreases the soil pH, whereas an increase occurs with the application of biochar to acidic soils [30]. It is well known that the addition of organic material to the soil significantly impacts the soil pH, which demonstrates that the addition of biochar can enhance the pH of acidic soil due to its high alkalinity [31]. Corn straw biochar's high $CaCO_3$ content and proton consumption ability increase soil pH and decrease the soil's exchangeable acidity [28]. This increase in soil pH helps exchangeable Al to participate as insoluble hydroxyl Al species [32]. Soil pH can be increased by adding biochar to soils by releasing the base cations into acid soils, which can participate in exchange reactions, replacing exchangeable Al and H from the soil surface and decreasing soil acidity [33,34].

Aluminum concentration in the soil is of more importance for soil acidity because of its higher charge and its ability to occupy more exchange sites and release a higher number of H^+ in the soil solution. Consequently, it decreases the soil pH and increases soil acidity [35]. Although in sandy-textured soil, there is no Al at toxic levels, due to the soil pH, it is more important to address it by increasing the soil pH. The reduction of exchangeable Al converted it to Al-OH, which precipitated in the presence of biochar. Reducing active Al^{3+} species in the soil is paramount for reducing soil acidity, and consequently enhancing soil fertility [10]. In one study, the authors reported that with the addition of biochar to corn crops, two factors acted for neutralization of Al; one was the alkaline effect of biochar, while the hydroxyl released from roots due to nitrate uptake acted in a complementary manner. In the present study, all biochar was mixed with soil at 2.5–3.0 cm depth to obtain consistent results. The biochar influenced the soil pH and exchangeable Al, moving downward, and had a minor influence. The addition of biochar increases the alkaline metals (Ca^{2+}, Mg^{2+}, and K^+) oxides in acidic soil, and hence, soluble Al^{3+} reduces with an increase in pH [36]. These results highlight the potential of biochar to enhance its role in agriculture by improving soil quality [37].

5. Conclusions

The findings indicate that applying all types of biochar, either alone or in combination with fertilizers, enhanced wheat growth parameters such as plant height, spikelet length, and DM yield. When nitrogen (N) was added with biochar, it improved the nutrient concentration in wheat straw and contributed to a balanced nutritional status. Biochar alone had no significant residual effect on soybean plant height and DM yield; however, when N had been applied to the preceding wheat crop, positive effects were observed. Nutrient concentrations in soybean's aerial parts followed a pattern similar to that of wheat biomass, with N addition exerting more potent effects than biochar alone. Overall, the study suggests that biochar enhances plant growth and crop yield when applied together with N fertilizer. Thus, biochar derived from animal manures and crop residues functions more effectively as a soil amendment than as a direct fertilizer. Due to its alkaline nature and high cation exchange capacity (CEC), biochar raises soil pH and effectively adsorbs Al in the topsoil, though these effects decline with increasing depth. Significantly, the influence of biochar varied with the feedstock type and application rate, reflecting the distinct characteristics of the parent material. This study underscores the promise of biochar as a tool for advancing sustainable farming practices and building a more resilient agriculture.

Author contributions

Qamar Sarfaraz: Conceptualization, data curation, formal analysis, methodology, writing—original draft; Rajesh Sharma: Writing—review and editing; Garson Laerson Drescher: Funding acquisition, project administration, writing—review and editing; Mohsin Zafar: Data curation, formal analysis, writing—review and editing; Muhammad Izhar Shafi: Formal analysis, validation, writing—original draft; Geoffrey Christie Anderson: Formal analysis, validation, writing—original draft; Leandro Souza da Silva: Conceptualization, data curation, formal analysis; Zakaria M. Solaiman: Resources, Visualization, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Use of Generative AI tools declaration

The authors declare they have not used artificial intelligence tools to create this article.

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Conflicts of Interest

The authors state that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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