Effects of maize straw biochar application on soil physical properties, morph-physiological attributes, yield and water use efficiency of greenhouse tomato

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Abstract: Tomato (*Solanum lycopersicum* L.) production was threatened by the inefficiency of fertilizers, contributing to the deterioration of the soil environment under greenhouse conditions in southern China. Biochar application could ameliorate the physical properties of soil and enhance the growth and productivity of tomatoes. In this study, a pot experiment was conducted with four biochar addition rates of 0% (BA_0), 1% (BA_1), 3% (BA_3), and 5% (BA_5). Results showed that the soil physical properties, morph-physiological indicators, yield, and water use efficiency (WUE) of tomatoes with biochar addition were significantly higher than those of tomatoes without biochar addition. Among the different treatments, BA_5 provided the highest total porosity (53.09%), field capacity (40.73%), plant height (72.5 cm), net photosynthetic rate (16.04 mmol/m^2·s), total dry matter (184.65 g/plant), yield (54.9 t/hm^2), and WUE (38.5 kg/m^3). The yield and *WUE* increased from 44.5 t/hm^2 and 31.2 kg/m^3 under BA_0, respectively, to 54.9 t/hm^2 and 38.5 kg/m^3 under BA_5, respectively. The results suggest that BA_5 can maximize improvements in soil physical properties to augment plant growth, thereby increasing the yield and WUE of tomatoes. However, the effects of BA_3 and BA_5 on WUE were not significantly different. Thus, from the perspective of economic investment, BA_3 is recommended.

Keywords: maize straw, biochar application, soil properties, water use efficiency, tomato, greenhouse

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1 Introduction

In recent years, facility horticulture in southern China has developed rapidly. As an important cultivation vegetable crop, tomato plays a vital role in facility horticulture. China is one of the largest tomato-producing and consuming countries, and almost one-third of the world's total tomato acreage is planted in China[1]. Erosion and unstable organic matter due to long-term continuous cropping and excessive application of chemical fertilizers gradually decrease soil fertility, consequently affecting the yield and quality of tomatoes[2,3]. Yellow-brown loam as a typical soil in southern facility production, which has the characteristics of soil viscosity and poor physical properties[4], is susceptible to the influence of facility planting.

In recent decades, interest in the addition of biochar to soils to improve fertility for crop production has increased[5]. Adding biochar to soil has high application value and environmental benefits in agriculture and can improve soil physicochemical properties and water characteristics[6,7]. Biochar can change soil physicochemical properties, water retention, and fertilizer retention because of its porosity, huge surface area, large adsorption capacity, and cation exchange capacity[8]. Biochar can improve soil capillary porosity and aeration porosity and increase soil field water capacity[9,10]. Long-term positive effects of biochar addition on soil physical properties (soil porosity and macro agglomerate formation) improve crop productivity and soil function[11]. Biochar is a constructive soil amendment to heighten crop growth and yield through amelioration in soil properties[12,13]. Good soil conditions are necessary to produce high-quality plants, such as tomatoes. Adding 40 t/hm^2 of maize straw biochar to soil can increase tomato yield by 60%[14]. Ding et al.[15] also reported that biochar application can significantly increase tomato yield (by up to 41%), photosynthetic effects, and biomass accumulation.

Bulk density (BD), total porosity (P_T), and field capacity (FC) are key indicators used to measure the physical quality of soil[16]. the physical properties of soil are improved after biochar is added[17,18]. Soil BD decreases significantly with increasing biochar application rates[19,20]. Liu et al.[21] revealed that soil properties, plant growth, and crop yield are largely influenced by soil BD. Glab et al.[22] observed that biochar application increases soil porosity, but this effect is dependent on the types of biochar and soil used. Biochar can improve the water holding capacity of soil, thereby enhancing crop growth and other growth parameters in the soil[23]. Lévesque et al.[24] revealed that biochar application to soil can enhance the growth and productivity of tomatoes, and adding 5%-15% biochar increases the water use efficiency (WUE) of tomato plants and the dry weight yield of tomato fruits by up to 32%.

Previous studies on the capability of biochar to improve soil physical properties, crop yield, or WUE only focused on a single aspect. However, limited data are available about the synergistic effect of biochar on soil physical properties, tomato growth, yield, and WUE. Therefore, it conjectured that adding maize straw biochar to soil would effectively reduce soil BD and increase P_T and FC,

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which would improve tomato yield, dry matter, and WUE. Furthermore, adding biochar can promote tomato growth by improving the physical properties and regulating the water-holding capacity of the soil, thus positively affecting tomato yield and WUE. To test the above hypothesis, this study scrutinized the effect of increasing biochar addition on the BD, P_T, and FC of facility soils, and also measured the effects of the morpho-physiological attributes, yield, dry matter, and WUE of tomatoes with increasing biochar addition in a greenhouse trial. The research was expected to provide a theoretical basis to improve facility soil quality and promote the sustainable development of protected horticulture.

2 Materials and methods

2.1 Experimental site description

Pot experiments were conducted in a greenhouse at the water-saving Park of Hohai University (31°57'N 118°50'E, 144 m above sea level) from July 25, 2020, to January 11, 2021, in a greenhouse of 5 m wide and 20 m long without temperature control under natural light conditions. The greenhouse is located in Jiangning District, Nanjing City, Jiangsu Province, China. The climate of the region is humid subtropical, influenced by the East Asian monsoon. The average annual temperature in the region was 15.7°C. The absolute maximum temperature reached 40.4°C in August 2020, and the absolute minimum temperature dropped to –13.3°C in January 2021. The rainy season spanned from July to September. The average annual rainfall in the area was nearly 1 025.12 mm, which was concentrated in the rainy season-summer. The annual sunshine time was 2200 h, and the annual average evaporation was approximately 900 mm.

2.2 Soil and biochar analysis

The experimental soil was classified as a typical yellow-brown loam according to the Chinese classification[25]. The tested biochar was maize straw biochar (purchased from Henan Lize Environmental Protection Technology Co., Ltd, China). The main physical and chemical properties of the soil before the experiment and the maize straw biochar are listed in Table 1.

Soil pH was measured using the Remag pH meter in a 1:5 soil and water extract[26]. Soil organic matter was determined using the high-temperature oxidized organic carbon method[27]. Available soil nitrogen in the soil and biochar solutions was measured using a UV-Vis spectrophotometer (L007, 7522112059A; Essence Technology Instruments, Shanghai, China)[28,29]. Available soil phosphorus was determined using the UV-Vis spectrophotometric method[30]. Available soil potassium was measured using the flame photometric method with 1 mol/L NH_4OAC solution as a leaching agent[31].

Table 1 Basic physical and chemical properties of biochar and soil in the study area.

Property	Soil	Biochar
Bulk density/g·cm^{-3}	1.41	--
Total porosity/%	46.32	--
Field capacity/%	28.73	--
pH value	7.07	9.40
Organic matter/%	1.04	41.1
Available nitrogen/mg·kg^{-1}	11.1	390
Available phosphorus/mg·kg^{-1}	5.81	56.4
Available potassium/mg·kg^{-1}	101	58 513

Note: Values are the average of three replicates of each measurement.

2.3 Experimental design

The experiment was conducted in a completely randomized block design with eight replications (Figure 1). The irrigation management level of all treatments was DI_{100}, where 100% of ET_0 was received. ET_0 (mL/d) was determined as follows[32]: 1 d before the treatment, each pot of BA_0 was irrigated completely until the soil moisture content reached the field capacity. I mass of each pot of BA_0 after controlling the water for 24 h was weighed and recorded (W_1). After 48 h, the mass was weighed for the second time (W_2) to calculate the transpiration (ET_0) of each pot, which was the daily irrigation volume, and applied to all treatments.

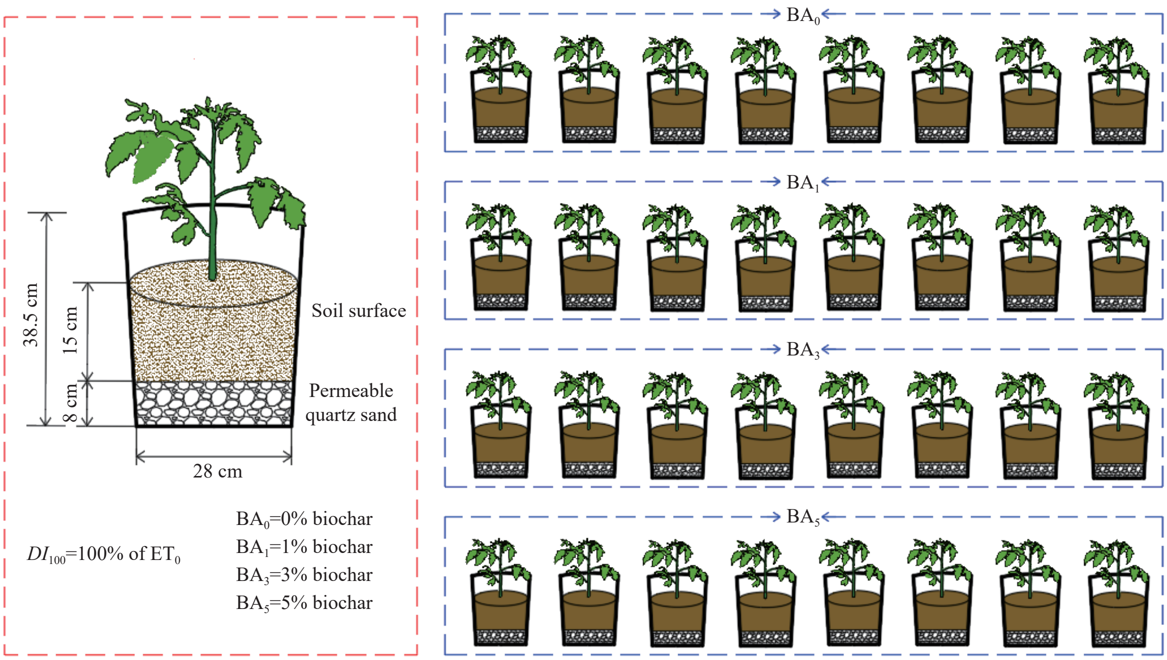


Figure 1 Layout diagram of the pot experiment in the greenhouse

$$ET_0 = W_1 - W_2 \quad (1)$$

During the experiment period, the irrigation of the experiment was once a day. Then, the mass was weighed and the irrigation amount was checked every 5 d, and the method was the same as above. The irrigation management started after the seedlings were transplanted in the pot for a week and continued until the plants were harvested.

The main treatment was biochar amendment with four application rates: BA_0 (0%), BA_1 (1%), BA_3 (3%), and BA_5 (5%) on a mass basis. BA_1 was 12 kg soil+120 g biochar, BA_3 was 12 kg soil+360 g biochar, BA_5 was 12 kg soil+600 g biochar, and BA_0 was 12 kg soil. Experimental pots were fixed in an open shelter covered with plastic films. Each pot (upper diameter: 32.5 cm, lower diameter: 28 cm, depth: 38.5 cm) was filled with 8 cm-high quartz sand in consideration of the water permeability and air permeability of the roots. The soil was air-dried and passed through a 6.3 mm sieve, and each pot was filled with 12 kg of soil (Figure 1). Afterward, biochar was weighed in proportion, added to each treatment, and then mixed with the soil thoroughly to a depth of 30 cm. The amount of biochar at a rate of 1% (BA_1) was committed on a mass basis to establish a soil BD of 1.25 g/cm^3. The amount of biochar at a rate of 1% (BA_1) was tripled and quintupled to achieve rates of 3% (BA_3) and 5% (BA_5), whereas no biochar was applied at a rate of 0% (BA_0).

In this study, tomato variety 'cooperative 903', one of the most widely grown vegetables in Jiangsu Province, China, was used. In addition to the high value of tomato as a vegetable crop, this plant was selected for evaluation because of its short life cycle. Seeds were sown at a density of 2-3 seeds per plug disk cell and diluted to one plant per well after 2 weeks of germination. When the seedlings had five leaves and one heart, seedlings with similar growth were selected and transplanted to the pots on 25th August 2020.

Fertilizers used were as follows: 20 g compound fertilizer (N: P: K=15:15:15) was applied as base fertilizer for each pot before transplanting. The tomatoes were managed uniformly according to the experience of local agronomic practices. That is, each pot was frequently weeded by hand, each inflorescence of each pot left four fruits, and three leaves were left in the upper part after the fruits set in the second inflorescence. In addition, field management in the greenhouse was carried out for pest and disease control to avoid yield losses. The ultimate harvest time was completed in January 2021.

2.4 Measurement items and methods

2.4.1 Determination of soil physical properties

After the tomato was harvested, soil samples were collected from 0-5 cm depth using a cutting ring (5.05 cm in diameter, 5 cm in length). The soil BD and P_T were measured using the ring knife weighing method[33] as follows:

$$\mathrm{BD} = \frac{M_s}{V_s} \tag{2}$$

$$P_T = \left(1 - \frac{\mathrm{BD}}{\mathrm{PD}}\right) \times 100\% \tag{3}$$

where, BD is the bulk density, g/cm^3; M_s is the dry weight of the soil, g; V_s is the volume of the ring knife, cm^3; P_T is the total porosity, %; PD is the soil particle density, here PD=2.65 g/cm^3[34].

The FC was determined following the method described by Gao et al.[35]:

$$\mathrm{FC} = \frac{M_w - M_d}{M_d - M_c} 100\% \tag{4}$$

where, FC is the field capacity, %; M_c is the mass of soil sample container, g; M_w is the total mass of wet soil+container, g; M_d is the total mass of dry soil + container, g.

2.4.2 Determination of plant growth parameters and physiological traits

The plant height (PH, in cm), stem diameter (SD, in mm), and relative chlorophyll content (SPAD) in plants were collected starting on the 24th day after transplanting and ended after pinching the plant on the 59th day after transplanting, which was measured weekly. The PH was determined from the stem base to the plant growth apex. The SD was measured at the lower node of the first inflorescence by using a Vernier caliper. The relative chlorophyll content (SPAD) of the first leaf at the lower part of the first inflorescence was measured with a CL-01 rapid chlorophyll meter (Hansatech, UK).

After the tomato was harvested, the plants of each treatment were harvested by hand cutting at the soil surface and were partitioned subsequently into stems, leaves, and fruits. The roots were collected individually by sampling the soil–root cores for each pot and were separated by washing the soil samples carefully. All plant samples were packed in separate paper bags, placed in the oven at 105°C for 30 min and then at 75°C for 72 h, and weighed to obtain the total dry mass (DM_T).

Photosynthesis-related indexes were obtained as follows: the net photosynthetic rate (P_n), stomatal conductance (G_s), transpiration rate (T_r), and intercellular CO_2 concentration (C_i) of the first fully expanded leaves at the lower part of the first inflorescence of each treatment plant were determined from 9:00 a.m. to 11:00 a.m. on a sunny day at the flowering and fruit setting stages under an artificial light source with a radiation flux density of 1000 μmol/m^2·s by using a portable photosynthesis system (Li-6800, LI-COR, USA). The limitation of stomatal conductance (L_s) was calculated using the following equation[36]:

$$L_s = 1 - \frac{C_i}{C_a}, \tag{5}$$

where, C_a is the ambient CO_2 concentration; other symbols are the same as above.

2.4.3 Determination of tomato yield and WUE

Plant yield was measured at the mature stage of tomato. Each picking was weighed and recorded with an electronic scale with an accuracy of 0.01 g, and the yield per plant was calculated cumulatively. The total yield was converted by planting density (plant/hm^2). The WUE was determined using the following equation[37]:

$$\mathrm{WUE} = \frac{Y}{\mathrm{TWU}} \tag{6}$$

where, WUE is the water use efficiency, kg/m^3; Y is the crop yield, kg/hm^2; TWU is the total water use, m^3/hm^2.

For the above indicators, four pots with similar plant growth were selected for each measurement as four repetitions.

2.5 Data processing and analysis

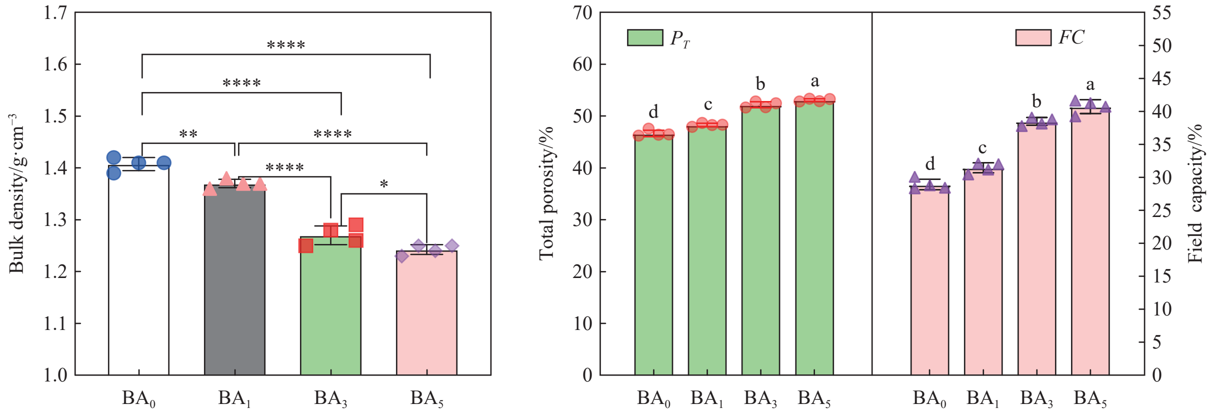
Excel 2010 was used for data recording and organizing. GraphPad Prism 8.0 was used for One-way ANOVA and chart drawing. SPSS26.0 software was used for ANOVA, in which Duncan's multiple-range test was applied to compare the means at the 0.05 significance level. Statistical significance was considered at $p \leq 0.05$. A Pearson correlation analysis was performed independently between soil physical properties, plant growth parameters, and physiological traits, and yield to determine the degree of relationship between each of the variables mentioned.

3 Results

3.1 Impact of biochar addition on soil physical properties

The effects of different biochar applications on soil physical properties are shown in Figure 2. Results showed that the biochar application reduced the BD and increased the P_T of the soil.

Significant differences in physical properties were observed between the soil samples treated with BA_1, BA_3, and BA_5 (p<0.05), and the difference between the soil samples treated with BA_3 and BA_5 (p<0.05) was not as apparent as that between the soil samples treated with BA_1 and BA_3 (p<0.000 1). Compared with BA_0, BA_1, BA_3, and BA_5 decreased the BD by 1.37 g/cm^3, 1.28 g/cm^3, and 1.24 g/cm^3, respectively (Figure 2a), while increased the soil P_T % by 3.56%, 11.85%, and 13.83%, respectively (Figure 2b).



a. Effects of biochar on the soil bulk density

b. Effects of biochar on the total porosity and field capacity

Note: *, * *, * * *, and * * * * mean significant levels (p<0.05, p<0.01, p<0.001, and p<0.0001). Means of P_T and FC are significantly different between BA rates (p≤ 0.05) when followed by different lowercase letters according to Duncan's multiple-range test analysis.

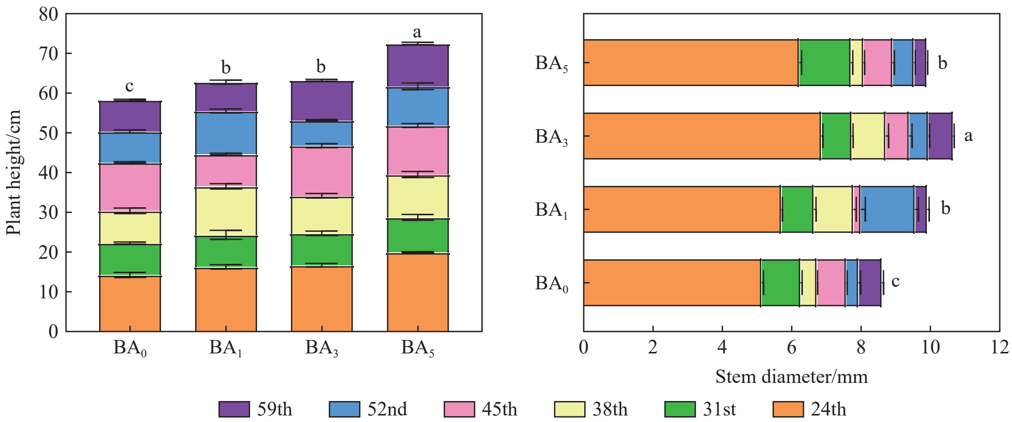
Figure 2 Effects of biochar addition on soil physical properties

The results indicate that the application of biochar to the soil significantly influenced (p≤0.05) its field capacity (FC), and the FC of all the soil samples with biochar application was higher than that of the soil samples without biochar application (Figure 2b). Compared with BA_0, BA_3, and BA_5 significantly increased the FC of the soils by 33.07% and 40.91%, respectively. The FC of the soil samples treated with BA_1 was only 8.83% higher than that of the soil samples treated with BA_0, the FC of the soil samples treated with BA_3 was 22.29% higher than that of the soil samples treated with BA_1, and the FC of the soil samples treated with BA_5 was 5.90% higher than that of the soil samples treated with BA_3. This result indicated that the addition of biochar between 1% and 3% considerably better improved the FC of soil.

3.2 Impact of biochar application on tomato growth parameters and physiological traits

As shown in Figure 3, biochar significantly improved plant growth in a dose-dependent manner. Plant growth under BA_1, BA_2, and BA_5 was significantly better than that under BA_0 (p<0.05). The highest PH values were obtained under BA_5 (72.5 cm), followed by BA_3 (63.3 cm) and BA_1 (62.8 cm), whereas the lowest PH values were obtained under BA_0 (58.3 cm). At the initial stage (24th day after transplanting), the SD of the plants under BA_3 was significantly higher than those of the plants under the other treatments (p<0.05) until the fruit setting period. On the 59th day after transplanting, the coarsest SD values were obtained in the plants under BA_3 (10.67 mm), followed by those under BA_5 and BA_1 (9.92 mm and 9.93 mm), whereas the thinnest SD values were obtained in the plants under BA_0 (8.62 mm).

As shown in Figure 4, the relative chlorophyll content (SPAD values) of the plants under each treatment initially increased and then decreased. The SPAD values of the plants under BA_1, BA_3, and BA_5 were significantly higher than that of the plants under BA_0 (p<0.05) at all measurement periods. The application of biochar promoted the accumulation of relative chlorophyll content, and the peak SPAD values were reached by the plants under all treatments (BA_0: 31.3, BA_1: 34.5, BA_3: 36.8, BA_5: 34.8) on the 31st day after transplanting. Biochar inhibited chlorophyll decline in the later growth stage, and the decline rate of the plants under BA_3 was

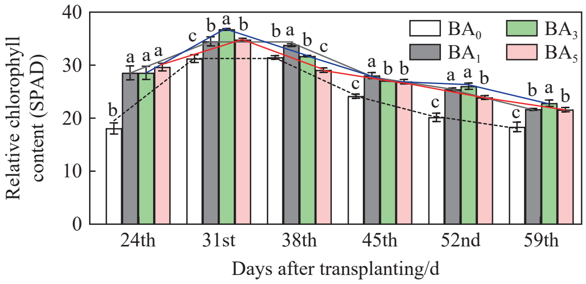


a. Effects of biochar on the plant height

b. Effects of biochar on the stem diameter

Note: "24th, 31st, 38th, 45th, 52nd, and 59th." indicate the day after transplanting. Means of PH and SD are significantly different between BA rates (p≤0.05) when followed by different lowercase letters.

Figure 3 Effects of biochar on the plant height and stem diameter of tomato

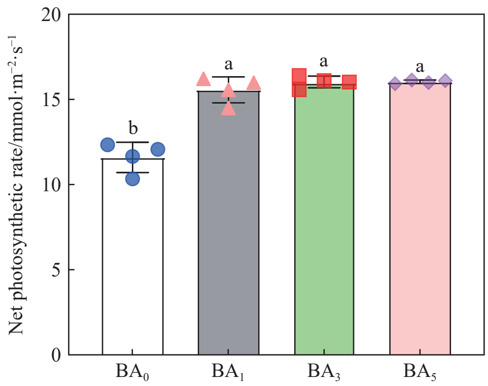


Note: Means of relative chlorophyll content are significantly different between BA rates ($p \le 0.05$) when followed by different lowercase letters in the day after transplanting.

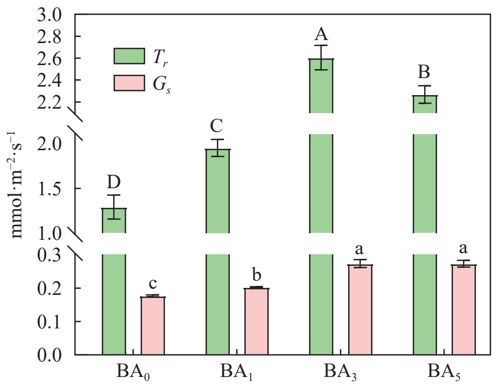
Figure 4 Effects of biochar on the relative chlorophyll content of tomato leaves

slower than that of the plants under the other treatments. The minimum SPAD values of the plants in all treatments were recorded on the 59th day after transplanting (BA_0: 18.4, BA_1: 21.7, BA_3: 22.8, BA_5: 21.6).

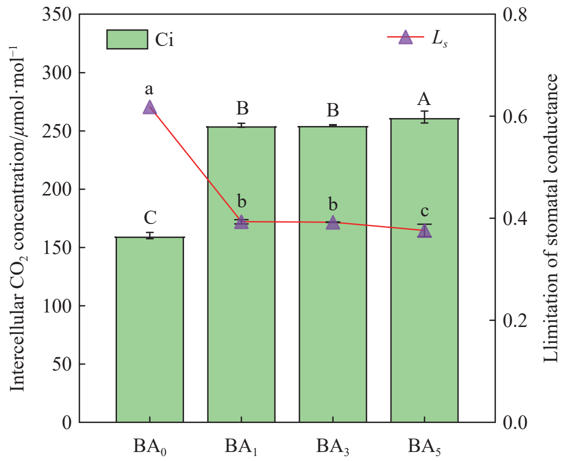
The P_n, T_r, G_s, C_i, and L_s of the plants under the different treatments during the flowering and fruit setting stages are shown in Figures 5a-5c. The addition of biochar significantly increased P_n, T_r, G_s, and C_i while significantly decreasing L_s. For P_n and C_i, this positive impingement was elevated with increasing biochar application (BA_0<BA_1<BA_3<BA_5). At the flowering and fruit setting stages (Figure 5a), the highest P_n was achieved by the plants under BA_5 (16.04 mmol/m²·s), followed by those under BA_3 and BA_1 (16.03 and 15.57 mmol/m²·s, respectively), whereas the lowest P_n was achieved by the plants under BA_0 (11.61 mmol/m²·s).



a. Effects of biochar on P_n



b. Effects of biochar on T_r and G_s



c. Effects of biochar on Ci and L_s

Note: Means of P_n, G_s, and L_s are significantly different between BA rates ($p \le 0.05$) when followed by different lowercase letters. Means of T_r and C_i are significantly different between BA rates ($p \le 0.05$) when followed by different uppercase letters.

Figure 5 Effects of biochar on photosynthesis-related indexes of tomato leaves

As shown in Figure 5b, the T_r rates of the plants under BA_3 were significantly higher than those of the plants under the other treatments, and no significant differences in G_s were found between the plants under BA_5 and BA_3. The maximum T_r and G_s were observed in the plants under BA_3 (2.61 and 0.27 mmol/m²·s), followed by the plants under BA_5 (2.27 and 0.27 mmol/m²·s) and BA_1 (1.95 and 0.20 mmol/m²·s), whereas the lowest values were recorded in the plants under BA_0 (1.29 and 0.18 mmol/m²·s). The increase in C_i of the plants under BA_1, BA_3, and BA_5 was accompanied by a decrease in L_s. The highest C_i was recorded in the plants under BA_5 (262 μmol/mol), followed by the plants under BA_3 and BA_1 (255.0 and 254.7 μmol/mol), whereas the lowest values were observed in the plants under BA_0 (160 μmol/mol). The L_s values of the plants under BA_1, BA_3, and BA_5 decreased by 36.40%, 36.55%, and 39.17%, respectively, compared with that of the plants under BA_0.

3.3 Impact of biochar application on the dry matter, *Y*, and *WUE* of tomato

Tomato dry mass production is closely related to biochar application (Table 2). The mean mass of dry matter amplified with increasing biochar application, whereas the root, stem, leaf, and fruit improved increasingly in the order of BA_0<BA_1<BA_3<BA_5. The average dry mass of the roots, leaves, and fruits of the plants under BA_1, BA_3, and BA_5 was significantly higher than that of the plants under BA_0 (p<0.05). No significant differences in average dry mass were found between the plants under BA_3 and BA_5.

Table 2 Effects of biochar on the mean mass of dry matter per plant

Treatments	Mean mass of dry matter per plant/g				
	Root	Stem	Leaf	Fruit	Total weight
BA_0	1.42±0.03[c]	13.80±2.45[a]	41.28±1.04[b]	97.90±7.56[b]	154.40±6.95[c]
BA_1	1.53±0.07[bc]	14.06±0.84[a]	42.08±1.83[ab]	111.92±8.90[a]	169.60±8.57[b]
BA_3	1.63±0.10[b]	15.62±0.57[a]	45.50±4.67[a]	118.28±6.74[a]	181.02±5.26[a]
BA_5	1.79±0.14[a]	15.97±0.42[a]	46.21±0.22[a]	120.68±7.63[a]	184.65±7.05[a]

As shown in Table 3, the average Y and WUE of tomatoes were significantly affected by biochar application (p<0.05). In specific, these parameters increased with increasing biochar addition rate. However, no significant difference in these parameters was found between plants under different biochar rates. Thus, the average single fruit weight of the first inflorescence of each treatment was higher than that of the second inflorescence, and the results were in the order of BA_5>BA_3>BA_1>BA_0. When the TWU of each treatment was 1425 m³/hm², the Y and WUE increased gradually with increasing biochar addition levels and peaked under BA_5 (54.9 t/hm² and 38.5 kg/m³, respectively), and the Y and WUE of the plants under BA_1, BA_3, and BA_5 were 14.32%, 20.81%, and 23.27% higher, respectively, than those of the plants under BA_0.

3.4 Correlation analysis between soil physical properties, plant growth parameters, physiological traits, and yield

The correlation analysis between soil physical properties (BD, P_T, and FC), plant growth parameters (PH, SD, and DM_T), physiological traits (P_n, T_r, G_s, C_i, and L_s), and Y are presented in Table 4. Every two of P_T, FC, PH, SD, DM_T, P_n, G_s, T_r, C_i, L_s, and Y had a highly significant positive correlation (R>0.6) besides PH with SD and T_r, and all these factors showed a highly significant negative correlation with BD and L_s. The plant growth parameters (PH, SD, and DM_T), physiological traits (P_n, T_r, G_s, C_i, and L_s), and Y showed a highly significant correlation with soil physical properties (BD, P_T, and FC), indicating that the improvement in soil physical properties was conducive to enhance plant growth and increase yield. DM_T and Y were strongly correlated with plant growth parameters (PH and SD) and physiological traits (P_n, T_r, G_s, C_i, and L_s). Thus, the energy transformed by photosynthesis was mainly supplied to promote plant growth and increase dry matter, thereby increasing tomato yield.

Table 3 Effects of biochar on tomato yield and water use efficiency

Treatment	Average fruit weight per fruit/g		Yield per plant/g	Y/t·hm^{-2}	WUE/kg·m^{-3}
	First inflorescence	Second inflorescence			
BA_0	135±17[a]	112±4[c]	990±76[b]	44.5±3.4[b]	31.2±2.4[b]
BA_1	147±11[a]	136±12[b]	1132±90[a]	50.9±4.0[a]	35.7±2.8[a]
BA_3	150±14[a]	149±4[a]	1196±68[a]	53.8±3.1[a]	37.8±2.1[a]
BA_5	157±23[a]	148±8[a]	1220±77[a]	54.9±3.5[a]	38.5±2.4[a]

Note: ± means standard deviation. Means are not significantly different between different BA rates when followed by the same lowercase letter, means are significantly different between BA rates (p≤0.05) when followed by the different lowercase letters.

Table 4 Correlation analysis between soil physical properties, plant traits, and yield

Factor	BD	P_T	FC	PH	SD	P_n	T_r	G_s	C_i	L_s	DM_T	Yield
BD	1											
P_T	–0.998	1										
FC	–0.993	0.993	1									
PH	–0.828	0.823	0.839	1								
SD	–0.732	0.752	0.717	0.455	1							
P_n	–0.726	0.740	0.719	0.675	0.888	1						
T_r	–0.842	0.857	0.839	0.574	0.951	0.879	1					
G_s	–0.950	0.958	0.959	0.744	0.798	0.782	0.915	1				
C_i	–0.735	0.752	0.726	0.707	0.891	0.964	0.861	0.753	1			
L_s	0.735	–0.752	–0.726	–0.707	–0.891	–0.964	–0.861	–0.753	–1	1		
DM_T	–0.835	0.843	0.830	0.753	0.769	0.828	0.814	0.823	0.801	–0.801	1	
Yield	–0.700	0.713	0.703	0.666	0.713	0.807	0.745	0.727	0.755	–0.755	0.963	1

Note: Pearson correlation coefficient 0.8-1.0 means very strong correlation, 0.6-0.8 means strong correlation, 0.4–0.6 means medium correlation, 0.2-0.4 means weak correlation, and 0.0-0.2 means very weak correlation or no correlation.

4 Discussion

4.1 Biochar application reduced soil *BD* and improved soil P_T and *FC*

The biochar application significantly affected soil physical properties. Biochar addition to the soil effectively decreased BD, and P_T negatively correlated with BD; therefore, P_T was increased (Figures 2a and 2b). In addition, compared with the control treatment, the addition of biochar ameliorated the FC of the soil. The relationship between soil FC and BD was $FC=p_m/BD$-1, in which the negative correlation parameter was determined by soil density after moisture absorption (p_m). Adding biochar to soil can effectively improve soil quality and FC because biochar has high porosity, high soil aeration, and high water storage capacity[38-40]. Moreover, biochar can effectively improve the texture and structure and enhance the water holding capacity of soil[41,42]. In the current study, the soil physical properties improved with increasing biochar application. These results agree with the findings of Fu et al.[43] that increasing the quantity of biochar addition decreases the BD and increases the P_T of soil. These results are also consistent with the results of Wang et al.[44] that biochar addition increases P_T and decreases BD, thereby improving soil physical conditions. Furthermore, Rasa et al.[45] reported that biochar application can improve soil FC by increasing soil P_T. In the present study, the decrease in BD and increase in P_T synergistically promoted FC, which is consistent with the measurement results (Figure 2b).

4.2 Tomato growth parameters and physiological traits in response to biochar application

All growth parameters and physiological traits of tomato were advantageously affected by biochar application. Biochar application increased PH and SD. The pH of the plants under BA_5 was significantly higher than those of the plants under the other treatments. BA_3 exerted the most significant effect on promoting SD (Figure 3). Biochar application increased relative chlorophyll content, and the effect of BA_3 was stronger than those of BA_1 and BA_5 (Figure 4). Biochar application significantly enhanced photosynthetic parameters (P_n, T_r, C_i, and G_s). BA_3 treatment exerted the best lifting effect. These results agree with the findings of Du et al.[46] that adding biochar can promote the healthy growth of plants and that the optimal treatment is 3% biochar application. These results are also commensurate with the results of Sun et al.[47], who reported that 1%-5% biochar application can significantly improve PH, SD, leaf chlorophyll content, and P_n. Biochar improved tomato growth, and the positive effect of BA_3 was better than that of BA_5. This phenomenon can be explained by the fact that biochar has high adsorption. Thus, high biochar contents (e.g., 5%) increase small and large pores in soil, thereby reducing the amount of effective pores[48]. This condition affects the movement of water and nutrients to plant roots, which decreases the absorption of water and nutrients and inhibits plant growth. Thus, 3% biochar was more suitable than 5% biochar. Given that the experiment was carried out for a short period, the mechanism by which biochar application affects plant growth and physiology warrants further investigation through long-term experiments.

4.3 Biochar application increased dry matter, *Y*, and *WUE* of tomato

Biochar application increased the dry matter, *Y*, and WUE of the tomato. The average dry mass of root, stem, leaf, and fruit; *Y*; and WUE increased with increasing biochar application. Biochar can promote plant height and leaf growth and significantly increase aboveground dry matter[49,50]. Zhang et al.[51] also showed that biochar application can promote the absorption capacity of tomato plants to nutrients and improve tomato yield. These results are consistent with those of Zhou et al.[52], who revealed that biochar can significantly improve crop yield, and its optimal application rates are 1% and 3%. Faloye et al.[53] showed that biochar application can improve WUE, which is closely related to yield. While no significant difference in dry matter, *Y* and WUE, were observed between the plants under BA_3 and BA_5, which could be explained by the plant SD, relative chlorophyll content, and photosynthesis (Figures 3b, 4, and 5) of the plants under BA_3 were more conducive to increasing plant dry matter, *Y* and *WUE* than those of the plants under BA_5. Under the experimental conditions, the irrigation level of each treatment was the same. Thus, the application of biochar significantly improved the WUE, which is consistent with previous research results (Table 3). Meanwhile, the single fruit weight of the second inflorescence was lower than that of the first inflorescence, which may be related to the low temperature and weak plant growth in the later stage of the experiment, but the fruit development of the plants under biochar treatment was significantly better than that of the plants under control treatment. Thus, the addition of biochar was conducive to maintaining good growth.

4.4 Improvement of soil physical properties promoted plant growth and increased yield

Correlation analysis results revealed that the improvement of soil physical properties was conducive to promoting plant growth and development, improving physiological traits, and ultimately increasing dry matter and yield. The results are consistent with those of Glab et al.[54,55], which revealed that FC is related to soil P_T and BD. The FC of soil is important to the growth of crops; it determines the absorption and transportation of water by plants and thus affects the physiological status and yield of plants. A previous study also found that biochar addition enhances crop production by improving soil's physical properties[56]. These results are also in agreement with those of Zhang et al.[57], who disclosed that photosynthesis is an important physiological process affecting dry matter and yield.

5 Conclusions

This study analyzed the effects of maize straw biochar application rate on the physical properties of soil and the growth, physiology, yield, and WUE of tomatoes under greenhouse conditions. Results showed that the different biochar application rates, especially BA_5, positively affected soil physical properties. The improvement of soil physical properties consequently enhanced the morph-physiological attributes, dry matter, yield, and WUE of tomatoes. Biochar application effectively increased the SPAD values and photosynthesis of leaves, which promoted PH and SD and ultimately increased dry matter, yield, and WUE. However, the effect of BA_3 on plant growth parameters and physiological traits was better than that of BA_5. The yield and WUE of the plants under 3% and 5% biochar addition showed no significant differences. The WUE of the plants under BA_1, BA_3, and BA_5 increased from 31.2 kg/m^3 (BA_0) to 35.7 kg/m^3, 37.8 kg/m^3, and 38.5 kg/m^3, respectively. The current results delineated that maize straw biochar can promote plant growth by improving soil physical properties to increase the yield and WUE of tomatoes. These results suggest that maize straw biochar can be used as an effective agronomic measure to improve the quality of facility soils, strengthen plant growth, and enhance tomato yield. From the perspective of economic investment, 3% biochar was more suitable than 5% biochar.

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