Increasing the okra salt threshold value with biochar amendments

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ABSTRACT

Soil salinity is a severe worldwide environmental problem that adversely affects soil properties and the crop growth such as okra. We hypothesized that biochar soil amendments could increase the okra salt threshold, alleviate salt stress and improve soil productivity. In this study, a pot experiment was conducted to investigate whether biochar could ameliorate the effects of salinity on okra plants. Three biochar amendment (BA) soil applications (0%, 5% and 10% by mass of soil) were considered for seven irrigation water salinity levels (0.75, 1.0, 2.0, 4.0, 5.0, 6.0 and 7.0 dS m\(^{-1}\)) in a randomized block design with three replications. The Maas and Hoffman salt tolerance model was used to evaluate the effects of BA on okra plant growth parameters (e.g. yield, biomass) and water use efficiency for each salinity treatment. The results showed that increasing the soil salinity levels caused significant decreases in plant yields and yield components. However, biochar application rates of 5% and 10% increased the okra threshold by 19.7% and 81.2%, respectively, compared to the control (0%). The 10% biochar application rate also resulted in the greatest okra plant growth and increased yield, indicating that the effects of salt stress were ameliorated; moreover, the soil bulk density was decreased, and the water content was increased. Hence, biochar soil amendments could be considered as an important agronomic practice that could potentially overcome the adverse effects of salt stress.

1. Introduction

Salinization is a major constraint that confronts the development of irrigated agriculture in many arid and semi-arid regions of the world as well as in some humid areas. Worldwide, approximately 4 × 10^8 ha of land becomes unavailable for agricultural production annually because of salinization problems (Li et al. 2014). Many soils in China are affected by salinity. In 2006, the total salt-affected area was estimated to be approximately 36 × 10^6 ha, which is equivalent to approximately 4.8% of the agricultural lands. These soils mainly extend across an area from northwest China to the coastal regions (Yang 2006).

Increasing salt concentrations in soil surface layers leads to higher levels of soil surface sealing, crust formation and soil compaction (Niñerola et al. 2016). These problems are symptomatic of the weaker coherence and stronger clay dispersion that adversely affect soil aggregation and soil hydraulic properties in a salt-affected soil and consequently results in reduced plant productivity (Patra et al. 2016). Increased salinity levels in soils and/or in irrigation water causes salt stress in plants. Salt causes stress in plant physiology due to its effects on osmosis and ionic interactions (Taïbi et al. 2016). Osmotic stress occurs because high concentrations of salt in the root zone decrease soil water potential and, thereby, the availability of water for the plant causing dehydration at the cellular level (Shahid et al. 2011). Adverse ionic interactions are affected by excessive amounts of toxic ions such as sodium and chloride, which create an ionic imbalance by reducing the uptake of beneficial cations such as potassium, calcium, and magnesium (Parihar and Rakshit 2016). Plants typically have some tolerance to salinity, and salinity can increase without affecting yield or other plant attributes. However, at a critical threshold value, further increases in salinity begin to affect yield and plant growth (Maas and Hoffman 1977).

Biochar is a solid material that is produced from a thermochemical conversion of organic materials in an oxygen-limited environment (Najar et al. 2015). It is often used as a soil amendment since it has been demonstrated to have beneficial effects on the physical, chemical, and biological properties of a soil (Mukherjee and Lal 2013). These effects are attributed to its highly porous structure and large specific surface area (Tang et al. 2013). Only a few studies have investigated the potential of biochar to mitigate the negative effects of salt stress on plants. Among these, Usman et al. (2016) reported that the application of biochar to coarse-textured soils irrigated with saline or non-saline water increased the plant growth, yield and fruit quality of tomato plants, as well as their water use efficiency (WUE) and soil nutrient availability. Ali et al. (2017) stated that the promoted growth of plants under biochar addition could have resulted from the improved soil properties such as the increased soil organic matter (SOM) and cation exchange capacity (CEC), the decreased amount of exchangeable sodium (Ex-Na) and exchangeable sodium percentage (ESP), and the rhizosphere effect (e.g. decreased soil pH). Similar results were obtained by Lashari et al. (2013, 2015) who studied the ability of biochar-manure compost to alleviate salt stress and improve leaf bioactivity of maize in a saline soil from central China.
Okra (*Abelmoschus esculentus* L.) is a vegetable crop that is grown in various regions including those with tropical, subtropical, and Mediterranean climates (Martin et al. 1981). Okra is a high-value crop because it is a source of nutrients that are important to human health, e.g. vitamins, potassium, calcium, carbohydrates and unsaturated fatty acids such as linolenic and oleic acids (Asare et al. 2016). Since okra is often grown under irrigation, especially where the summers are typically dry, e.g. in Mediterranean countries, it can be subject to salt stress resulting in very low pod yields (Habib et al. 2016). Okra is classed by the FAO as moderately sensitive to salinity based on pod yields (Tanji and Neelte 2002); the FAO cites one study where the salinity threshold was determined to be 6 dS m\(^{-1}\) (Palival and Maliwal 1972). There are a variety of approaches to ameliorate the effects of salt stress on plants such as by inoculating the soil with plant growth-promoting rhizobacteria (Habib et al. 2016) or using proline foliar applications to reduce sodium uptake (Khan et al. 2015). Altering the plant genome has also been considered; for example, Sabouri et al. (2009) changed the quantitative trait locus (QTL) in a section of DNA for rice (*Oryza sativa* L.) to enhance its salt tolerance. We hypothesized that biochar soil amendments could also increase the okra salt threshold and alleviate salt stress by potentially improving the soil structure thereby affecting its hydrologic properties as well as by altering the ionic composition of the soil solution. Hence, the objective of this study was to test different biochar amendment application rates under different conditions of salinity by measuring plant characteristics, including yield, and soil properties related to soil quality.

2. Materials and methods

2.1. The experimental design and layout

The study was conducted in a greenhouse at the Hohai University Water-Saving Park in Nanjing, Jiangsu Province, China (31°57′N; 118°50′E), which is 144 m above sea level. The climate of the study area is humid subtropical under the influence of the East Asia monsoon. The mean annual temperature is 15.7°C, the mean pan evaporation is 900 mm, and the mean annual precipitation is 1073 mm (Shao et al. 2015).

In this study, okra was grown in pots in a greenhouse under different levels of irrigation water salinity and biochar amendment. Seven levels of irrigation water salinity, as indicated by electrical conductivity (ECi), were applied: S0 = 0.75; S1 = 1.0, S2 = 2.0, S3 = 4.0, S4 = 5.0; S5 = 6.0; and S6 = 7.0 dS m\(^{-1}\). The intended level of salinity was obtained by dissolving NaCl in tap water (adding 0.5843 g NaCl L\(^{-1}\) and increasing ECi by 1 dS m\(^{-1}\)). Three rates of biochar amendment (BA) were investigated: B0 = 0%; B1 = 5%; and B2 = 10%. The B0S0 combination was considered the control treatment. A randomized complete block design was used, comprising three blocks, with each block receiving a different BA; within each block, pots received a randomly allocated saline irrigation water treatment. Each treatment had three replications. A silt loam soil was collected from a nearby field, air-dried and sieved through a 4-mm mesh to remove large particles, hard clogs and debris. The initial chemical and physical properties of the soil are given in Table 1. The biochar amendment was produced from wheat straw, pyrolyzed at 350–550 °C in a vertical kiln made of refractory bricks and was provided by Sanli New Energy Company, Henan Province, China; 30% of the wheat straw dry matter was expected to be converted to biochar (Liu et al. 2014). The physical and chemical properties of the biochar are presented in Table 1.

The okra plants were grown in 63 pots with upper and lower diameters of 28 and 18 cm, respectively, and a depth of 26 cm (Figure 1). For each pot, approximately 10 kg of the air-dried soil was mixed thoroughly with biochar to achieve the desired application rate; and the soil-biochar mixture was then poured into the pot. One okra seedling (7 days old) was planted in the center of each pot on 14 April 2016. During the two weeks after transplanting the seedlings, the pots were irrigated with tap water, which had the lowest salinity level considered in the study (S0), to establish the okra plants; the amount of water added was meant to restore the soil water content to field capacity (FC) (section 2.4). Saline water treatments commenced on 28 April. On 24 August, the irrigation experiment was ended. The air temperature inside the greenhouse was kept at 30.5°C ± 2 during the growing season (14 April to 24 August, 2016), while the temperature ranged from 18.5 to 41.0°C during the same period outside the greenhouse.

2.3. Measured plant growth parameters

During the growing season, plant growth parameters, i.e. plant height (PH), mid-stem diameter (MSD), fresh above-ground biomass (AGB), number of pods per plant (NPP) and leaves per plant (NLP), and the pod yield of all 63 plants were determined. These parameters were used in the salt tolerance model (section 2.5). The four plant growth stages (initial, developing, middle, and late) corresponded to the periods of 14 April to 30 April, 30 April to 15 June, 15 June to 15 July and 15 July to 24 August, respectively. The MSD was measured using calipers at the midpoint of the stem, and the PH was measured from the base of the stem to the soil surface to the top of the plant using a metal measuring tape. The NPP and NLP were counted at weekly intervals. The plants were harvested on 24 August. The plant stems were cut 1 cm above the soil surface, and the fresh plant AGB was determined by weighing. Photosynthesis (Pn) and transpiration rates (Tr) for two leaves selected in the upper canopy of each plant were measured during the period of 09:00–12:00 h using a portable photosynthesis system (Li-Cor 6400 portable photosynthesis measurement system, Li-Cor, Lincoln, NE, USA). Four measurements were carried out in the growing season of 2016 (18 May, 15 June, 6 July, and 31 July). The mean values calculated from the measurements made on the

| Property                      | Unit       | Soil          | Biochar       |
|-------------------------------|------------|---------------|---------------|
| Silt                          | %          | 30            | –             |
| Sand                          | %          | 50            | –             |
| Clay                          | %          | 20            | –             |
| Field capacity                | %          | 25.8          | –             |
| Total N                       | g kg\(^{-1}\)| 0.18          | 5.9           |
| Total P                       | g kg\(^{-1}\)| 0.66          | 14.43         |
| Total K                       | g kg\(^{-1}\)| 0.4           | 11.5          |
| Cation exchange capacity      | cmol kg\(^{-1}\)| 14.94       | 21.7          |
| Bulk density                  | g cm\(^{-3}\)| 1.35          | 0.40          |
| pH                            | –          | 7.7           | 9.9           |
| Electrical conductivity       | dS m\(^{-1}\)| 1.42          | 1.0           |
four dates were used to represent the photosynthesis and leaf transpiration rates.

2.4. Measured soil physical and hydraulic properties

At the end of the growing season, a disturbed soil sample (~1 kg) was collected from each pot, sealed in plastic bags and transported to the laboratory. The soil samples were air dried and crushed to pass through a 2-mm mesh. A soil-to-water ratio of 1:5 was utilized to measure the electrical conductivities (ECe) using a glass electrode. At the beginning of the experiment, the soil FC in each pot was determined by saturating the soil with tap water. The pots were left to drain, while the surface of the soil was covered by a plastic sheet to prevent evaporation. Each pot had been weighed prior to saturation, and they were weighed again after drainage ceased. The soil water content was then calculated as the difference in masses, taking into account the air-dried soil water content, and was assumed to be equivalent to the FC of the soil. During the growing season, each pot was weighed before each irrigation event. The amount of water applied to each pot was determined by taking the difference between the mass of the pot when the soil was at FC and the mass of each pot before irrigation; the mass of the okra plants was ignored as most of the mass was composed of the soil and water. The total water consumption (ET) from each pot during the okra growing season was calculated by summing all the water amounts added for every irrigation event. After harvesting, a cylindrical stainless steel soil cutter (5 cm internal diameter, and 5 cm deep) was used to collect soil samples from the 0 to 10 cm soil layer to determine the final soil bulk density (BD), calculated from the known soil volume and the soil mass following oven drying to constant mass (105°C) (Blake and Hartge 1986). Care was taken when positioning the core to avoid any surface irregularities. The mean BD value was calculated using three replicates from each pot. The available water content (AWC) for each pot was calculated as the difference between the FC and the permanent wilting point (PWP), which was determined at the end of the experiment by the weighing method (Gelderman and Mollarino 1998). The mechanical analysis of the soil was determined by the hydrometer method (Gupta 2000). The

2.5. Measured soil chemical property

Calcium (Ca), magnesium (Mg), sodium (N), and potassium (K) contents were determined from a soil-to-water ratio of 1:5 (Richards 1954), using an atomic adsorption spectrophotometer. The CEC was determined using the ammonium acetate method (Chapman 1965). The total nitrogen (TN) was determined following the method of Olsen and Sommers (1982). The total phosphorus (TP) was determined following Olsen and Sommers (1982). The total potassium (TK) was determined following the method of Tan (1996).

2.6. Adoption of salt tolerance model to okra

The salt tolerance model suggested by Maas and Hoffman (1977) was applied to each okra plant growth parameter (i.e. yield, PH, AGB, MSD, NPP, NLP) to calculate its soil salinity threshold value and the slope (the rate of decline of the parameter with increasing salinity, as indicated by its ECe, beyond the threshold value for a given salinity and BA rate combination treatment). Using yield as an example of the okra plant growth parameter, the salt tolerance model (Maas and Hoffman 1977) is given by:

\[
\frac{Y_a}{Y_m} = 1 - (ECe - ECethreshold) \times \frac{b}{100},
\]

where \(Y_a\) is the mean measured okra pod yield for a given water salinity and biochar treatment (g); \(Y_m\) is the maximum okra yield measured for the S0 control treatment (g) for the given biochar treatment; \(ECethreshold\) is the soil salinity threshold value (dS m\(^{-1}\)); \(ECe\) is the soil salinity beyond the threshold value (dS m\(^{-1}\)); and \(b\) is the slope value, which represents the rate of declining yield with increasing ECe beyond the threshold value.

2.7. Statistical analysis

The experimental data were analyzed using the Minitab statistical analysis software (Minitab 17). The general linear model procedure was used to perform analysis of variance. When F values were significant, mean values were compared by applying the least significant difference (LSD) test at the 0.05 level of significance.

3. Results

3.1. Soil physical and hydraulic properties

Analysis of variation detected significant differences (\(P < 0.05\)) among the mean values of ECe, BD, FC, PWP, AWC and ET for all treatments (Table 2). The mean ECe values increased with increasing salinity levels of the applied irrigation water (ECi). The highest ECe value was observed for the highest ECi treatment (18.5 dS m\(^{-1}\) for S6) with a10% BA rate (B2). The ECe also increased with increases in the BA rate.

Figure 1. A schematic of the pot used in this study and its dimensions.
The mean BD values decreased with increases in the BA rate. However, the BD tended to increase with increases in the EGI values and, thus, the highest values of BD occurred under the B2S0, B2S6 and B2S0 treatments, respectively. The mean values of ET were decreased by increases in the ECi. However, they were enhanced under the BA treatments, particularly at the high BA rates. These results are in agreement

Table 3. Mean values of okra plant morphological parameters for different biochar application rates (B) and irrigation water salinity (S).

| Biochar Rates | Water salinity | MSD | PH | AGB | NPP | NLP |
|---------------|----------------|-----|-----|-----|-----|-----|
|               | Initial        | Dev. | Mid | Late | Initial | Dev. | Mid | Late |
| B0            | 50             | 3.31±B | 9.9 ±C | 12.3 ±B | 14.6 ±B | 29.5 ±C | 73.1 ±C | 136 ±B | 11.0 ±C | 8.70 ±C |
| S1            | 3.27±C | 9.7 ±C | 12.1 ±C | 14.8 ±B | 29.4 ±C | 72.9 ±C | 135 ±B | 11.0 ±C | 8.00 ±B |
| S2            | 3.18±C | 9.6 ±B | 12.0 ±B | 14.8 ±B | 27.3 ±B | 67.7 ±B | 134 ±B | 10.0 ±A | 7.70 ±B |
| S3            | 3.14±C | 9.5 ±B | 11.9 ±B | 17.8 ±A | 26.3 ±B | 61.5 ±B | 129 ±B | 8.00 ±A | 6.70 ±B |
| S4            | 3.06±C | 9.4 ±A | 11.3 ±B | 11.3 ±A | 20.2 ±B | 30.9 ±B | 124 ±B | 6.00 ±C | 4.00 ±B |
| S5            | 3.03±C | 9.3 ±A | 11.0 ±B | 2.0 ±C | 11.8 ±C | 0.00 ±C | 0.00 ±C | 0.00 ±C | 0.00 ±C |
| S6            | 2.38±B | 8.9 ±C | 0.0 ±C | 0.0 ±C | 0.0 ±C | 0.00 ±C | 0.00 ±C | 0.00 ±C | 0.00 ±C |
| B1            | 50             | 3.67±A | 10.4 ±A | 13.4 ±A | 19.8 ±A | 136 ±B | 11.0 ±C | 8.70 ±C |
| S1            | 3.58±B | 10.2 ±A | 13.1 ±A | 19.6 ±A | 136 ±B | 11.0 ±C | 8.70 ±C |
| S2            | 3.50±A | 10.1 ±B | 13.1 ±B | 19.5 ±A | 136 ±B | 11.0 ±C | 8.70 ±C |
| S3            | 3.46±A | 10.0 ±B | 12.9 ±B | 18.3 ±B | 136 ±B | 11.0 ±C | 8.70 ±C |
| S4            | 3.34±A | 9.9 ±B | 12.0 ±B | 13.0 ±B | 136 ±B | 11.0 ±C | 8.70 ±C |
| S5            | 3.33±A | 9.8 ±B | 10.9 ±B | 9.6 ±B | 136 ±B | 11.0 ±C | 8.70 ±C |
| S6            | 2.62±B | 9.4 ±B | 9.7 ±B | 10.1 ±B | 136 ±B | 11.0 ±C | 8.70 ±C |
| B2            | 50             | 3.70±A | 11.4 ±A | 15.0 ±A | 20.3 ±A | 234 ±B | 18.0 ±A | 14.7 ±B |
| S1            | 3.85±A | 11.1 ±A | 14.7 ±A | 20.2 ±A | 252 ±B | 17.0 ±A | 14.0 ±B |
| S2            | 3.79±A | 11.1 ±A | 14.6 ±A | 19.8 ±B | 248 ±B | 16.0 ±A | 14.0 ±B |
| S3            | 3.70±A | 10.9 ±B | 14.4 ±A | 19.5 ±A | 242 ±B | 16.0 ±B | 14.0 ±B |
| S4            | 3.64±A | 10.8 ±A | 14.2 ±A | 19.4 ±B | 237 ±B | 12.0 ±A | 10.3 ±B |
| S5            | 3.24±A | 10.7 ±A | 14.2 ±A | 19.0 ±A | 229 ±B | 9.0 ±A | 10.3 ±B |
| S6            | 2.87±A | 10.2 ±A | 13.5 ±A | 18.3 ±A | 225 ±B | 8.0 ±A | 10.3 ±B |

Notes: Means of different uppercase and lowercase letters indicate a significant difference among different biochar application levels and salinity levels. Note: MSD, mid stem diameter (mm); PH, plant height (cm); AGB, fresh aboveground biomass (g); NLP, number of leaves per plant; NPP, number of pods per plant; Initial, Developing (Dev), Mid and Late refer to plant growth stages. B0, B1 and B2 represent mixtures of soil with 0%, 5% and 10% of biochar by mass. 50 to 56 d soil samples were used at initial, salinity levels of 0.75, 1, 2, 4, 5, 6 and 7 d m⁻¹. Means are not significantly different when followed by the same letter between the biochar application rates (uppercase) or between salinity levels (lowercase) (P ≤ 0.05); LSD, least significant test; ANOVA, analysis of variance test; ns, not significant; and *, **, *** denote significant differences at P ≤ 0.01, 0.05, and 0.001, respectively, among treatments.
with the findings of Gląb et al. (2016) for a sandy soil amended with biochar.

### 3.2. Morphological parameters

Table 3 shows that the increases in water salinity from S1 to S6 significantly reduced the mean values of the MSD, PH, AGB, NPP and NLP of the okra plants regardless of the BA treatment. Biochar applications beneficially increased all these plant characteristics. Among the BA, the maximum values of MSD, PH, AGB, NP, and NLP were observed for the B2 treatment.

There were significant differences ($P \leq 0.05$) in the PH of okra grown under the different salinity levels for any given plant growth stage (initial, developing, middle, and late) (Table 3). However, there were some non-significant differences in the effects of BA on the mean values of the PH that varied for the four growth stages. During the initial stage, few statistically significant differences were observed for the mean PH values among the BA treatments (Table 3). At the later stages, there were obvious significant differences ($P \leq 0.05$) among the mean PH values of the different BA treatments. The mean PH values increased with the increases in the BA rate.

There were some significant differences ($P \leq 0.05$) among the pod yields under certain treatments. In general, okra pod yields decreased with the increasing salinity levels of the applied irrigation water but increased with increases in the BA ($P \leq 0.05$) (Figure 2). The maximum yield per plant (138.3 g) occurred under the B2S0 treatment; however, this yield was only significantly different from those of the S5 and S6 treatments.

### 3.3. Physiological parameters

#### 3.3.1. Photosynthesis and transpiration rates

As shown in Figure 3(a, b), the Pn and Tr rates varied significantly within salt stress levels and biochar addition rates. The leaf Pn and Tr were reduced significantly ($P \leq 0.05$) for plants grown under saline water irrigation (S1-S6) compared to those grown under the control (S0). The Pn under S6 (7 dS m$^{-1}$) was the lowest followed by the S5 compared to the control (S0). After the biochar addition the plants showed good recovery at all salinity levels but more recovery was found in the level B2 (10%), where the Pn increased by 24.7% compared to the salt stress results. The highest (17.08 µmol m$^{-2}$ s$^{-1}$) and lowest (7.2 µmol m$^{-2}$ s$^{-1}$) Pn rates were observed for the combined treatments of S0 with B2 and S6 with B0, respectively. Similarly, the Tr rate followed the same trend of the Pn rate, where it decreased significantly under salt stress and increased significantly under the biochar addition. The plant showed a sudden decrease in transpiration at S4, but a gentle reduction was observed in the control (S0).
at S6. However, the S0B2 recorded the highest value (9.1 mmol H₂O m⁻² s⁻¹) while the lowest one (0.93 mmol H₂O m⁻² s⁻¹) was recorded under S6B0.

3.3.2. Water use efficiency

In general, significant differences in WUE values were observed among the irrigation water salinity treatments (P ≤ 0.05) (Figure 4). The WUE values decreased with increasing salinity and increased with the increasing BA rate. Hence, the lowest WUE (0.00 gL⁻¹) occurred under the most saline treatment (S6), but it was not significantly different (P ≤ 0.05) from the WUE of the S4 and S5 treatments. The highest WUE (9.4 gL⁻¹) occurred under the S0 treatment, but it was not significantly different (P ≤ 0.05) from the WUE of the S1 and S2 treatments. Under the biochar treatment, the results revealed that the maximum WUE value was found for the B2 followed by those for the B1 and B0. The interaction between the BA and water salinity treatments showed significant differences (P ≤ 0.05) among the WUE mean values, where the highest value of WUE was obtained for the B2S0 treatment, although this was not significantly different from those for the B2S1, B2S2 and B2S3 treatments.

3.4. Okra salt threshold identified by the salt tolerance model

The crop salt tolerance mathematical model (Equation (2)) was adopted to evaluate the performance of the BA in increasing the threshold values based on the yield, MSD, and other relevant parameters. The model equations for different BA treatments are shown in Figure 5. The threshold values for each treatment are indicated by the intersections of the yield curves with the x-axis. The results demonstrate the effectiveness of biochar in increasing the threshold values for okra under varying saline conditions.
PH, AGB, NPP and NLP of the okra. The salt tolerance model for okra pod yield is presented in Figure 5 as functions of the yield against measured the ECe values for each BA treatment. For the B0, there was no reduction in yield for the ECe values between 0 and 3.2 dS m$^{-1}$. However, for the ECe values greater than this threshold value (i.e. 3.2 dS m$^{-1}$), an 8.51% yield decrease per unit increase in ECe was observed (Figure 5(a)). For the B1, the threshold value increased to 3.8 dS m$^{-1}$, above which there was a 4.54% yield decrease per unit increase in the ECe (Figure 5(b)). For the B2, there was a more noticeable increase in the threshold value to 5.8 dS m$^{-1}$, while the slope value decreased to 2.63%.

For the MSD, the threshold values were 4.3, 5.2, and 5.6 dS m$^{-1}$, while the corresponding slope values were 11.1%, 4.9%, and 0.6% for the B0 (Figure 6(a)), B1 (Figure 6(b)) and B2 (Figure 6(c)) treatments, respectively. For the B0, the PH remained constant until the ECe exceeded 4.1 dS m$^{-1}$, but it decreased by 11.4% per unit of further increases in the ECe (Figure 7(a)). For the B1 (Figure 7(b)) and B2 (Figure 6(c)), the respective threshold values were 4.5 and 5.2 dS m$^{-1}$, while the slope values were 3.6% and 3.3%.

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For the B0, the threshold and slope values were 4.3 dSm$^{-1}$ and 11.6%, respectively, for the AGB (Figure 8(a)). The threshold values increased to 4.9 and 5.1 dS m$^{-1}$ for the B1

Figure 6. Okra MSD as a function of soil salinity (ECe) and BA. Soil-biochar mixtures (% by mass): (a) B0 = 0%; (b) B1 = 5%; and (c) B2 = 10%. Lines represent the salt tolerance model; are data points.
(Figure 8(b)) and B2 (Figure 8(c)) treatments, respectively, while the slopes were reduced to 1.1% and 0.8%. The threshold values for the NPP under the B0 (Figure 9(a)), B1 (Figure 9(b)) and B2 (Figure 9(c)) increased on the order of 3.1, 3.5 and 4.3 dS m$^{-1}$. For the ECe values above the threshold values, the NPP decreased by 10.0%, 4.8% and 3.8% per unit increase of ECe for B0, B1 and B2, respectively. The NLP was not reduced by increases in the ECe to the threshold values of 3.2, 3.8 and 5.8 dS m$^{-1}$ for the B0 (Figure 10(a)), B1 (Figure 10(b)) and B2 (Figure 10(c)), respectively. Decreases in the NLP of 8.5%, 4.5% and 2.6% occurred for further increases per unit of ECe for the B0, B1 and B2, respectively.

4. Discussion

4.1. Soil physical and hydraulic properties

Both BA and irrigation with saline water significantly affected the physical and hydraulic properties of the silt loam soil in this study. The FC, PWP and AWC values were increased by increasing the BA rates, as was the ECe, while the BD was reduced. Such changes reduced the impacts of increased salinity on the soil structure and improved soil quality in this respect. These beneficial changes in the soil physical properties can be attributed to the mixing of the soil with a less dense material, and they were evident immediately after the addition of biochar. A similar conclusion was drawn by

Figure 7. Okra plant height (PH) as a function of soil salinity (ECe) and BA. Soil-biochar mixtures (% by mass): (a) B0 = 0%; (b) B1 = 5%; and (c) B2 = 10%. Lines represent the salt tolerance model, are data points.
Glab et al. (2016) for the results obtained by mixing a sandy soil with biochar. The decreases in BD values following the biochar additions were due to the increases in the total soil pore volumes. These increases naturally resulted because the mean particle densities of the soil-biochar mixtures were less than that of the soil alone, having been decreased by the lower density of the biochar. Decreases in BD following biochar addition were also reported by Mukherjee and Lal (2013) and Glab et al. (2016).

The AWC reflects the amount of water held between the FC and PWP, which were measured characteristics of the soil and soil-biochar mixtures in this study. Many factors can affect the AWC such as aggregation, SOM content, and soil texture. According to Peake et al. (2014), the application of biochar increased the AWC in a clay soil; but the effect was greater in a soil with a higher sand content. Similar results for the correlation between a biochar addition and soil physical properties in a silt loam soil were obtained by Herath et al. (2013). These findings confirmed that soil physical quality can be improved due to a biochar addition.

The higher ECe values observed under the biochar treatments were attributed to the sorptive properties of the biochar (Thomas et al. 2013). The biochar used had high ECi values that led to the observed increases in the soil ECe. Usman et al. (2016) also noted that ECe increased when using biochar under different levels of salinity.

**4.2. Growth parameters**

Our results demonstrated that all the measured growth parameters of the okra plants investigated in this study were negatively affected by salt stress. When the threshold value of the ECe for the various parameters was exceeded, the salts negatively affected plants due to reductions in osmosis and increases in ion toxicity (Akhtar et al. 2014). However, this study showed that amending the soils with applications of biochar had beneficial effects and enhanced the okra...
plant growth parameters. Mitigation of the salt stress effects was greatest at the higher rate of biochar addition (B2). As indicated by our results (Table 4), the soil Na concentration was reduced under the biochar treatments. The same findings were obtained by Głowowska et al. (2016), who found that biochar mitigated salinity stress in plants by capturing transient sodium ions, which are preferentially absorbed onto the biochar surfaces, and reducing ion toxicity, while releasing potassium, calcium and magnesium ions from biochar into the soil solution. Absorption of large amounts of sodium was facilitated by the large specific surface area of the biochar that led to its high adsorption capacity. The contents of the beneficial ions (Ca, Mg and K) in the soil solution were also increased by the additions of biochar (Table 4). Furthermore, the biochar decreased the osmotic stress, especially of the water held at lower potentials (near FC), by increasing the AWC. Thus, the growth and yield of okra benefited from the addition of biochar.

Biochar seems to be more effective when conditions are worse for plant growth (Novak et al. 2012). In this study, plants subjected to the higher salinity levels and salt stress had the best responses to the biochar additions. Similarly, Atkinson et al. (2010) found that better responses of plants to biochar addition were expected when conditions were worse, such as conditions of poorer soil quality (salt-affected soils), nutrient shortages, high soil acidity, or low water holding capacity. Other studies support this expectation, with larger benefits observed in relatively nutrient-poor, acidic, and coarse-textured soils (Jeffery et al. 2011). Even so, the plant growth benefits of biochar have still been documented when the soils are of relatively better quality and under more favorable conditions (Rajkovich et al. 2012). This study provides evidence that biochar could be used in salt-affected soils and/or when irrigation water is of low quality (Table 4). Additionally, Thomas et al. (2013) reported that when biochar is applied at high rate (50 t ha⁻¹) as a top dressing, it completely alleviated salt-induced mortality and prolonged survival of plants through its salt sorption capability. Luo et al. (2017) concluded that under salt stress, biochar decreased Na⁺ uptake, while it increased K⁺ uptake by plants. Biochar-mediated increases in salt tolerance of plants are primarily associated

Figure 9. Number of pods per okra plant (NPP) as a function of soil salinity (ECe) and BA. Soil-biochar mixtures (% by mass): (a) B0 = 0%; (b) B1 = 5%; and (c) B2 = 10%. Lines represent the salt tolerance model; are data points.
with improvement in soil properties, such as increasing plant water status, reduction of Na$^+$ uptake, increasing uptake of minerals, and regulation of stomatal conductance and phytohormones. Moreover, the reduction in growth may have been due to the partial regulation of various physiological parameters involved in the plant growth processes. Physiological parameters such as photosynthetic capacity have a strong relationship with plant growth (Saleem et al. 2011). As noted in the results, salt stress reduced the photosynthesis and transpiration rates and the WUE. The decrease in the Pn rate may be due to a high salt concentration present in the water, which increases the osmotic potential of the soil, and the plant cannot easily take up water, as in the case with non-saline water. The deficiency of water decreased the water potential. Due to the excess amount of salt present in the water, deficiency stomatal closure occurs, which reduces the transpiration rate (Agebna et al. 2017, Ahmad et al. 2017).

4.3. Salt tolerance model assessment for okra

In this study, correlations among irrigation water salinity, pod yield, and other plant growth parameters of okra were studied. The salt tolerance parameters for the growth variables including AGB were different from the salt tolerance parameters for the yield. The threshold ECe values indicated that yield was more sensitive to salinity than the AGB for okra. This further suggests that the yield was less tolerant to salinity than the vegetative growth. It is likely that a high ECe level with a biochar addition would result in only a slight decrease in vegetative growth above the ECe threshold values (Van Zwieten et al. 2010, Verheijen et al. 2010). Maintaining a high level of

![Figure 10. Number of leaves per okra (NLP) as a function of soil salinity (ECe) and BA. Soil-biochar mixtures (% by mass): (a) B0 = 0%; (b) B1 = 5%; and (c) B2 = 10%. Lines represent the salt tolerance model; are data points.](image-url)
vegetative growth while yields decline would reduce WUE. Thus, salinity effects on different aspects of plant growth should be taken into account in water consumption calculations.

5. Conclusion

This study was carried out to determine if biochar applications would ameliorate the salt stress effects on okra while improving the soil. The basic soil physical parameters, such as ECe, BD, FC, PWP and AWC, were negatively affected by salinity and were all improved by the biochar addition with the exception of ECe; however, sodium ion content in the soil solutions was reduced with the addition of the biochar. Saline water irrigation significantly reduced the MSD, PH, AGB, NPP and NLP. The addition of biochar enhanced all of these okra morphological parameters. The mean WUE values decreased with the increasing salinity levels of the applied irrigation water and increased with the increasing BA rate. The threshold ECe values indicated that pod yield was more sensitive to salinity than vegetative growth. Maintaining a high level of vegetative growth while yields decline would reduce WUE. Therefore, salinity effects on various plant components should be taken into account in water consumption calculations. This study indicates that biochar could be used in salt-affected soils and/or when irrigation water is of low quality. It can be concluded that biochar could strongly mitigate or even eliminate the stress effects of salt on okra and may do so for other plants.

Disclosure statement

No potential conflict of interest was reported by the authors.

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