Effects of Corn Straw Biochar Application on Soybean Growth and Alkaline Soil Properties

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Pot experiments were conducted to investigate the impact of biochar loading level on soybean growth and physico-chemical properties of alkaline soil. Biochar derived from corn straw was mixed with alkaline soil at 0%, 2.5%, 5%, and 10% loading levels and exposed to the natural elements. Soybean was used as the test crop. The results indicated that a single application of biochar positively and significantly improved soybean productivity and quality attributes of the tested alkaline soil. Soybean yield peaked at 5% loading level, but it declined at 10% loading. Applications of biochar at 5% and 10% loading significantly increased total soil porosity by 4.14% and 5.09%, and decreased the soil pH value by 0.07 and 0.24 units, respectively. Biochar addition significantly increased water holding capacity, total organic carbon content, total nitrogen, Olsen-P, available potassium, and cation exchange capacity. The results indicated that applications of corn straw biochar to alkaline soil improved soybean growth and promoted the physico-chemical properties of alkaline soil. However, the negative effects of increased C:N ratios and soil exchange sodium percentages at higher biochar loading levels should be taken into account when applying biochar as amendments to alkaline soils.

Keywords: Alkaline soil; Biochar; Plant growth; Soil properties

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INTRODUCTION

The semi-arid areas in western Heilongjiang Province are located in the western part of the Songnen Plain and collectively make up the largest soda saline-alkali area in China (Wang *et al*. 1993). The saline-alkali land area has now reached 3.937 million ha (Sun and Wang 2016). The soda saline-alkali soil in this area has a high pH value, and the main salts include Na_2CO_3 and $NaHCO_3$. Most of the land in this area is alkaline and is one of the most important commodity grain and animal husbandry production bases in China. The main crop in this area is corn. The area has low natural precipitation and it is unevenly distributed. Low water retention and soil organic matter levels have always been the main restricting factors on agricultural development in this area, and they ultimately restrict local agricultural production and ecological restoration (Lai *et al*. 2014). At the same time, the environmental pollution caused by corn straw burning has brought about serious debate, and crops residues are difficult to be decomposed after being returned to the fields, which usually results in the reduced emergence rates for next season crops. This means that the utilization of straw resources is becoming more important. There are growing demands to revise the agricultural management strategy to enhance soil nutrient recycling, nutrient supply, and soil quality (Delate and Cambardella 2004; Lal 2006).

Recently, increased scientific attention has been paid to the use of biochar in ecological restoration and as a soil amendment because it has the potential to improve the physico-chemical and biological characteristics of soils (Yamato *et al.* 2006; Zhang *et al.* 2019a) and increase crop growth (Lehmann *et al.* 2003; Rajkovich *et al.* 2012; Arif *et al.* 2017).

Biochar is produced from the thermal decomposition of biomass under low oxygen conditions and is widely used as a soil amendment (Lehmann *et al.* 2006). The use of biochar in the current agricultural system has been emphasized as a promising strategy to improve nutrient utilization efficiency and enhance plant growth by improving soil physico-chemical properties and nutrient cycling (Lehmann *et al.* 2003; Laird *et al.* 2009; Spokas *et al.* 2012). Singh *et al.* (2010) revealed that high porosity within biochar usually leads to increased water holding capacity (WHC). Furthermore, biochar-modified soils have higher moisture retention levels, which help increase crop productivity and reduce irrigation frequency or intensity (Sohi *et al.* 2009). A meta-analysis by Jeffery *et al.* (2011) indicated that the benefit of biochar amendment on crop productivity ranged from -28% to 39%, with a 10% mean increase in tropical and subtropical regions. A field experiment conducted by Arif *et al.* (2017) indicated that biochar application increased wheat and maize grain yields by 18% and 24%, respectively, compared to the control with no biochar addition. Uzoma *et al.* (2011) also reported similar results and indicated that biochar addition enhanced maize yield compared to the control without biochar.

To date, most studies have focused on the effectiveness of adding biochar to acidic, highly weathered tropical and subtropical soils, especially infertile acidic soils. These benefits can be attributed to the high biochar C content and cation exchange capacity (CEC). However, either no knowledge or less detailed knowledge is available regarding the effect of adding biochar to temperate soils, especially temperate and infertile alkaline soils. Numerous reports have confirmed the improvements in water retention and soil fertility after biochar application, making biochar a possible conditioner for alkaline soils in the semi-arid area of the Western Songnen Plain. The Songnen Plain is located in a semi-arid region, and most of the soils in this area are alkaline with pH values ranging from 7.8 to 8.5 or higher. It has been suggested that the increase in pH values after biochar application to alkaline soil may result in negative impacts on soil characteristics and plant production.

In this study, pot trials were conducted to evaluate the impact of biochar on soybean growth and soil properties. Pot trials are beneficial to accurately assess the effects of experimental factors and the results of pot trials tend to have good regularity. However, the results of short-term pot trials lack practical and instructive value. Methodologies that integrate field trials with pot trials could improve their practical and instructive value (Jeffery *et al.* (2011).

The objectives of the current research were to determine the impact of biochar amendment on soybean growth and alkaline soil properties, and to evaluate the agricultural potential of biochar as a soil amendment for alkaline soils in semi-arid regions. This study can also be used in conjunction with the field-scale experiments to confirm any observations that can be further developed into future projects.

EXPERIMENTAL

Materials

The soil samples used in this study were obtained from a plow layer with a depth of 0 cm to 15 cm and without organic litter at the Heilongjiang Bayi Agricultural University experimental area, which is located in Daqing, Heilongjiang, China (46°62′N, 125°19′E, 146 mH). The soil was a typical alkaline soil.

The biochar was purchased from Liaoning Jinhefu Agricultural Development Co., Ltd. (Anshan, China) and was produced from the thermal decomposition of corn straw at a temperature of approximately 450 °C for 2 h. Detailed information about the biochar manufacturing method can be found in the Chinese patent CN102092709B (Chen *et al.* 2012). The biochar was ground and filtered before it was used as amendment. The characteristics of the alkaline soil and biochar are shown in Table 1.

Table 1. Characteristics of Alkaline Soil and Biochar

Properties	Alkaline Soil	Biochar
pH	8.25	7.94
Total Carbon Content (g/kg)	-	715
Total Nitrogen Content(g/kg)	-	15.35
Total P Content (g/kg)	-	7.82
Total K Content (g/kg)	-	16.82
Alkali-hydrolyzed N (g/kg)	127.70	-
Olsen-P (g/kg)	10.06	-
Available K (g/kg)	162.60	-
Organic matter (%)	2.89	-

Methods

Treatments

The trial was set up in open-air conditions using plastic pots that were 290 mm in height and 145 mm in inner diameter. The biochar was applied at levels of 0%, 2.5%, 5%, and 10% (w/w). It was thoroughly mixed into the alkaline soil, and the mix was used to fill the pots. Each treatment, including the un-amended controls (CK), was repeated four times. A drain hole under the pots was plugged with nylon mesh to prevent soil loss due to irrigation and rainfall, and water in the pots was allowed to drain freely. Each pot contained 20 kg of dried soil plus additions and reached a depth of approximately 220 mm. Soybean (variety: Kennong 18; Heilongjiang Bayi Agricultural University, Daqing, China) was selected as the test plant, and adequate water was added to maintain field capacity at 85%. A total of 10 seeds were sown at a depth of 25 mm on May 20th, 2017. After soybean emergence, each pot was thinned to three plants and a regular watering schemes was implemented twice a week to minimize plant water stress. The soils moisture content was adjusted to 60% of the maximum water holding capacity by weight during the soybean growth season. All treatments received standard fertilizer at an application dosage of 45 kg/ha for urea (Luxi/N 46.4%, Luxi Chemical Co., Ltd., Shandong, China), 135 kg/ha for diammonium phosphate (Sinochem/P_2O_5 46%, Sinochem Fertilizer Holdings Co., Ltd., Beijing, China), and 60 kg/ha for potassium sulfate (K_2O 50%, Zhongnong International Fertilizer Import and Export Group Yantai Co., Ltd., Shandong, China).

Sample collection and measurement

After 5 months of growth, the seeds and vegetative plant parts of the soybean were harvested, dried, and separately weighed. The results were scaled up to kg/ha according to the pot surface area (660 cm^2). Leaf chlorophyll content was measured using an Minolta SPAD-502 chlorophyll meter (Minolta Camera Co., Ltd., Osaka, Japan) during pre-flowering stage (60 d after sowing, DAS). Soil samples were taken at different soybean growth stages (seeding stage, early bloom stage, full bloom stage, pod stage, and harvest) from the pots for physical and chemical measurements. Bulk density (BD) was evaluated from samples taken from the 0 cm to 15 cm soil layer using metal cylinders. The soil samples were dried and weighed at 105 °C until they reached a constant weight. The total porosity was calculated using the following formula: Total porosity (%) = (1 - bulk density/particle density) × 100 (particle density (PD) 2.65 Mg/m^3).

The water holding capacity was measured as follows: a soil sample of 10 g was weighed and placed in a plastic cylinder with nylon mesh at the bottom. The cylinder was then placed in water. After 24 h, the water in the water-saturated soil was allowed to drain until there was no water release, and then the sample was weighed again to calculate the soil water holding capacity. The soil pH and EC were measured with a soil-to-$CaCl_2$ ratio (0.01 mol/L) of 1:5 (w/v) and were analyzed by a pH meter (PHS-3C; Shanghai Precision & Instrument Co., Ltd., Shanghai, China) and a portable multiparameter analyzer (DZB-718; Shanghai Leici Instrument Co., Ltd., Shanghai, China). Total organic carbon (TOC) and total organic nitrogen (TON) in the soil were determined by dry combustion on a VarioMax CN analyzer (Elementar, Hanau, Germany). Cation exchange capacity (CEC) was measured using the NaOAc exchange and flame luminosity methods described by Lu (2000). Olsen-P was estimated using the 0.5 M $NaHCO_3$ method described by Bao (2007). Available potassium (AK) was measured using flame atomic absorption spectrophotometer methods described by Lu (2000). Exchangeable sodium percentage (ESP) was calculated according to Eq. 1:

$$\text{ESP} = \text{exchangeable sodium content} / \text{cation exchange capacity} \quad (1)$$

Statistical analysis

All statistical analyses were performed using SPSS V 21.0 software (IBM, Armonk, NY, USA). The data were analyzed by a one-way analysis of variance (ANOVA) followed by Duncan's *post hoc* procedure.

RESULTS AND DISCUSSION

Effects of Biochar Application on Soybean Growth and Yield Components

Biochar incorporation enhanced soybean growth and yield components compared to the control with no biochar addition. Significantly positive effects relative to soybean height and biomass were observed, and the highest soybean height, biomass, and yield were obtained at the 5% biochar loading. Biochar loading also had a significant effect on soybean pod number per plant, soybean seed number per plant, soybean 100-seed weight, soybean seed yield, and harvest index (HI) (Table 2). Biochar application significantly increased pod number per plant, number of soybean seeds per plant, 100-seed weight, and seed yield. The highest yield was obtained at the 5% biochar loading, whereas the 10%

biochar loading level slightly decreased soybean seed and biomass yields. The HI significantly increased for all treatments when biochar was added to the soil.

Table 2. Effects of Biochar Loading Levels (0%, 2.5%, 5%, and 10%) on Soybean Biomass Production and Yield Components

Biochar Treatment (%, w/w)	Height (cm)	Pod Number	Seed Number	100-seed Weight (g)	Seed Yield (kg/ha)	Biomass (kg/ha)	Harvest Index
0%	87.6c	13.97c	35.52c	21.59c	2485c	4060.6c	61.20c
2.5%	89.1b	14.63b	37.38ab	21.96b	2621b	4161.6b	61.29c
5.0%	92.4a	15.84a	37.25b	22.56a	2758.5a	4389.2a	62.98a
10%	91.2b	14.74b	37.97a	22.52a	2673b	4361.2ab	62.84b

Different letters indicate statistical differences at $p < 0.05$ (n = 4)

Effects of Biochar Application on Alkaline Soil Bulk Density, Soil Porosity, and Water Holding Capacity

Table 3 shows that biochar application significantly decreased soil bulk density, but it enhanced soil total porosity, saturated soil water content, and water holding capacity. The bulk density decreased 6.7% at the 10% biochar loading compared to the control. The total soil porosity in the 5% and 10% biochar treatments increased 4.14% and 5.09%, respectively, compared to the control. The saturated water content in the 2.5%, 5%, and 10% treatments increased 2.75%, 5.09%, and 6.61% compared to the control treatment (Table 3), respectively. Water holding capacity significantly increased from 32.3% in the control treatment to 34.2% and 34.6% in the 5% and 10% treatments ($p < 0.05$), respectively, which represented an increase of 6.00% and 7.12%, respectively. There were no differences between the 0% and 2.5% treatments or between the 2.5% and 5% treatments.

Table 3. Effects of Biochar Loading Levels on Bulk Density, Soil Porosity, and Water Holding Capacity

Biochar Treatment (w/w)	Bulk Density (g/cm^3)	Total Soil Porosity ($cm^3 \cdot cm^{-3}$)	Saturated Water Content ($cm^3 \cdot cm^{-3}$)	Water Holding Capacity ($cm^3 \cdot cm^{-3}$)
0%	1.26 ± 0.04 a	52.67 ± 2.01 c	44.01 ± 1.11 c	32.31 ± 1.21 b
2.5%	1.23 ± 0.02 b	53.18 ± 2.41 b	45.22 ± 0.96 bc	33.42 ± 0.91 b
5.0%	1.22 ± 0.03 b	54.85 ± 2.75 ab	46.25 ± 1.32 b	34.25 ± 1.85 a
10%	1.18 ± 0.02 c	55.35 ± 3.21 a	46.91 ± 1.05 a	34.61 ± 2.41 a

Note: Values are means of four replications ± standard deviation (SD); different letters indicate statistical differences at $p < 0.05$ (n = 4)

Effects of Biochar Application on Alkaline Soil pH and Electrical Conductivity

The soil pH values and electrical conductivities (EC) after 5 months of incubation are shown in Fig. 1. Soil pH value showed a decreasing trend as the biochar loading levels increased. It decreased from 8.25 in the control treatment to 8.18 and 8.01 in the 5% and 10% treatments ($p < 0.05$), respectively. The 10% biochar treatment showed the largest pH decrease, which was 0.24, whereas the pH in the 2.5% biochar treatment only decreased 0.03. The soil EC showed an increasing trend as the biochar loading rose, except that the

5% biochar treatment EC decreased to some extent. The 10% treatment showed the largest EC increase, which was 26 μS/cm.

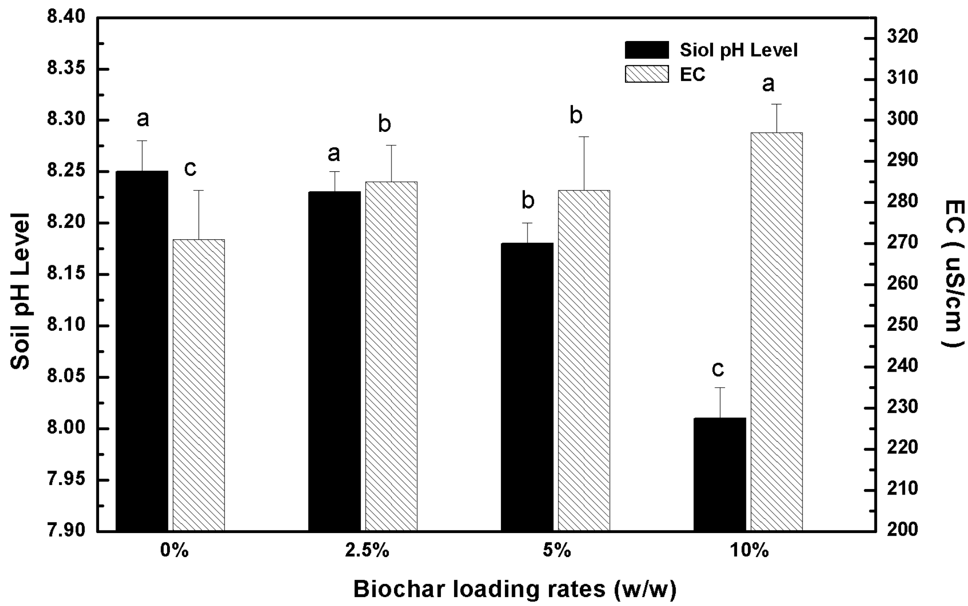

Fig. 1. Effects of biochar loading (0% w/w, 2.5% w/w, 5% w/w, and 10% w/w) on soil pH and EC; bars are the means of the replicates ± standard error of the mean (n = 4)

Effects of Biochar on Alkaline Soil TOC, Soil TON, and the C:N Ratio

Table 4 shows that biochar amendment significantly influenced the soil total organic carbon content at all five soybean growth stages. The 5% and 10% biochar treatments significantly increased soil total organic carbon content across the whole growth season compared to the control treatment. The 2.5% biochar treatment showed varying degrees of increase in soil total organic carbon content. There were no significant effects during the soybean early bloom and full bloom stages compared to the control treatment. Additionally, TOC content first increased and then decreased for the same treatment as the growth season progressed.

Table 4. Effects of Biochar Loading Levels on Soil Organic Carbon during the Soybean Growth Season

Biochar Treatment (w/w)	Soil Total Organic Carbon Content (g/kg)				
	Seeding	Early Bloom	Full Bloom	Pod	Maturity
0%	15.60 ± 0.60 c	17.29 ± 0.77 b	21.02 ± 0.65 c	17.52 ± 0.78 c	15.87 ± 0.55 c
2.5%	18.27 ± 0.45 b	18.35 ± 0.32 b	22.08 ± 0.5 bc	20.73 ± 0.81 b	16.96 ± 0.99 b
5.0%	22.80 ± 0.34 b	23.17 ± 0.35 a	23.97 ± 1.57 b	24.16 ± 1.67 a	20.17 ± 0.62 a
10%	26.55 ± 0.48 a	26.22 ± 0.89 a	27.56 ± 0.63 a	26.22 ± 2.45 a	21.97 ± 0.20 a

Different letters indicate statistical differences at $p < 0.05$ (n = 4)

Table 5 shows that biochar had a significant impact on soil total nitrogen during different growth stages. The 5% and 10% biochar treatments significantly increased soil total nitrogen content across the whole growth season compared to the control treatment, but no differences were observed between the 0% and 2.5% biochar treatments from the soybean early blooming stage to the pod stage. The flowering and pod stages were the most vigorous periods for soybean growth and development, and they were the key fertilizer requirement periods during soybean growth. The total nitrogen content in the 5% and 10% biochar treatments during the flowering stage increased 3.8% and 13.2%, respectively, and 17.1% and 12.9% during the pod stage, respectively, but either no increase or a low increase was observed in the 2.5% biochar treatment during these periods.

Table 5. Effects of Biochar Loading Levels on Soil Total Nitrogen during the Soybean Growth Season (g/kg)

Biochar Treatment (w/w)	Soil Total Nitrogen Content (g/kg)				
	Seeding	Early Bloom	Full Bloom	Pod	Maturity
0%	1.56 ± 0.32 c	1.73 ± 0.44 c	2.13 ± 0.32 c	1.94 ± 0.41 c	1.87 ± 0.37 d
2.5%	1.61 ± 0.31 b	1.82 ± 0.28 c	2.14 ± 0.32 c	1.94 ± 0.23 c	1.96 ± 0.42 c
5.0%	1.87 ± 0.21 a	1.98 ± 0.41 b	2.21 ± 0.48 ab	2.12 ± 0.32 b	2.01 ± 0.42 b
10%	1.91 ± 0.44 a	2.16 ± 0.36 a	2.26 ± 0.27 a	2.27 ± 0.27 a	2.04 ± 0.38 a

Different letters indicate statistical differences at $p < 0.05$ (n = 4)

Biochar application significantly altered soil total organic carbon and total nitrogen contents, which affected the soil C:N ratio. Table 6 shows that the soil C:N ratios were significantly higher in the biochar treatments than in the control treatment during the different growth periods, especially for the 10% biochar treatment. The treatments increased the C:N ratios 39%, 27.8%, 24.2%, 27.9%, and 20.4%, respectively. The higher C:N ratios might have contributed to the decline in soybean yield in the 10% biochar treatment compared to the 5% biochar treatment because nitrogen availability decreased at the higher C:N ratios produced by the 10% biochar loading level.

Table 6. Effects of Biochar Loading Levels on soil C:N Ratio

Biochar Treatment (w/w)	Soil C/N				
	Seeding	Early Bloom	Full Bloom	Pod	Maturity
0%	10.01 ± 0.32 d	9.50 ± 0.48 d	9.82 ± 0.32 c	9.03 ± 0.41 c	8.49 ± 0.37 d
2.5%	11.61 ± 0.33 c	10.61 ± 0.24 c	10.36 ± 0.32 b	10.69 ± 0.23 b	8.65 ± 0.42 c
5.0%	12.19 ± 0.21 b	11.79 ± 0.41 b	10.85 ± 0.48 b	11.39 ± 0.32 a	10.03 ± 0.42 b
10%	13.90 ± 0.44 a	12.14 ± 0.36 a	12.19 ± 0.27 a	11.55 ± 0.27 a	10.22 ± 0.38 a

Different letters indicate statistical differences at $p < 0.05$ (n = 4)

Effects of Biochar Application on Soil Available Nitrogen, Available Phosphorus, and Available Potassium

Figure 2 shows that biochar application significantly decreased the soil available nitrogen content during different growth stages. The 10% biochar treatment showed the maximum reduction, as it decreased 10.95% compared to the control treatment at the pod stage. The decreases in soil available nitrogen content were highly consistent with reduction in leaf SPAD values (data not shown).

Figure 3 shows that the biochar amendment increased soil available phosphorus content during the different growth stages. The 5% and 10% biochar treatments significantly increased soil available phosphorus content compared to the control treatment, and soil available phosphorus generally increased in proportion to biochar loading levels. After 5 months of incubation, the available phosphorus content in the 2.5%, 5%, and 10% biochar treatments increased 23.7%, 29.2%, and 32.9%, respectively, compared to the control treatment. Additionally, the soil available phosphorus content also first increased, but then decreased for the same treatment as the growth season progressed.

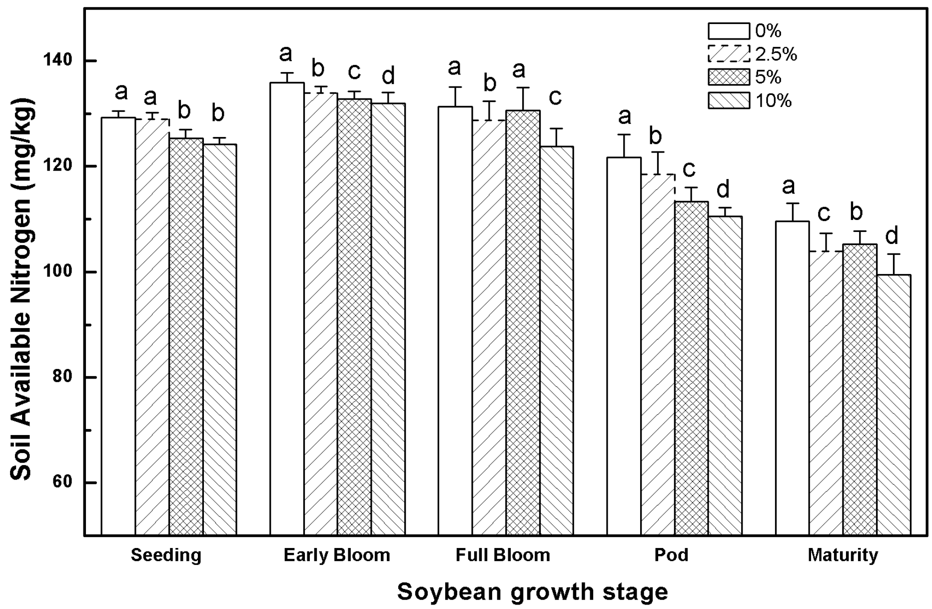

Fig. 2. Effects of biochar loading levels (0% w/w, 2.5% w/w, 5% w/w, and 10% w/w) on soil available nitrogen; different letters indicate statistical differences at $p < 0.05$

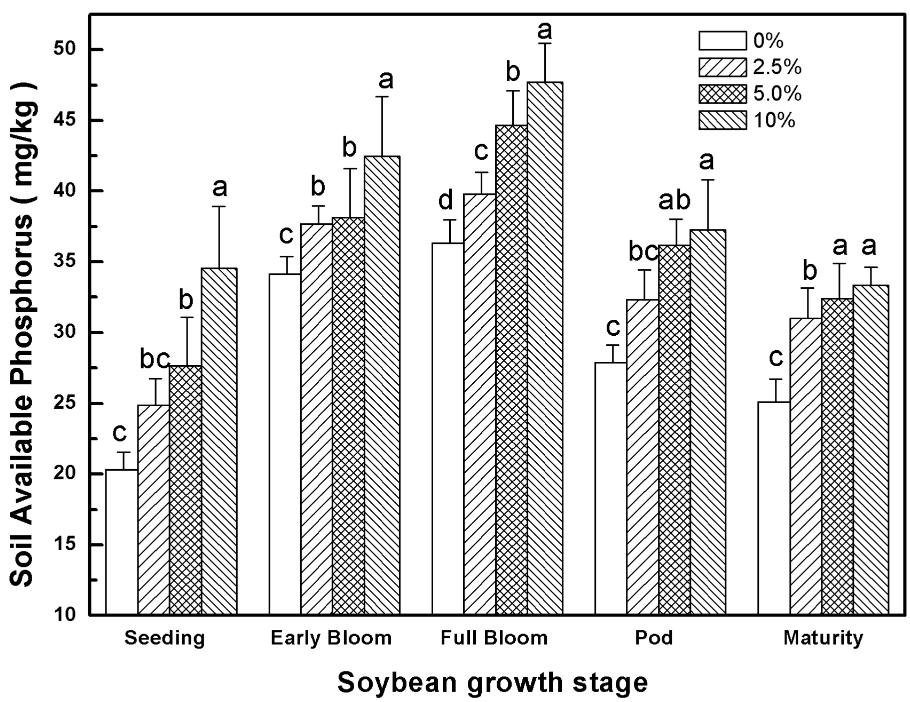

Fig. 3. Effects of biochar loading levels (0% w/w, 2.5% w/w, 5% w/w, and 10% w/w) on soil available phosphorus; different letters indicate statistical differences at $p < 0.05$

Figure 4 shows that for each growth stage, the available potassium content in biochar-modified soil increased as the biochar loading levels increased, especially for the

5% and 10% treatments. There was either no difference or only a small difference from the full bloom stage to maturity stage between the 2.5% biochar treatment and the control treatment

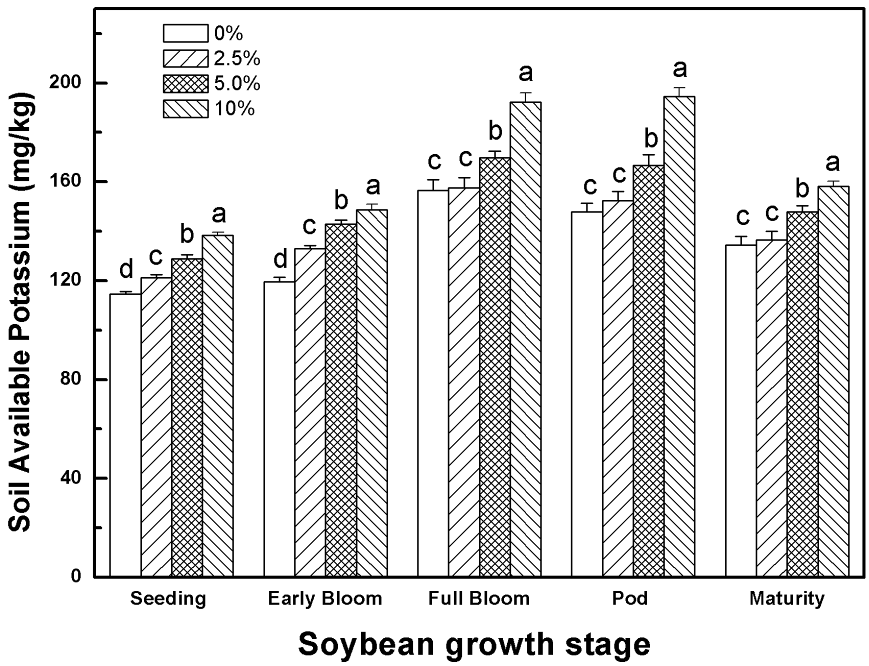

Fig. 4. Effects of biochar loading levels (0% w/w, 2.5% w/w, 5% w/w, 10% w/w) on soil available potassium; error bars represent the standard deviation (n = 4). Different letters indicate statistical differences at $p < 0.05$.

Effects of Biochar Application on Soil Exchangeable Cations (Ca, Mg, and Na), CEC, and ESP

Table 7 shows that biochar had either no effects or only small effects on the levels of exchangeable calcium and exchangeable magnesium. However, the exchangeable sodium increased significantly by 6.4% and 15.4% in the 5% and 10% treatments ($p < 0.05$), respectively. Biochar application also significantly increased the soil CEC levels, especially in the 5% and 10% treatments where the CEC levels rose 6.61 cmol/kg and 8.26 cmol/kg, respectively. Soil ESP significantly decreased from 30.07% in the control to 23.81% and 25.19% in the 5% and 10% treatments, respectively.

Table 7. Effects of Biochar Loading Levels on Exchangeable Cations (Ca, Mg, and Na), Soil CEC, and ESP

Biochar Treatment (w/w)	Exc. Ca (cmol/kg)	Exc. Mg (cmol/kg)	Exc. Na (cmol/kg)	CEC (cmol/kg)	ESP (%)
0%	0.46 a	0.43 a	5.78 c	19.22 c	30.07 a
2.5%	0.49 a	0.46 a	5.95 c	21.61 c	27.53 b
5.0%	0.55 a	0.48 a	6.15 b	25.83 b	23.81 d
10%	0.57 a	0.54 a	6.67 a	27.48 a	25.19 c

Different letters indicate statistical differences at $p < 0.05$ (n = 4); CEC: cation exchange capacity, ESP: exchange sodium percentage; Exc: exchangeable

Correlation of Soil Characteristics with Soybean Growth and Yield Parameters

The correlation analysis of the soil chemical properties with the soybean growth and yield parameters is shown in Table 8. The results indicated that soil pH, soil exchangeable sodium, soil available nitrogen, and soil exchangeable sodium percentage had significant or very significant negative correlations with soybean biomass production and yield parameters. The results additionally showed that soil pH, soil exchangeable sodium, soil available nitrogen, and soil exchangeable sodium percentage had the greatest impact on the growth and development of soybeans under saline-alkaline soil conditions.

Table 8. Analysis of the Correlation between Soil Chemical Properties and the Soybean Growth and Yield Parameters

	Height	Pod Number	Seed Number	100-seed Weight	Seed Yield	Biomass	Harvest Index
Total Soil Porosity	0.701	0.37	0.823*	0.813	0.641	0.761	-0.202
Saturated Water Content	0.803*	0.617	0.814*	0.872**	0.862*	0.805*	0.124
Water Holding Capacity	0.812*	0.732	0.822*	0.827**	0.811*	0.826*	0.203
pH	-0.329	-0.212	-0.321*	-0.423	-0.472	-0.211	0.317
Electric Conductivity	0.614	0.316	0.825*	0.773	0.631	0.703	0.042
Soil Organic Carbon	0.837	0.613	0.719	0.814*	0.782	0.804*	-0.072
Total Nitrogen	0.820*	0.731	0.814*	0.861**	0.892*	0.844*	0.251
C/N	-0.529*	-0.421	-0.721**	-0.723**	-0.522*	-0.674*	-0.711*
Exc. Ca	0.718	0.819*	0.182	0.652	0.742	0.714	0.391
Exc. Mg	0.623	0.217	0.681	0.752	0.492	0.724	-0.324
Exc. Na	-0.621*	-0.814**	-0.022	-0.433	-0.632**	-0.428*	-0.591*
Cation Exchange Capacity	0.821*	0.619	0.811*	0.717**	0.827	0.716*	0.156
Exchange Sodium Percentage	-0.731*	-0.436	-0.828**	-0.813**	-0.721*	-0.772*	-0.175
Available Nitrogen	-0.529	-0.321	-0.724*	-0.713	-0.529	-0.695	-0.043
Available Phosphorus	0.816	0.712	0.828**	0.912*	0.902*	0.839*	0.414
Available Potassium	0.709	0.418	0.715	0.818*	0.627	0.828	-0.215
Note: * = $p < 0.05$; ** = $p < 0.01$							

Impacts of Biochar on Soybean Biomass and Seed Yield

Previous studies reported that biochar application can significantly promote crop biomass accumulation, growth and development, and grain yield (Steiner *et al.* 2007; Major *et al.* 2010; Farhangi-Abriz and Torabian 2018). Our studies indicated that biochar application promote the soybean growth and yield components. The similar results were also reported by Wu *et al.* (2019), who showed that amending red soil with biochar increased the number of effective cotton branches, bolls, and buds, and led to early bud formation. Increases in productivity after biochar application have also been recorded for other leguminous plants, such as alfalfa (Nishio and Okano 1991), common bean (Rondon *et al*. 2007), and clover (Quilliam *et al.* 2013; Mia *et al*. 2014). It has been widely accepted that biochar application affects plant growth and promotes crop yield by ameliorating soil physico-chemical characteristics, such as reductions in soil bulk density (Novak *et al*. 2009; Busscher *et al*. 2010; Laird *et al*. 2010), enhanced soil porosity (Baiamonte *et al*. 2015), water holding capacity (Liu *et al*. 2012a; Basso *et al*. 2013), and soil cation exchange capacity (Glaser *et al*. 2002; Rondon *et al*. 2007). Furthermore, nutrients contained within biochar and improvements in nutrient retention after biochar addition might account for the short-term enhancement of crop productivities (Lehmann *et al*. 2003; Steiner *et al*. 2007). Apart from direct nutrient supply and retention within biochar, other possible mechanisms that contributed to increased crop yields after biochar application include changes in soil structure and nutrient status (Lin *et al*. 2018). Biochar also promotes nutrient uptake by improving soil microbial activity (Chan *et al*. 2008; Sohi *et al*. 2009). The experiment conducted by Zhang *et al*. (2019a,b) indicated that application of biochar had a much greater effect on bacteria community and alpha diversity in acid soils than in alkaline soils.

These results also showed that the excessive addition of biochar (10% biochar loading) inhibited soybean growth. Similar results were also reported by Rondon *et al*. (2007), who showed that the yield of the common bean (*P. vulgaris* L.) was the highest at the 78 t/ha biochar loading but decreased when the biochar loading exceeded this threshold. In this experiment, the available nitrogen in the soil decreased significantly at the highest loading (10%), which might have contributed to the low soybean productivity. The low soil available N (Fig. 2) and low leaf SPAD values (low tissue N concentrations) suggested that nitrogen was probably immobilized at the 10% loading. Lower foliar nitrogen was also detected in biochar-modified tropical soils cultivated with rice and legumes (Lehmann *et al*. 2003). Short-term immobilization induced by biochar addition has been reported after laboratory incubations (Nelson *et al*. 2011; Bruun *et al*. 2012) and field trials on tropical nitrogen-deficient soils (Asai *et al*. 2009). In contrast, there have been fewer reports on biochar-induced short-term nitrogen immobilization in field or incubation experiments with temperate alkaline soil under semi-arid conditions. Another potential yield-inhibiting factor was that the Na^+ contents could have limited soybean growth at the 10% biochar loading. In this experiment, soil exchangeable sodium had a significantly negative correlation with soybean biomass production and yield parameters. Sodium is reported to be the most toxic ion for crops grown in weak alkaline soil and might account for the inhibition of crop growth at the 10% biochar loading (Fortmeier and Schubert 1995). Biochar addition might have also increased soil salinity, as indicated by the high EC values (Fig. 1), especially at the highest biochar loading. Therefore, these negative factors should be considered when applying high biochar loading to saline-alkaline soil.

Impacts of Biochar on Alkaline Soil Bulk Density, Porosity, and Water Holding Capacity

Some incubation and field experiments have focused on the benefits of biochar when it is added to weathered, tropical, or subtropical soils that are characterized by poor fertility, low clay activity, and strong acidity. These soils are considered to be degraded soils. In contrast, the tested alkaline soil used in this study had poor soil structure with high alkalinity, high swelling pressure, and low hydraulic conductivity (Su *et al*. 2018), which resulted in poor water physical properties. The results indicated that biochar application significantly increased saturated soil water content and water holding capacity after 5 months of incubation (Table 3). The results agreed with those reported by Xiao *et al*. (2016) for the semi-arid Loess Plateau. They reported that biochar application enhanced the soil permeability and water retention capacity of the mixed soil. The effects could be explained by the reduced soil bulk density (Busscher *et al*. 2010; Laird *et al*. 2010) and enhanced soil permeability (Hardie *et al*. 2014), which increased soil moisture retention (Liu *et al*. 2012a; Basso *et al*. 2013). Jeffery *et al*. (2011) reported that the water holding capacity increase after biochar addition was possibly the main contributor to overall yield improvements (Table 8). In this study, the reduced soil bulk density was related to the low biochar bulk density. Furthermore, the porous structure of biochar increased the formation of large macrospores around the biochar particles and prevented pores from clogging.

Impacts of Biochar on Alkaline Soil Chemical Characteristics

Numerous studies have demonstrated that biochar application could increase acidic soil pH values. In this study, the biochar-amended soils had lower pH values than the control treatment at the harvest stage, and the 10% biochar loading showed the largest pH decrease (0.24). Similar results were also reported by Zhang *et al*. (2019c) who revealed that biochar amendments had no impact on the pH value of the lou soil, but significantly reduced the pH value of the black soil, which taken from Daqing (Heilongjiang, China) with a higher background pH value than that of the biochar. The results were also consistent with a previous study that investigated on five types of alkaline soils (Liu and Zhang 2012b). The alkaline soil used in this study had high Na_2CO_3 and $NaHCO_3$ contents. The addition of biochar promoted the conversion of Na_2CO_3 and $NaHCO_3$ to neutral calcium salt, $CaCO_3$, and $Ca(HCO_3)_2$. The decrease in soda salt (Na_2CO_3 and $NaHCO_3$) and the replacement of exchangeable sodium by exchangeable calcium decreased the pH value of the alkaline soil. Another reason for the pH decline was that acidic substances produced by the oxidation and decomposition of soil organic matter (Senesi and Plaza 2007; Dias *et al*. 2010) could neutralize soil alkalinity and lower the soil pH value (Zavalloni *et al*. 2011). The results suggested that applying low or intermediate biochar loading to slightly alkaline soil did not increase soil pH. Therefore, adding biochar with a lower pH value than the tested soil at low or intermediate loading could potentially reduce the soil pH value.

Soil electrical conductivity (EC) is a method for measuring soil salt content and is a good indicator of nutrient availability, utilization efficiency, soil texture, and available water capacity. In this study, biochar application increased soil electrical conductivity, and the 10% biochar treatment significantly increased EC 26 μS/cm. This result agreed with Hossain *et al*. (2011), who reported a significant rise in soil EC after biochar application. The high soil EC in biochar-modified soil might be related to the large amount of ash in biochar. Soil EC cannot directly measure specific ions or salt components, but it is associated with the nitrate, potassium, sodium, chloride, sulfate, and ammonia concentrations in total ash. Total ash contains nutrients that are beneficial to plant growth. However, it also contains high concentrations of salts that are harmful to plants, such as sodium ions.

Applying biochar increased soil total organic carbon content, which was positively correlated with the biochar loading. The increase in TOC content contributed to the high levels of organic matter in the biochar-amended soils. Biochar addition also enhances microbial activity and stimulates the decomposition of biological residues and biogenic humic substances, which promotes the formation of humus (Laird *et al*. 2009; Liang *et al*. 2010). The results also indicated that biochar addition increased the total nitrogen in biochar-amended alkaline soil. In addition to the nitrogen nutrients in biochar, another reason for the yield increases could be that biochar inputs increased the organic content of the tested soil (Cui *et al*. 2008). In this study, the C:N ratios in the biochar treatments were significantly higher than for the control treatment during the five growth periods. In particular, the 10% biochar treatment increased the C:N ratio 39%, 27.8%, 24.2%, 27.9%, and 20.4% in the five growth periods, respectively. The higher C:N ratios might have contributed to the decline in soybean yield at the 10% loading compared to the 5% treatment because available nitrogen declined at higher C:N ratios. Lehmann *et al.* (2003) and Chan *et al*. (2008) reported that increasing the biochar addition levels increased soil TOC content more than the soil total nitrogen content, which resulted in higher C:N ratios. This would cause nitrogen immobilization and lead to nitrogen deficiency. In this study, the detected decreases in soil available nitrogen content were highly correlated with the reduction in leaf SPAD values (data not shown).

Phosphorus and potassium are essential macro-elements for plant growth and development, and phosphorus availability is highly pH-dependent. The tested soil was alkaline with a pH value of 8.25, which would inhibit the availability of phosphorus. Furthermore, the tested soil had a higher total phosphorus content, but a lower available phosphorus content. The addition of biochar lowered the tested soil pH value (Fig. 1), which increased the content and availability of phosphorus in the modified soil during the different growth periods. Apart from the altered soil pH and direct release of phosphorus from biochar, biochar application also promotes microbial activity and therefore indirectly influences the mineralization of phosphorus (DeLuca *et al*. 2015). The results showed that there was a significant increase in available potassium in the alkaline soil after biochar addition. Incorporating biochar caused the available potassium to increase from 134.5 mg/kg to 158.3 mg/kg at the highest biochar loading level during the harvest stage. This indicated that biochar application improved the availability of soil potassium, probably because biochar made from corn straw contained free nutrient cations (*e.g.*, potassium) that did not volatilize (*e.g.*, nitrogen) or exist in an insoluble form (*e.g.*, magnesium) during the pyrolysis process. Furthermore, the potassium was preserved and converted to potassium salts, which are highly soluble, during the production of biochar (Karim *et al*. 2017). The increase in soil available potassium may also be due to short-term interactions and reactions between biochar and soil, such as dissolution and precipitation, adsorption and desorption, and redox reactions (Joseph *et al.* 2010).The same results were also reported by McElligott (2011), who found that biochar application increased the availability of soil potassium.

Cation exchange capacity is an indicator of the nutrient cation retention capacity when the nutrients are in a plant-available form, which is a form that prevents nutrient leaching losses (Sohi *et al*. 2009). In this study, biochar addition improved the CEC in biochar-modified soils compared to the control with no biochar addition, which was consistent with previous reports (Lehmann *et al*. 2003; Chan *et al*. 2008; Hossain *et al*. 2011; Major *et al*. 2012).

The application of biochar increased soil nutrient contents and CEC, but it also significantly increased the exchangeable sodium content, which had negative effects on plant growth, especially at the high biochar loading level. This result had rarely been reported in previous studies. Fortmeier and Schubert (1995) reported that sodium was the most toxic ion to crops grown in slightly alkaline soil. The increased exchangeable sodium content might account for the inhibition of crop growth at the 10% loading level. In addition, biochar addition had the potential to increase slightly alkaline soil salinity. The high EC values at the high biochar loading level suggested that this might have happened in the soils used in this study. Therefore, scientific attention should focus on amending saline-alkaline soil with the optimal biochar loading. This is important when biochars are used to ameliorate alkaline soils.

Relationships between Soil Characteristics and Soybean Growth and Yield Parameters

The correlation analysis results showed a relationship between soybean yields and the alkaline soil physico-chemical properties after 5 months of incubation. The enhanced yield was probably due to the improved soil physico-chemical characteristics. For example, a reduction in soil bulk density enhances water holding capacity (Liu *et al*. 2012a) and soil nutrients' status (*e.g.*, soil organic carbon, and soil P and N contents). However, excessive biochar application inhibited soybean growth, which was observed in this study. The increase in the C:N ratio after biochar application is often regarded as the main reason for soybean yield inhibition at high biochar loading levels because it leads to nitrogen immobilization (Lehmann *et al*. 2003; Rondon *et al*. 2007; Streubel *et al*. 2011). Table 8 shows that the soil C:N ratio after biochar application was negatively associated with soybean height ($r = -0.529$, $p < 0.05$), seed number ($r = -0.721$, $p < 0.01$), 100-seed weight ($r = -0.723$, $p < 0.01$), seed yield ($r = -0.522$, $p < 0.05$), and harvest index ($r = -0.711$, $p < 0.05$). The increase in soil exchangeable sodium content is also regarded as a potential yield-inhibiting factor (Rajkovich *et al*. 2012). In this study, soil exchangeable sodium was negatively associated with soybean pod number ($r = -0.814$, $p < 0.01$), seed yield ($r = -0.632$, $p < 0.01$), biomass ($r = -0.428$, $p < 0.05$), and harvest index ($r = -0.591$, $p < 0.05$). A pot experiment conducted by Rajkovich *et al*. (2012) suggested that the decline in plant growth caused by sodium may be explained by the significant increase in osmotic potential after biochar addition, which would reduce water uptake by the plant. In addition, available nitrogen (related to the C:N ratio), soil pH, and the soil exchangeable sodium percentage (related to exchangeable sodium) were also negatively correlated with soybean growth.

This short-term study revealed that a single application of biochar derived from corn straw could improve alkaline soil quality and increase crop productivity under the semi-arid soil incubation conditions used in this study. Corn straw biochar applications to the alkaline soil significantly improved soil physico-chemical properties, *e.g.*, soil porosity, water holding capacity, and soil nutrients' status. The correlation analysis indicated that among the detected soil properties, nutrient content and soil water holding capacity were the main contributors to the increased soybean productivity, whereas increased nitrogen immobilization and exchangeable sodium content after biochar application inhibited soybean growth and yield parameters. This indicated that biochar had the potential to improve plant growth and soil properties in infertile alkaline soil. However, the negative effects should be taken into account when applying high biochar loading levels to alkaline soils. These results have important implications when using biochar to ameliorate alkaline soils. Additional field studies are still needed to further understand the impacts of corn straw biochar on soil physico-chemical characteristics and crop productivity under different conditions, such as different soil types, biochar types, loading levels, and fertilizer inputs. There is also a need for longer-term field experiments.

CONCLUSIONS

1. Short-term single application of biochar positively and significantly improved quality attributes of the tested alkaline soil, increased soil water holding capacity, total organic carbon content, total nitrogen, Olsen-P, available potassium, and cation exchange capacity.
2. Single application of biochar enhanced soybean growth and yield components. The highest soybean height, biomass, and yield were obtained at the 5% biochar loading level, but the benefits decreased when the biochar loading rate exceeded this threshold.
3. Negative effects should be taken into account when applying high biochar loading rates to alkaline soils.

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