Biochar Amendment Enhanced Okra Root Water Uptake, Water Productivity and Water Balance under Salt Stress

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Abstract*: Investigating root water uptake (RWU) is necessary since it has direct relationship with water use efficiency and crop productivity. However, abiotic stresses negatively influence theRWU rateespecially under salinity stress conditions.In this works, a field and a column experiment werecarried out to test the hypothesis thatbiochar soil amendments (BA) could increase the okra RWU, water balance, improve water productivity and alleviate salt stress.For column experiment, twoBA applications (BC0, 0% and BC1, 10% w/w) were considered for three irrigation water salinity levels, i.e.0.75 dS m^{-1} (S0), 3.0 dS m^{-1} (S1) and 6.0 dS m^{-1} (S2).. For field experiment, three BA soil applications, i.e. 0 ton ha^{-1} (B0), 12.5 ton ha^{-1} (B1) and 25 ton ha^{-1} (B2), were considered for the sameirrigation water salinity levels. The HYDRUS-1D model was utilized to simulate and evaluate the effects of BA on okra RWU for each salinity treatment under field conditions. The model was calibrated and validated using the column experiment.The results obtained showed that, for non BA treatments, the maximum value of RWU (0.45 cmday^{-1}) was obtained in S0 while S2 gave the minimum value (0.30 cmday^{-1}). The B1 increased the RWU by 2%, 5% and 16 % for S0, S1 and S2, respectively. Meanwhile for B2, the increment in RWU under S0, S1 and S2 were 4%, 5% and 26 % respectively. The results indicated that biochar diminished salt stress in Okra by adsorbing transient sodium ions and reducing ion toxicity, while releasing potassium, calcium, and magnesium ions to the soil solution. Hence, BA can be considered as an effective practice to enhance RWU under salt stress and alleviate the negative salinity impacts.*

Key words: HYDRUS-1D; root-water-uptake; salinity; biochar; Okra

1. Introduction

Agricultural crops are often exposed to abiotic stresses such as salinity (Osakabe et al. 2014; Parihar et al. 2015; Rizwan et al. 2016a).Among the abiotic stresses, salt stress is one of themost critical threats to agricultural production that cause extensive crop yield losses all over the world (Schwabe 2006 and Shao et al., 2016). About 8×10^{8} hectare of world lands is salt affected with an annual increase of 1–2% (Munns and Tester 2008).The yield of most crops is reduced when the electrical conductivity (EC) of the saturation extract in the root zone exceeds 4 dS m^{-1} (Munns, 2005; Jamil et al., 2011). Additionally, Romero-Aranda et al.,(2001) stated that high salt concentration in soil water solution can reduceplantroot water uptake (RWU). Moreover, the reduction in RWU negatively affects the crops growth and productivity (Hamee et al., 2002).

` Plenty ofstudies have been carried out on the elimination of surplus salt from the root zone by applying various techniques like scraping, flushing and leaching (Jouyban 2012). Nonetheless, other researcheshavefocused on minimizing the salinity impact by applying different irrigation strategies (Alomran et al. 2012; Soomro et al. 2012; Patil et al. 2014). Others have researched on growing halophyte crop utilizing saline water (Khan et al. 2000; Khan and Duke 2001; BelkheiriandMulas 2013). Recently, pyrolysis of biomass under no or limited oxygen supply resultsin production of carbon-rich material, which is known as biochar gained popularity as a soil amendment (Ali et al. 2017). According toBamminger et al. (2016) and Lim et al. (2016), biochar application has received significant attention for its ability to enhance soil physicochemical properties such as soil pH, cation exchange capacity (CEC), soil structure, water holding capacity (WHC), and surface area under abiotic stresses. Biochar application can also reduce sodium ion (Na^{+}) uptake and increase potassium (K^{+}) uptake under salt stress (Wu et al. 2014; Drake et al. 2016; Usman et al. 2016). Furthermore, under salt stress, biochar addition increased the soil organic matter content and CEC and decreased the exchangeable Na (Luo et al. 2017).The application of biochar significantly decreased Na+ concentrations in the xylem sap of potato, while increasing K+ concentrations and Na+/K+ ratio in the xylem sap as compared to the control (Lashari et al. 2015; Akhtar et al. 2015). Similarly, biochar decreased Na uptake by lettuce under salt stress (Ali et al. 2017).

Okra (Abelmoschusesculentus L.) is recognized as an annual herbaceous plant grown in tropical and subtropical areas and serves as a source of carbohydrates, fats, vitamins and various minerals (Elshakhet al.2018). Okra plant at earlier growth stages is more sensitive to salinity which affectsokra water uptake and consequently reduce its productivity (Elshaikh et al. 2018).Since the RWU is directly reflecting crop water consumption and therefore, recognizing its behavior especially under salt conditions is required for proper soil management (Consoli et al. 2017). Unlikely, the RWU is subjected to many factors such as, rooting depth, rooting density, root distribution, evaporative demand and soil water osmotic head (Mardaninejad et al., 2017). This makesdetermination of RWU in the field level difficult. Alternatively, researchers employ computer models to study the complex processes of RWU in the soil to provide management and planning guidance (Phogat et al. 2010). However, salt stress sharply decreases the plant RWU and consequently affects all the plant physiological processes. Therefore, the present investigation was carried out (i) tostudy the ability of biochar to mitigate salt stress and improves the okra RWU irrigated with different saline water (ii)to improve water balance and water productivity under salt stress and (iii) to simulate of the okra RWU using HYDRUD-1D.

2. Materials and methods

Two experiments were carried out to simulate the RWU,i.e. column and field experiments, in a shelter under nature light conditions without temperature control at the Water-Saving Park of Hohai University (31°57′N, 118°50′E),144 m above sea level, Nanjing, Jiangsu Province, China. The study was conducted using Okra as a test crop during the periods of May 18th to August 18th, 2017.

2.1 Column experiment

A column experiment was conducted to calibrate the HYDRUS 1D model for simulating the RWU for Okra crop; and to investigate the water balance in slit loam soil irrigated with three salinity irrigation waters, i.e. EC of 0.75 (S0), 3.0 (S1) and 6.0 (S2) dS m^{-1} with two biochar application rates of 0% (BC0) and 10 (BC1) weight by weight. The intended level of salinity was obtained by dissolving NaCl in tap water (adding 0.5843 g NaCl L^{-1} increased ECi by 1 dS m^{-1}). The BC0S0 combination was considered to be the control treatment Separate columns were used for different treatments. The physico-chemical properties of the soil and biochar are given in Table 1. The soil was packed in PVC columns (dia: 20 cm) to a depth of 150 cm which were closed from bottom and fitted with an outlet tube on the side wall to collect the percolated water. The biochar was mixed with the soil to 30 cm depth. At the bottom of each column, a gravellayer of 3 cm thickness was provided to facilitate the free drainage condition ensuring one dimensional movement of water.

2.1.1 Water balance calculations

At the end of the experiment the total applied water (Qi), the total deranged water (Qo), the wetness (Wt) were calculated by summing all the Qi and Qo andWt, respectively. The total actual water consumption was calculated by substractiong the total Qi from Qo plus Wt.

2.1.2 Water productivity

Water productivity (WP) means quantum of production per unit water used (Molden and Sakthivadivel, 1999). The denominator unit water used varies significantly with respect to scale. Different water productivities were expressed in terms of grain or biomass production Y (kg m^{-2}) divided by transpiration T (m^3 m^{-2}), evapotranspiration ET (m3 m-2), bottom flux added to ET and irrigation water used I (m^3 m^{-2}) as below:

$$WP_{ET} = \frac{Y}{ET}(1) WP_{ET} = \frac{Y}{ET + Q_o}(2) WP_i = \frac{Y}{Q_i}(3)$$

Here Q_i is the water inflow or irrigation applied, Q_o is the water outflow .

2.2 Field experiment

The field experiment was conducted under a plastic shelter. A randomized complete block design was used, comprising three blocks, each receiving a different level of saline irrigation water. Within each block, there were plots that received an allocated BA treatment. The blocks each received one of the three saline irrigation waters: 0.75dSm^{-1} (S0), 3.0 dSm^{-1} (S1) and 6.0 dSm^{-1} (S3). The BA treatments for the plot in each block were applied at three rates: 0 t ha^{-1} (B0), 12.5 t ha^{-1} (B1), and 25 t ha^{-1}(B2); these rates were comparable with those used by Liu et al. (2014) and were considered appropriate for the soil which was structurally poor and relatively deficient in nutrients and organic carbon. Each treatment combination was replicated three times and distributed randomly in order to minimize any effects from the differences between plots. Thus, each block consisted of 9 plots (1.0 m× 0.7 m) and the experiment had a total of 27 plots. Irrigation water was delivered to the blocks via a gravity drip system. At the upper end of each block, a tank (61483 cm^3) was installed at a height of 1 m in which to store irrigation water. Each treatment plot had a separate drip line placed at the center of the plot; the emitters had 0.3m spacing.

2.3Model description

The HYDRUS-ID (Simunek et al. 2005) computer program was used for RWU and water movement studies. This model simulates one dimensional variably saturated water flow, heat movement and the transfer of solutes. It numerically solves the Richards equation for saturated and unsaturated water flow and convection, dispersion type equation for heat and solute transportation. The governing flow equation which solves the one dimensional water movement in a partially saturated porous medium is described by a modified form of Richards's equation (Molz and Remson 1970; Celia et al. 1990) with the assumptions that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left\{K\left(\frac{\partial h}{\partial x} + 1\right)\right\} - S \qquad (4)$$

Where θ is the volumetric water content (cm^3_ cm^{-3}), t is time (days), x is the vertical space coordinate (cm) (positive upward), K is the hydraulic conductivity function (cm_ day^{-1}), h is the water pressure head (cm), and S is the sink term (cm^3 cm^{-3} day^{-1}) defined as the rate of RWU.

2.4 Input parameters of the model

2.4.1 Estimation of potential ET and the van Genuchten (VG) parameters

For modeling the influence of soil water and solute stress on transpiration (root water uptake), HYDRUS-1D requires potential evaporation and transpiration (sink term in the Richards equation) as separate inputs in time steps which can be either per day, hour or minute. We used daily time steps. The FAO (1992) CROPWAT model was used to calculate reference crop evapo-transpiration (ET_0) from available climatic crop and soil parameters. The reference ET_0 as calculated by CROPWAT model (Table 2) was used to determine the potential crop $ET_c$by the equation as given:

$$ET_C = ET_0 \times K_C \qquad (5)$$

2.4.2 Estimation of potential evaporation (Ep) and potential transpiration (Tp)

This partitioning was achieved by crop leaf area index (LAI) which is a function of crop development stage as given by Belmans et al. (1983):

$$Ep = ETc \times e^{-Kgr \times LAI} \qquad (6)$$

Here, *Kgr* is the extension coefficient for global solar radiation and its value was taken as 0.313 for okra crop (Gausman and Allen, 1973). Tp was then obtained by subtracting Ep from ETc. The leaf area index in Eq. (3) was measured at the four plant growth sages basis using direct method (leaf length * leaf width/area).

Soil hydraulic characteristics (water retention and hydraulic conductivity) are required for many studies of water and solute transport in the vadose zone. Although measurements are the most obvious and precise way to obtain these characteristics, financial and time constraints place limits how much can be determined in the field or laboratory. Spatial variability of soil hydraulic characteristics further makes it doubtful whether limited soil hydraulic measurements are representative for the studied area. Alternatively, soil hydraulic characteristics can be estimatedusing pedotransfer functions (PTFs) that use widely available basic soil data (texture, bulk density, The van Genuchten (VG) parametersθr, θs, m, a and n used in the HYDRUS-ID model were estimated from pedotransfer functions (Schaap, 2001)(Table 3).

2.4.2 Root water uptake functions inputs

For the determination of the RWU the method proposed by Feddes et al. (1974) to include multiplicative water and osmotic stress was applied. The inherent water stress reduction term was parameterized with the function proposed by Feddes et al. (1978) and Homaee et al. (2002) using the following values, h_1 = 0 cm, h_2 = 33 cm, h_3 (high) = -160 cm, h_3 (low) = -250 cm, and h_4 = -15,000 cm. The h_1, h_2,h_3 andh_4 , represent different pressure head values which are affecting the root water uptake in the soil. The water uptake is assumed to be zero close to saturation (i.e., wetter than some arbitrary ‘‘anaerobiosis point’’, h_1). For h_4 (the wilting point pressure head), water uptake is also assumed to be zero. Water uptake is considered optimal between pressure heads h_2 and h_3, whereas for pressure head between h3 and h4 (or h1 and h2), water uptake decreases (or increases) linearly with h.

2.5 Soil samples collection and analysis

A soil sample (~1 kg) was collected for each treatment replicate from a depth of 30 cm by auguring, sealed in plastic bags and transported to the laboratory. Soil water content was determined gravimetrically at the four plant growth stages from May to August during the 2016 and 2017 growing seasons, utilizing the following equation:

$$SMC\% = \left(\frac{W_w - W_d}{W_w}\right) \times 100\% \quad (7)$$

Where SMC% represent the percentage soil moisture content on wet basis, Ww represent the soil sample wet weight, Wd represent the soil sample dry weight at 105 ^{0}C for 24 hours.

2.5 Statistical test

The root mean square error (RMSE) was calculated to compare the experimental and predicted ET values as below:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=I}^{N}(Mi - Si)^2} \qquad (8)$$

where,M_i and S_i are measured and simulated values for an output variable;*N* is the number of the observations.

3. Results

4.1 Water balance components asaffected by ECiw and BA

Measured components of the water balance as affected by different saline ECiw and BA are presented in Table 4. Generally, under the all treatments the amount of Q_i decreased as the EC_{iw}increased. For the non BA treatments, the relative decrease in the total water applied as compared to control treatment was 27.1 and 37.5 %, respectively, in B0S1 and B0S2 ECiw treatments. The Qo from the columns varied from 82 to 85 % of the total Qi in various salinity treatments (Table 4). However, the percent outflow ($QoQi^{-1}$) increased with the increase in the salinity of the irrigation water and it reached to 85% in EC_{iw} of B0S2 treatment. Figure 1 shows that the existence of salt accentuates the percolation losses of water in the soil. The ET requirement of okra ranged from 98.00 to 210.99 mm in different EC_{iw} treatments (Table 4). It was maximum (210.99 mm) in B0S0treatment and decreased as the ECiw increased. There was 46.4% decrease in ET requirement of crop in ECiw of B0S2 as compared to control. The percent ET demand (ETa Qi^{-1}) also decreased 15 to 13% with the increase of EC_{iw} (Fig. 1). For the BA treatments, as showed in Table 4 the all aforementioned parameters were enhanced with BA under the all ECiw treatments. The Qi increased by 31, 20.5 and 9.67% under B1S0, B1S1 and B1S2, respectively, compared to B0S0. The BA reduced the $QoQi^{-1}$ % by 2.4% at B2S2 compared to B0S2. The ET increased with BA and reached 316.66 mm at B1S0 while B1S2 recorded 209.4 mm higher than B0S2 by 111.4 mm. The $ETQi^{-1}$ % increased up to 19.5, 17.7 and 15.3 for B1S0, B1S1 and BS2, respectively (Fig. 1).

4.3 Water productivity as affected by ECiw and BA

Water useefficiency also known as water productivity (WP) is defined as the yield divided by evapotranspiration ET or irrigation. Total Qi, total ETa Qo^{-1} and ETa were the measured seasonal values. All the water productivity values decreased with the increase in ECiw and increased with increase in BA (Table 5). The maximum okra Py productivity of 894.73 kg m^{-3} was observed in B1S0 treatment. It reduced drastically by 65 and 82 % in ECiw of B0S1 and B0S2, respectively. The WP_{ET} ranged from 1.66 to 2.87 kg m^{-3} in various treatments. The WP_{ET} value of 2.87 obtained by B1S0 declined to 1.66 at B0S2.

As shown in Fig 2, 3 and 4 the minimum values of WP (0.21– 0.55 kg m^{-3}) in different treatments were obtained with Qi. The reduction in water productivity of Py with salinity showed a log normal relation with R^2 value of 0.99 irrespective of denominator indicating a sharp reduction in WP (Fig. 2). Whereas WP showed a polynomial increment with existence of BA at all the ECiw which confirms the gradual and fast increment as compared to non biochar amended treatments (Fig. 3).

3.1 The LAI as affected by ECiw and BA

The values of the LAI under salt stress decreased with increasing of ECiw, however, this decrement reduced by BA as shown in Fig. 5. The LAI values under non salt stress (S0) was 2.3 in the initial stage, 9.2 in the developing stage, and 10.2 on the maximum crop growth stage and declined to 7.6 in the late stage. For the S1, the values reduced by 56, 52, 35 and 32% compared to S0 for initial, developing, middle and late growth stage, respectively. The differences in LAI increased at S2 to reached 1.68 (initial), 7.07 (developing), 6.5 (middle) and 4.8 (late) compared to control. The BA enhanced the LAI under the all ECiw treatments (Fig. 5). The values of LAI at BA treatments increased by 40, 141 and 198% at initial stage; 20, 168 and 94% developing stage; 30, 31 and 54 % at; middle stage and 30, 39 and 110% at late stage for B1S0,B1 S1 and B1S2 compared to B0S0, B0S1 and B0S2, respectively.

3.2 Model calibration

The model was calibrated using the SMC; the actual and model predicted values of SMC in various treatments are presented in Fig 6. The RMSE values of 0.30, 0.61 and 0.55, were obtained in S1, S2 and S3 under BC0 while The RMSE values of 0.25, 0.64 and 0.59 were obtained in S1, S2 and S3 under BC1, respectively. The good matching between measured and model predicted values of SMC of Okra again confirmed that the HYDRUS-ID can be used satisfactorily to predict SMC demand and hence can be used to simulate root water uptake of Okra crop.

3.3Model validation

The model was validated using field experiment data. The model predicted daily root water uptake by okra in different ECiw and BA is depicted in Fig.7. Initially the root uptake was less and it picked up with the growth of crop and reached its maximum between 25 and 40 days after transplanting in all the treatments. The daily root water uptake declined drastically in the latter stages of the crop growth.

3.4Simulation of root water uptake under field condition

The model predicted ARWU of okra in different ECiw and BA is depicted in Fig. 8. As it can be seen that the RWU was less during initial 20 days of transplanting which increased sharply and it picked up with the growth stages till reached its maximum between 30 and 45 days after transplanting, then it declined drastically in the latter stages of the crop growth in the all treatments; and after 90 days of transplanting it remained almost constant. For non amended biochar treatments, the RWU tended to decrease with increase of EC_{iw}. The maximum value of ARWU(0.45cm day^1) was obtained in S0while S2 gave the minimum value (0.30 cm day^{-1}). For all the biochar amended treatments, the decrement of ARWU under salt stress was reduced particularly at the higher biochar addition rate. The B1 increased the ARWU by 2, 5 and 16 % for S0, S1 and S2, respectively. Meanwhile for B2, the increment in ARWU under S0, S1 and S2 were 4, 5 and 26 % respectively. Therefore, model HYDRUS-ID can predict the root water uptake, i.e. transpiration and the values are reasonably good because they depict the root water uptake to salinity very close to the crop performance in the experiment.

4. Discussions

4.1 Water balance and water productivity under salt stress

The amount of Qi decreased as the Ciw) increased due to the reduction in LAI (Fig. 2) owing to the decline in the vegetative growth of the crop and the consequent reduction in transpiration losses. The results of okra agree with those of Fapohunda (1992) with an observed ET of 460–470 mm per season was comparable to the value reported in this study. Allen et al. (1998) reported that factors, such as soil salinity and poor land fertility, may limit crop development and reduce ET. Singandhupe et al. (2002) also reported 83–85% percolation losses in light textured soils. Similarly, Bouman et al. (2007) accounted that nonproductive outflows of water by runoff, seepage, and percolation are about 25–50% of all water input in heavy soils with shallow water tables of 20–50 cm depth and 50–85% in coarse-textured soils with deep water tables of 1.5 m depth.Van Dam and Malik (2003) also observed decrease in water productivity with increase in the salt in irrigation water, which affects the crop transpiration adversely.Tuong (1999) also found a range of 0.40–1.61 kg fresh grain m^{-3}ETa. Zwart and Bastiaanssen (2004) reported 1.09 kg m-3 global average value of WPET for rice crop. Hence irrigation with ECiw of2 dS m-1 can be used in rice which produced higher WPET than global average provided the salinity build up is checked to a safer limit for the following crop. Relatively low values of WP_{ETa} than WP_{Tp}indicate the need to reduce soil evaporation by agronomic measures such as soil mulching and conservation tillage. Further including percolation (Qo) losses in the ETa reduces the WP_{ETa} to WP_{ETaQo}. The former reduced to one fifth when percolation is included in the productivity determination. It means that percolation is a major factor controlling rice productivity. Therefore, reduction in Qowill be helpful in improving the low WPETaQo in poor quality groundwater areas. Similar results in respect of WPI (water productivity of total water applied) were reported by Boumanand Tuong (2000) and van Dam and Malik (2003). In contrast, Lu et al. (2000) mentioned a WPI of up to 16 kg grain m-3, but in these cases rainfall covered a much larger fraction of water needs. The low WPI are ascribed to the high percolation losses (83–87%) in the present study.

Previous studies have reported that organic amendments have the potential for improving soil productivity and plant growth (Wong et al., 2009). Typically, this wasattributed to positive effects that improved the soil environment, such as by increasing macronutrient and water availability (Demir et al., 2010; Thomas et al., 2013), which could increase the plantresistance to stresses associated with salinity(Lashari et al., 2013; Thomas et al., 2013; Alling et al., 2014; Fiaz et al., 2014).

4.1 Root water uptake under salt conditions

As declared by our results the root water uptake decreases upon exposure to salt stress which directly affected the LAI (Fig 1 and 4). This decrease can be caused by both osmotic and toxic effects, depending on the salt concentration present. The decrement of RWU under saline conditions has been investigated by many researchers (Navarro et al., 2003; Boursiac et al.,2005; Silva et al.,2008; Nedjimi, 2009; Wan, 2010; Sutka et al., 2011). The RWU decrease upon salt exposure may be caused by an osmotic shock as a result of an aquaporin conformational change caused by negative pressures (Wan et al., 2004). Moreover, Wan,(2010). Reported that, applying water has a high NaCl concentration to maize reduced the RWU value, since the concentration would produce a high osmotic. Furthermore, Carvajal et al., 1999 stated that, the RWU could decrease as the result of a direct effect of Na+ ions in aquaporin functioning. Similarly, MunnsandTester (2008) who reported that , Many crops are sensitive to salinity stress caused by high concentrations of salts in the soil, which make (RWU) more difficult and are toxic. Also, Silva et al. (2008) found that pepper plants treated with a low concentration (30 mM) of NaCl, decreased their root water uptake rate. However, when the NaCl concentration was further increased to 60 mM their root water uptake reduced also. Similar results obtained by Sutka et al., 2011 who reported that the initial RWU decrease upon salt exposure may be caused by an osmotic shock as a result of an aquaporin conformational change caused by negative pressures. On the other, the reduction in LA, under saline conditions were also due to reduced growth as a result of decreased water uptake, toxicity as well as reduced photosynthesis.

4.2 Biochar addition to the soil enhanced RWU

This study provides evidence that biochar could be used to enhance *RWU* in salt-affected soils and/or when irrigation water is of low quality. Previous studies have reported that organic amendments have the potential for improving soil productivity and plant growth (Zhao et al., 2009 and Agebna et al., 2017). Typically, this was attributed to positive effects that improved the soil environment, such as by increasing macronutrient and water availability (Thomas et al., 2013), which could increase the plant resistance to stresses associated with salinity (Lashari et al., 2013; Thomas et al., 2013). Novak et al. (2012) reported that biochar has strong absorptive characteristics binding due to its high adsorption capacity. By adsorbing toxic ions, especially sodium, and/or by releasing more beneficial ions(Akhtar et al., 2015), biochar can thus diminish the negative impacts of salt stress on plants, either by reducing the exposure of plants to stress agents or by ameliorating the stress responses of plants. Soil water content can be increased because the addition of biochar can increase the water holding capacity of the soil, especially increasing the proportion of larger pores where water is held at lower potentials allowing plants to uptake water more readily (Novak et al. 2012). However, this study showed that amending the soils with applications of biochar had beneficial effects and enhanced the okra RWU. Mitigation of the salt stress effects was greatest at the higher rate of biochar addition (B2).As indicated by our results (Table 6), the soil Na concentration was reduced under the biochar treatments. The same findings were obtained by Głodowska 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 6). 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.

5. Conclusions

As declared by our results the RWU decreases upon exposure to salt stress which directly affected the LAI. For all the biochar amended treatments, the decrement of RWU under salt stress was reduced particularly at the higher biochar addition rate. Biochar addition enhanced the water productivity and water balance as well as enhanced the water balance under salt stress 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. The good matching between measured and model predicted values of SMC again confirmed that the HYDRUS-ID can be used satisfactorily to predict root water uptake of Okra.

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Table 1. Physical and chemical properties of the silt loam soil and biochar used in the study

Property	Silt	Sand	Clay	FC	Total N	Total P	Total K	CEC	BD	pH	EC

Soil	30	50	20	25.8	0.18	0.66	0.40	14.94	1.35	7.7	1.42
Biochar	-	-	-	-	5.90	14.43	11.5	21.70	0.40	9.9	1.00
units	%	%	%	%	g kg^{-1}	g kg^{-1}	g kg^{-1}	cmol kg^{-1}	g cm^{-1}	-	dS m^{-1}

BA	EC_{iw}	Q_i	Q_o	Wetness	ET	$QoQi^{-1}$ %
BC0	**S0**	1241.12	1020.57	9.557	210.99	82
	S1	904.03	750.344	20.03	133.65	83
	S2	774.79	654.695	22.09	98.00	85
BC1	**S0**	1626.78	1301.42	8.80	316.55	80
	S1	1492.55	1208.97	18.85	264.73	81
	S2	1361.19	1132.51	19.28	209.40	83

Table 2. Mean monthly values of metrological data and reference evapotranspiration of study area.

Month	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sun hours	Rad MJ/m²/day	ETo mm/day
May	15.5	25.4	80	156	4.9	17.2	3.29
June	20.2	29	77	156	4.1	16.3	3.66
July	24.3	32.1	77	147	5.4	18	4.27
August	23.9	32.2	77	138	6	18	4.34

Table 3 Values of residual moisture contentθr, saturated moisture content θs, van Genuchten parameters (a, n and m) and saturated hydraulic conductivity Ks for silt loam soil used in experiment

Soil type	θr (cm^3 cm^{-3})	θs (cm^3 cm^{-3})	α (cm^{-1})	n	m	Ks (cm h^{-1})
Silt loam	0.067	0.45	0.02	1.41	0.5	10.8

Table 4 . Water productivity as affected by biochar addition and salt stress

Table 5 Measured water productivity components for okra crop

BA	EC_{iw}	PY	$PYQi^{-1}$	$PYQo^{-1}$	$PYET^{-1}$
BC0	**S0**	606.13	0.49	0.59	2.87
	S1	316.41	0.35	0.42	2.37
	S2	162.71	0.21	0.25	1.66
BC1	**S0**	894.73	0.55	0.69	2.83
	S1	597.02	0.40	0.49	2.26
	S2	394.75	0.29	0.35	1.89

Table 6.Mean values of soil cation contents (g kg $^{-1}$) for different biochar application rates (B) and irrigation water salinity levels (S)

Biochar Rates	Water salinity	Ca	K	Mg	Na
B0	S0	0.07	0.01	0.01	0.05
	S1	0.27	0.05	0.03	2.90
	S2	0.28	0.06	0.03	3.75
B1	S0	0.49	0.23	0.05	0.02
	S1	0.79	0.47	0.09	1.55
	S2	1.09	0.63	0.12	2.06

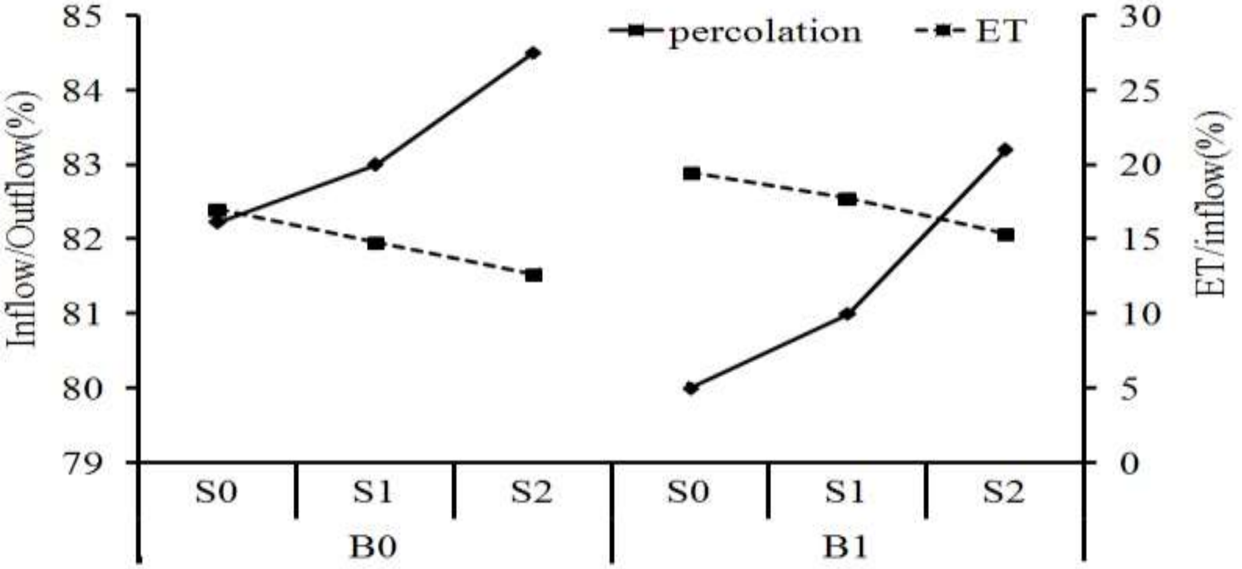

Fig.2. Percent percolation (Qo/Qi) and percent water consumption (ETa/Qi) as a function of outflow (Qo) under different biochar application (B) rate and different levels of irrigation saline water (S).

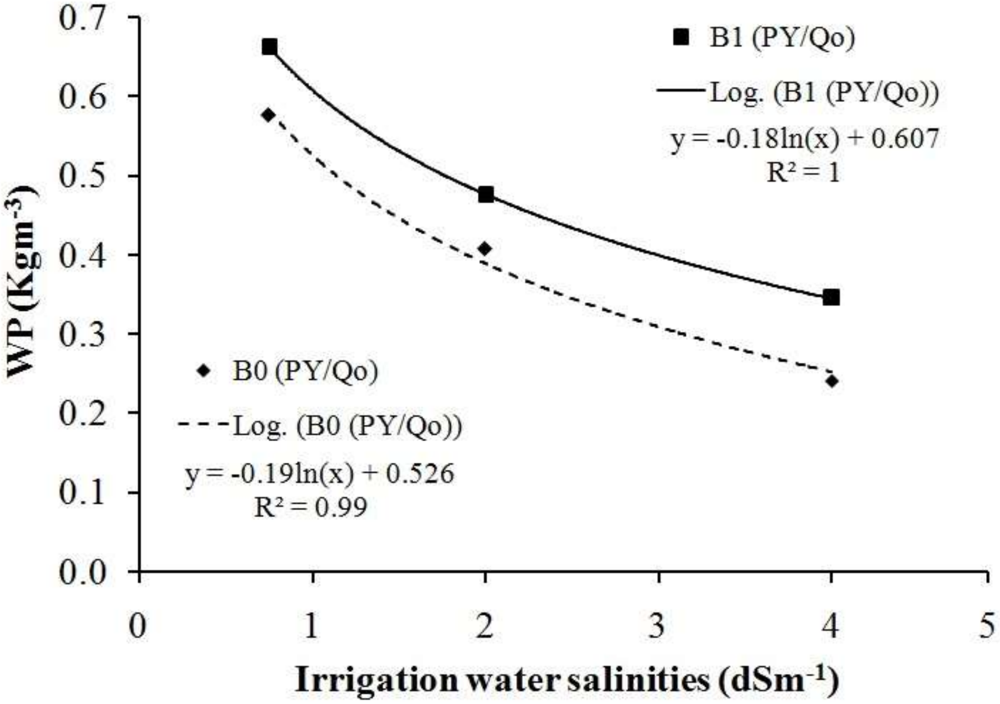

Fig.2. Water productivity (WP) as a function of outflow (Qo) under different biochar application (B) rate and different levels of irrigation saline water (S).

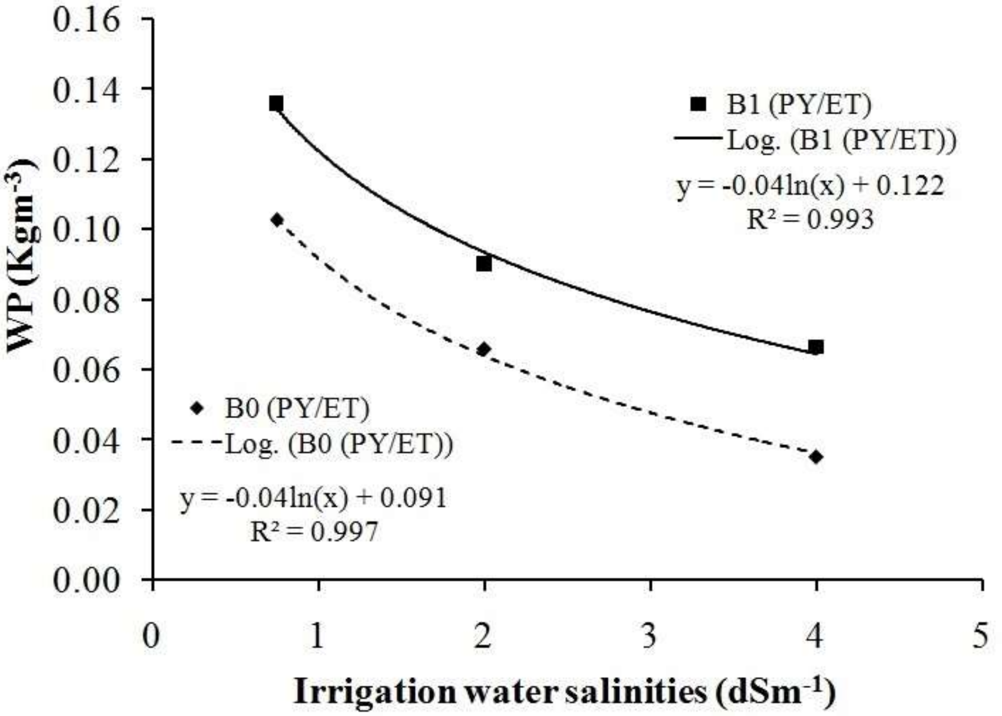

Fig.3.Water productivity (WP)as a function of water consumption (ET) under different biochar application (B) rate and different levels of irrigation saline water (S).

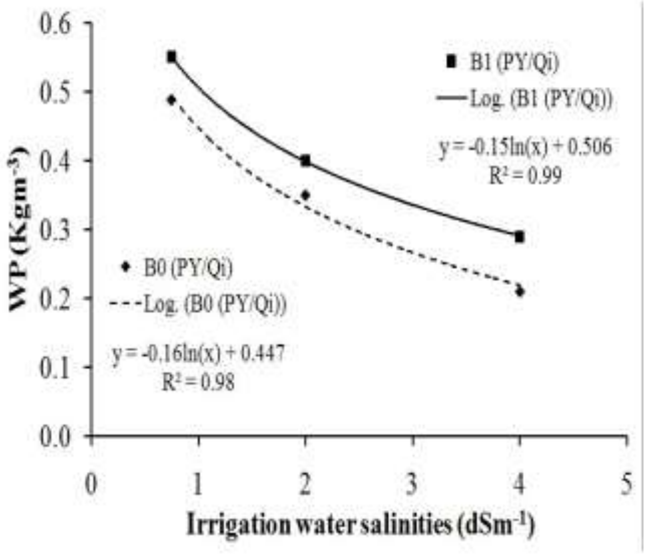

Fig.4. Water productivity (WP) as a function of intflow (Qi) under different biochar application (B) rate and different levels of irrigation saline water (S).

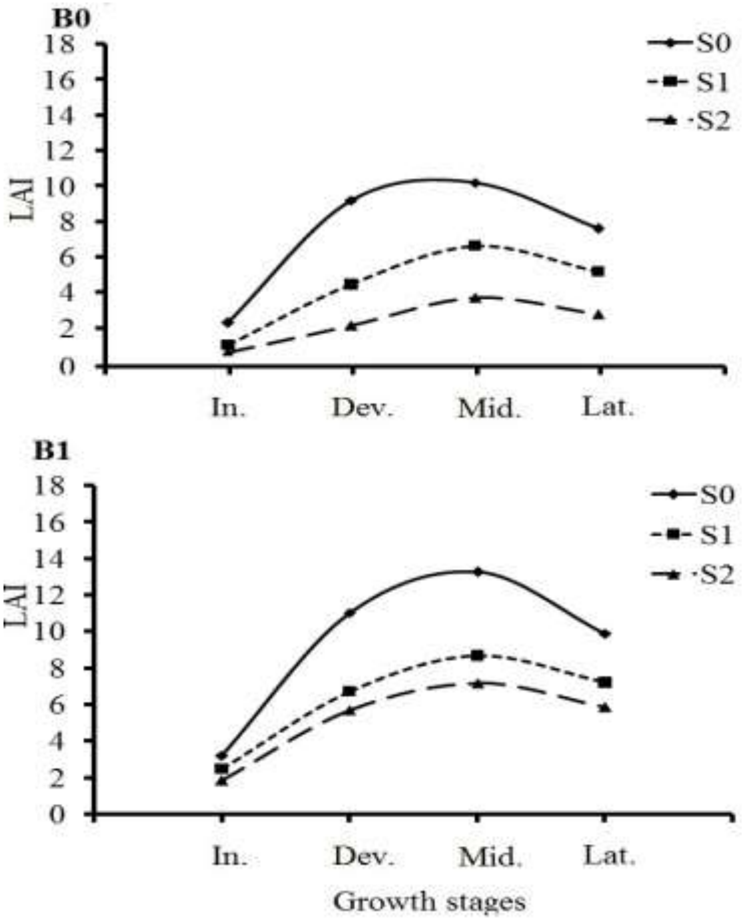

Fig. 4 the leaves aria index (LAI) of okra under different growth stages, irrigation water salinity (S) and biochar addition (BA), column experiment

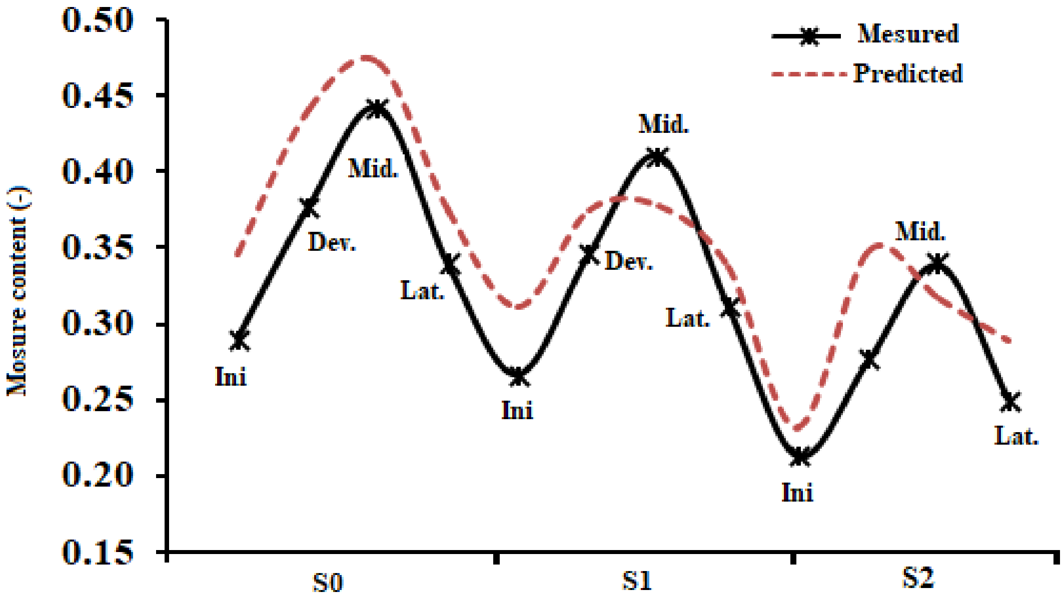

Fig.5. The actual and predicted ET (mm) , model calibration, column experiment

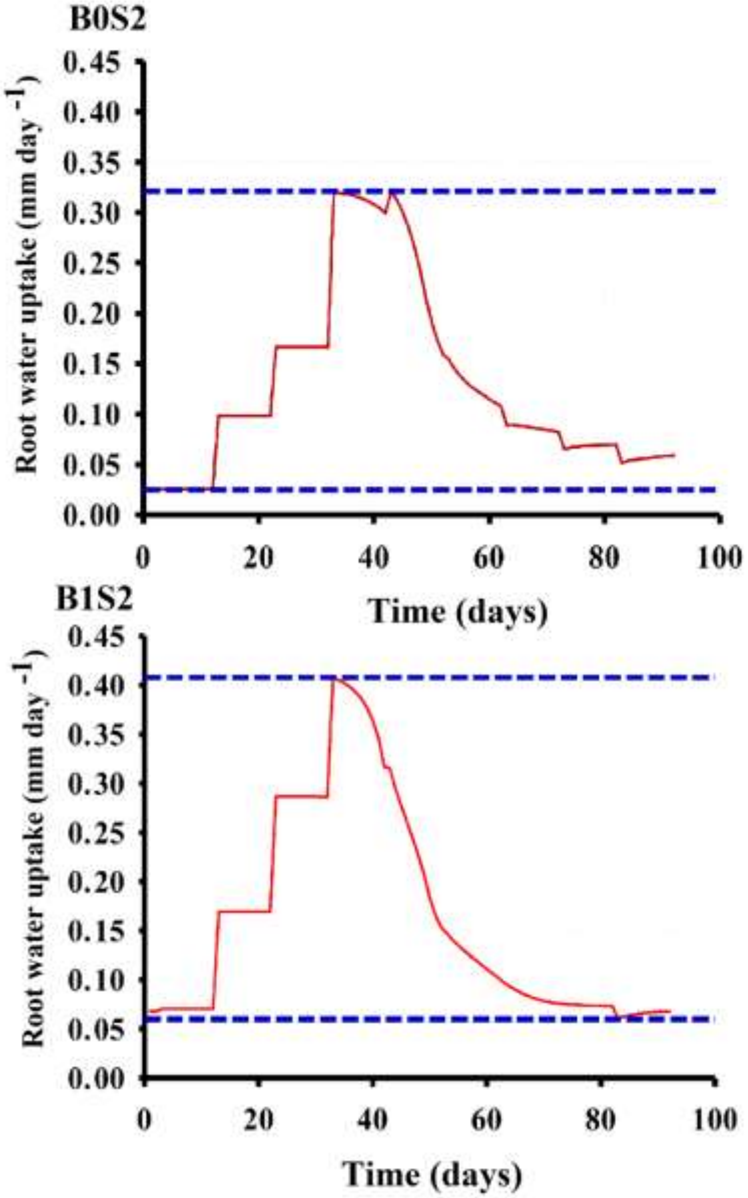

Figure 7 . The model validation, simulation RWU under column experiment

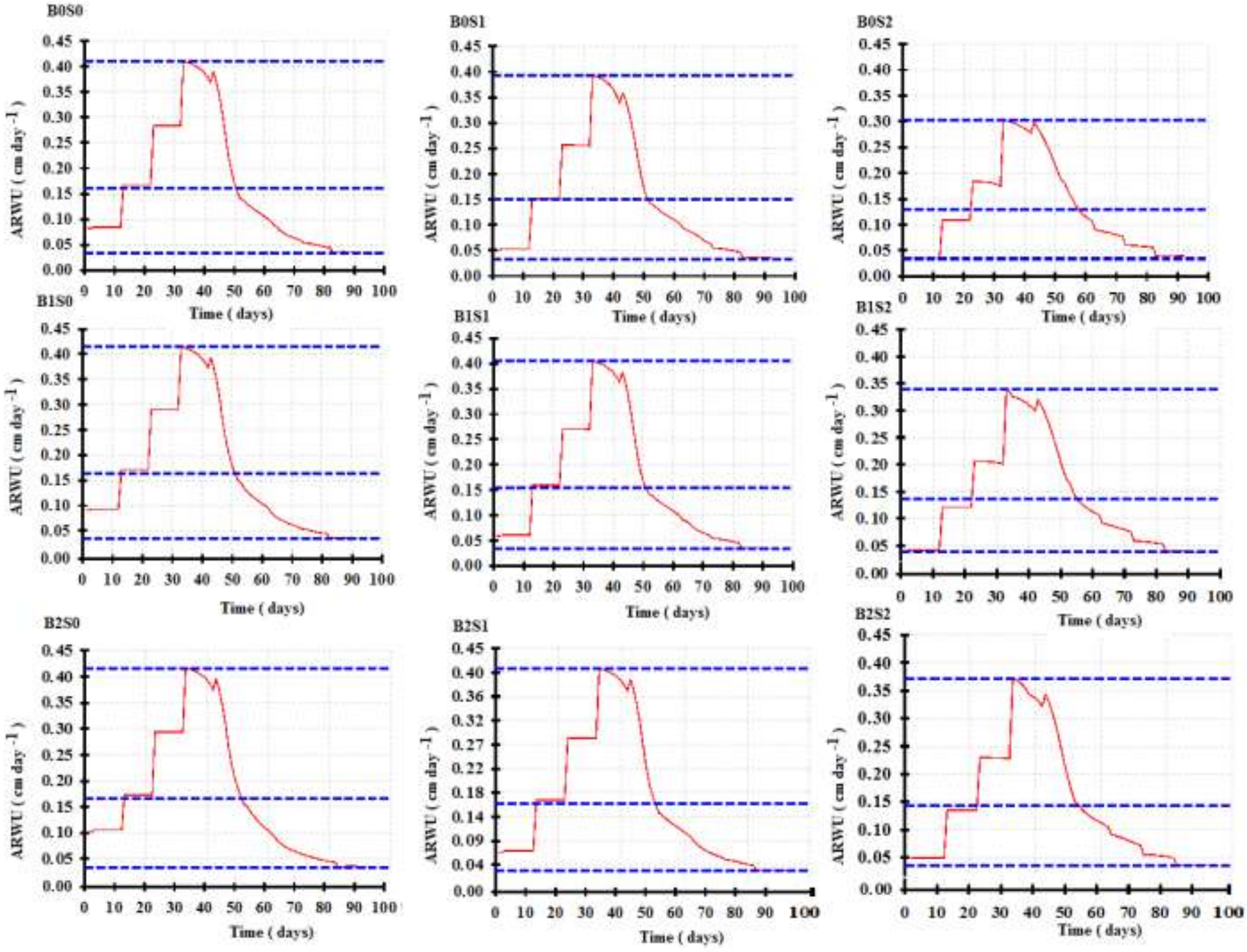

Fig 8 . Simulation of okra RWU under different irrigation water salinity (S) and biochar addition (BA), field experiment.