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Improving the yield of greenhouse tomato by adjusting the coupling coordination degree of soil–water–root system using a biochar

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ABSTRACT

The unreasonable management of water, fertilizer and pesticides has led to the deterioration of soil quality and a reduction in crop yields in facility agriculture. Due to its well-developed pores, large specific surface area, strong cation adsorption capacity and stable structure, biochar has the potential to improve soil quality and crop yield. Greenhouse experiments were conducted in 2021 and 2022 to study the effects of different application rates of biochar (0, 15, 30, 45 and 60 t·ha^{-1}) on soil structure, water-holding capacity, tomato root growth (the soil–water–root system), and their coupling coordination degree (*D*). Compared to no addition of biochar, adding biochar increased the content of aggregates with a diameter greater than 0.25 mm by 1.4%-22.8% and the mean weight diameter by 1.5%–34.5%, and the soil available water content (*SAWC*) increased by 6.9%–35.7%. Biochar makes the root system of tomato thinner and longer, increasing the surface area density and volume density of the roots. Adding biochar to the soil increased the *D* value of the soil–water–root system by 25.7–86.0%. Tomato yield and water use efficiency increased by 28.8%–33.3% and 21.4%–29.6% with the addition of biochar, respectively. Based on the CRITIC–TOPSIS model, considering indicators such as soil–water–root system, tomato yield and water use efficiency, the optimal biochar application rate under the conditions of this experiment was 30 t·ha^{-1}. Furthermore, through the structural equation model, it was concluded that biochar primarily affected the *D* value by increasing *SAWC*, which then had an indirect effect on tomato yield. These research results are of great significance for the sustainable development of facility agriculture.

1. Introduction

The tomato is one of the world's most popular vegetables because its fruit is rich in nutrients such as carotenoids, vitamin C, and soluble sugars (Maham et al., 2020; Gorni et al., 2022). In recent years, facility agriculture often uses too much water, fertilizer and pesticide in the production process, resulting in the destruction of facility soil structure, a decrease in water-holding capacity and the reduction of facility crop yield (Du et al., 2020; Jiang et al., 2024). As an environment-friendly soil amendment, biochar has a certain potential in soil quality and crop growth improvement (Cao et al., 2011; Suo et al., 2021). The application of biochar into soil can change the *SMC* by changing the soil water-holding capacity, which is primarily affected by soil *BD*, porosity, aggregates and other physical structures directly or indirectly (Acharya et al., 2024). Additionally, the root system is not only an essential organ for plants to absorb and transport water and nutrients but also the primary feedback organ for plants to respond to biochar changes (Wang et al., 2024). Currently, there is a lack of research into the quantitative analysis of the influence mechanism of biochar on tomato yield in terms of soil physical structure, water-holding capacity, and root growth (soil–water–root system). It is essential for the sustainable development of facility agriculture to find out the changes of soil–water–root system

List of abbreviations: BD, Bulk density g·cm^{-3}; TP, Total porosity %; R> 0.25, The content of aggregates with a diameter greater than 0.25 mm %; MWD, Mean weight diameter mm; FWC, Field water capacity cm^3·cm^{-3}; WP, Wilting point cm^3·cm^{-3}; GWC, Gravity water content cm^3·cm^{-3}; SAWC, Soil available water content cm^3·cm^{-3}; SMC, Soil moisture content cm^3·cm^{-3}; FRLD, Fine root long density cm·cm^{-3}; RSAD, Root surface area density cm^2·cm^{-3}; RVD, Root volume density cm^3·cm^{-3}; RD, Root diameter mm; RDM, Root dry matter g·plant^{-1}; ET_0, The reference crop evapotranspiration mm; ET, Evapotranspiration mm; WUE, Water use efficiency kg·m^{-3}; C, The coupling degree -; T, The comprehensive harmonic index -; D, The coupling coordination degree -.

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and its interaction with yield after biochar application.

Soil aggregates are the basic unit of soil structure (Yang et al., 2024). The stability of soil aggregates plays a key role in mediating the movement and storage of water in soils, promoting aeration, enhancing biological activity and ultimately improving crop growth and yields (Dai et al., 2024). Adding biochar can improve soil structure stability by promoting the formation of soil aggregates (Grunwald et al., 2018; Sun et al., 2020). As *BD* of biochar is significantly lower than that of soil, on average, biochar decreased *BD* by 9% across all soil textural groups (Razzaghi et al., 2020). In addition, biochar is loose and porous, and proper application of biochar can increase soil macro-porosity and improve soil pore connectivity. Excessive application of biochar may reduce soil macro-porosity, soil aeration and water conductivity (An et al., 2020; Singh et al., 2022). However, under different soil types, experimental conditions, biochar properties and application rates, the effects of biochar on soil physical structure are different (Islam et al., 2021). Film-mulched drip irrigation, as an efficient and economical water management technology, can effectively block the heat and water vapor exchange between the soil and the atmosphere through film mulching and improve the surface environment of the soil. As a result, the response of soil physical structure to the addition amount of biochar under film-mulched drip irrigation needs to be further explored.

The improvement of soil water-holding capacity plays an essential role in improving farmland productivity. Soil water characteristic curve is one of the essential means to study soil water-holding capacity (Wang et al., 2023). It is widely used in soil water transport, soil water absorption and utilization by crops and soil improvement (Nasta et al., 2021; Abyaneh et al., 2022; Mao et al., 2022). Results showed that compared with no addition of biochar, the addition of biochar moved up the soil water characteristic curve and improved the water-holding capacity of loam (Sun et al., 2024). The addition of biochar with a mass ratio of 5%–10% increased the saturated water content, residual water content and *SAWC* of silt and sandy soil (Hussain and Ravi, 2021). The relative increase in available water in sandy soil is higher than that in silty loam and clay (Zhang et al., 2021). A meta-analysis by Rabbi et al. (2021) revealed that plant available water, permanent wilting point and saturated hydraulic conductivity did not significantly increase at high biochar application rates (more than 50 $t \cdot ha^{-1}$) compared to low rates (less than 20 $t \cdot ha^{-1}$). However, to date, no studies have investigated the effects of biochar on facility soil hydraulic properties with film-mulched drip irrigation systems. It is essential to find out the influence degree of biochar on the soil water characteristic curve, *FWC*, *WP*, *GWC* and *SAWC* to improve the water-holding performance of facility soil.

The roots are the first contact point for the interaction between the biochar and the plant (Chang et al., 2021). The improvement of soil water-holding capacity is conducive to the absorption of nutrients by crops and the joint action of water and nutrients, which, in turn, affects the growth of crop roots (Besharat et al., 2010; Mai et al., 2019). Most studies have shown that the addition of biochar can increase the total root length, root surface area, root volume and root length density and can reduce the *RD* (Han et al., 2023; Li et al., 2023a; Wan et al., 2023). Meanwhile, adding a certain amount of biochar can improve the root activity (Li et al., 2023b). Additionally, studies suggest that applying biochar does not significantly impact crop root growth in the first year, but does significantly increase root length density in the second year (Singh et al., 2023). Crop root length, root surface area and root volume decreased at first and then increased with an increase in biochar application (Zhang et al., 2023a). Meta analysis of 627 pairs of data extracted from 57 articles showed that the average crop yield was increased by 25.3% by adding a certain amount of biochar compared with no biochar (Bai et al., 2022). However, the crop yield did not increase with an increase in biochar addition. Higher vegetable yields can be obtained at 20 $t \cdot ha^{-1}$ compared with 40 $t \cdot ha^{-1}$ biochar application (Li et al., 2020).

The coupling coordination degree model is an essential tool for evaluating the level of development of the coupling coordination between two (or more) systems and predicting future trends (Zhang et al., 2023b). Currently, it is primarily employed in agriculture to examine the relationship between food security and carbon emissions (Zheng and Liao, 2025). In summary, previous studies have mainly focused on the effects of biochar on soil physical structure, hydraulic characteristics, root growth and yield, and the degree of effect of biochar on them also varies with soil texture, meteorological conditions, biochar properties and other factors. However, no reports were found on the quantitative analysis of the effect of biochar on crop yield from the perspective of the soil–water–root system's coupling coordination. Exploring the effects of coupling and coordination among the soil physical structure, water-holding capacity, and morphology of tomato roots after biochar application, as well as the internal mechanisms of its action on yield, could greatly increase the yield of facility tomato.

We hypothesized that biochar can enhance the greenhouse tomato yield by improving the coupling coordination degree of the soil–water–root compound system, rather than through any single factor within them. The objectives of this study are the following: (1) to explore the effects of biochar on soil physical structure, hydraulic characteristics and tomato root growth under film-mulched drip irrigation, (2) to evaluate the response of the *D* of the soil–water–root compound system to the addition of biochar and (3) to reveal the mechanism by which biochar affects tomato yield through the coupling and cooperation of the soil–water–root compound system based on the structural equation model. Research results can provide theoretical basis for improving soil quality and tomato yield and for realizing sustainable development of facility agriculture.

2. Materials and methods

2.1. Study area and meteorological conditions

This study was conducted in 2021 and 2022 in the solar greenhouse of Liujiapu Tomato Industrial Park, Xiaodian District, Taiyuan City, Shanxi Province (112°24′–112°43′E, 37°36′–37°49′N). The annual average temperature of the study area is 9.5°C, the average sunshine hour is 2675.8 h and the frost-free period of the whole year is 202 days. Before the experiment, the *FWC* and *BD* of the 0–30 cm soil layer in the greenhouse were 0.28 $cm^3 \cdot cm^{-3}$ and 1.19 $g \cdot cm^{-3}$, respectively. The soil type of the experimental site is silt loam (Table 1).

Meteorological data in the greenhouse were recorded by Hobo weather station (Onset Computer, Pocasset, MA, USA), such as Fig. 1. In the 2021 and 2022 tomato-growing period (May to September), the average temperatures were 28.04°C and 26.37 °C, respectively. The average relative humidity values were 65.6% and 66.5%, respectively. The ET_0 values were calculated as 3.58 mm and 3.55 mm, respectively. The specific calculation method of ET_0 is as follows (Valiantzas., 2018):

$$ET_0 = 0.0135 k_{Rs-HS} \frac{R_a}{\lambda} (T_{\max} - T_{\min})^{0.5} (T_{mean} + 17.8) \quad (1)$$

where k_{Rs-HS} is the temperature coefficient, *Ra* is the astronomical ra-

Table 1
Physico–chemical properties of tested soil and biochar.

Properties	Soil	Biochar
Field water capacity ($cm^3 \cdot cm^{-3}$)	0.28	–
Bulk density ($g \cdot cm^{-3}$)	1.19	0.45
pH	8.34	9.00
Organic matter ($g \cdot kg^{-1}$)	35.30	925.70
Total N ($g \cdot kg^{-1}$)	1.83	15.30
Total P ($g \cdot kg^{-1}$)	0.67	7.30
Total K ($g \cdot kg^{-1}$)	44.37	16.6
Mass fraction of carbon (%)	–	47.20
Mass fraction of nitrogen (%)	–	0.70
Mass fraction of hydrogen (%)	–	3.80
C/N	–	67.43

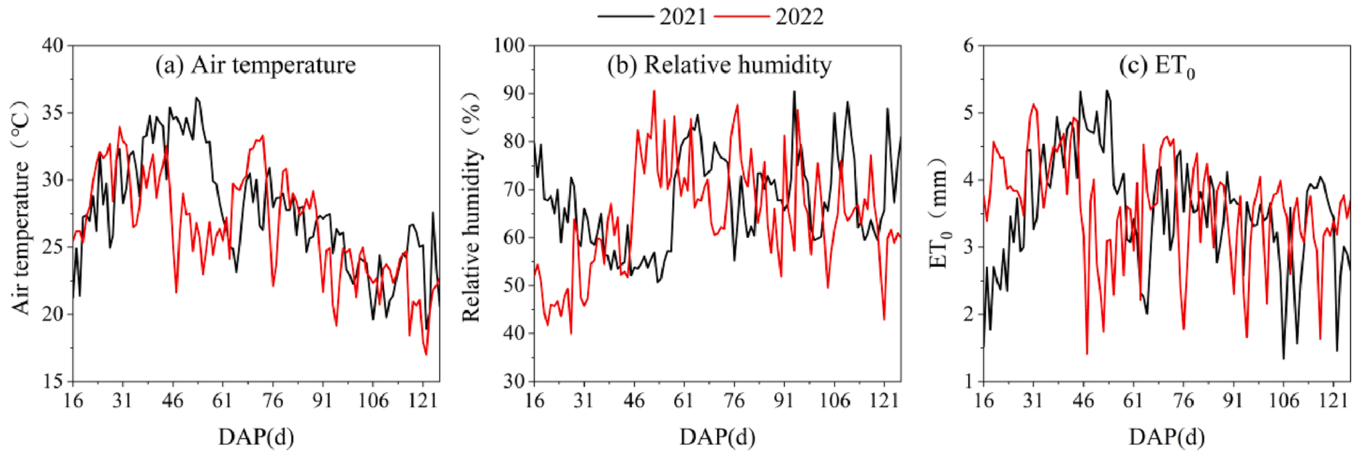

Fig. 1. Meteorological data of the tomato growth period.

diation ($MJ·m^{-2}·d^{-1}$), λ is the latent heat of vaporization of water, its value is 2.45 $MJ·kg^{-1}$, the average temperature (T_{mean},℃) is the mean of the maximum temperatures (T_{max},℃) and minimum temperatures (T_{min},℃).

2.2. Experimental design

On the basis of the research results of the effects of biochar on soil quality, tomato growth and yield (Li et al., 2018; Abdelghany et al., 2023; Jiang et al., 2024), five biochar additions were set in this experiment, which were 60 $t·ha^{-1}$ (T4), 45 $t·ha^{-1}$ (T3), 30 $t·ha^{-1}$ (T2), 15 $t·ha^{-1}$ (T1) and 0 $t·ha^{-1}$ (T0). The experiment adopted a completely randomized block design, with three replicates for each treatment. The total area of the greenhouse is 600 m^2, and the area of each plot was 28.8 m^2 (8 m×3.6 m), totaling 15 plots. Before the test in 2021 (30 April), biochar was turned into the 0–30 cm soil layer by a rotary tiller at one time and then continuously observed. The biochar applied in this study was purchased from Liaoning Jinhefu Agricultural Development Co., Ltd. It was produced by pyrolysing corn stalks at 450 °C for five hours, with a particle diameter of less than 2 mm. The parameters of the tested biochar are shown in Table 1.

2.3. Field management

The tomato 'Shou Yan PT326' was planted on 17 May 2021 and 25 May 2022, with row spacing of 60 cm and plant spacing of 50 cm, respectively, and planting density of 35,417 $plants·ha^{-1}$. After planting, 25 mm of planting water was irrigated for two years to ensure the survival of the seedlings. The growth period of tomato was divided into the seedling stage (Stage I: 17 May to 22 June 2021; 25 May to 30 June 2022), flowering and fruiting stage (Stage II: 23 June to 13 July 2021; 1 July to 22 July 2022), fruit expansion stage (Stage III: 14 July to 25 August 2021; 23 July to 4 September 2022) and fruit ripening stage (Stage IV: 26 August to 22 September 2021; 5 September to 30 September 2022). Here, 15 d after planting (DAP = 15 d) is the slow seedling stage of tomato, and no test treatment is performed. Subsequently, when the average *SMC* drops to 70% (±5%) of the *FWC*, the irrigation amount is calculated using the following formula, and irrigation is performed through the drip irrigation system. Herein, 20,000 $kg·ha^{-1}$ organic fertilizer was applied in the experimental area every year. Other field management practices are consistent with local practices.

$$I = 1000 \times (\theta_1 - \theta_2) \times \rho \times h/\eta \quad (2)$$

where I is the irrigation water quota (mm), θ_1 and θ_2 are the upper and lower limits of irrigation, with values of 90% and 70% of the *FWC*, respectively. In this paper, h is the depth of the planned wet layer, which is 0.6 m. ρ is the wetting ratio of drip irrigation, which is 0.9 in this paper. η is the utilization coefficient of drip irrigation water, which is 0.9 (Friedman., 2024).

2.4. Measurement indices and methods

2.4.1. Soil BD, TP and aggregate

At the end of Stage I, Stage II, Stage III and Stage IV, soil samples were collected from the 0–30 cm soil layer on the ridge. Soil *BD* was measured using the ring knife method, and *TP* was calculated. Soil water stability aggregates were determined using a soil aggregate analyzer (XDB0601, Beijing New Landmark Soil Equipment Co., Ltd., China). Soil particles with a particle size greater than 2 mm were called large aggregates, those with a particle size between 0.25 and 2 mm were called small aggregates, and those with a diameter less than 0.25 mm were called micro-aggregates. The stability of the aggregates with $R > 0.25$ and the *MWD* (Li et al., 2024b).

$$MWD = \sum_{i=1}^{n} \overline{x_i} w_i \quad (3)$$

where $\overline{x_i}$ is the average diameter of soil of each grain grade (mm) and w_i is the mass percentage of soil of each grain grade (%).

2.4.2. Soil water characteristic curve, water constant and SMC

At the end of the growth period in 2022, a soil-water test system (Hyprop 2, METER, Germany) and dew-point water potential meter (WP4C, METER, Germany) were used to determine the soil water characteristic curve of the 0–30 cm soil layer, each treatment was tested for 3 repetitions. The Hyprop 2 soil-water test system measures soil suction in the range of −100–0 KPa. The soil water characteristic curve with soil suction less than −100 KPa was measured using the WP4C dew-point water potential meter. It was fitted with RETC software. According to the fitting results, the soil water contents when the soil suction values were 0, 33 and 1500 KPa were soil saturated water content, *FWC* and *WP*. The difference between the soil saturated water content and *FWC* is *GWC*. The difference between the *FWC* and *WP* is the *SAWC*. Before the experiment, a TRIME tube was buried 15 cm radially away from tomato plants. *SMC* was measured every 7 days using a time domain reflectometer (TRIME-PICO-IPH, IMKO, Germany), and additional measurements were conducted before irrigation and one day after irrigation. The *SMC* measured using time domain reflectometer was calibrated regularly using the drying method during the test.

2.4.3. Root morphology

Three representative tomato plants were selected at the each growth stage, and root samples were taken 15 cm from the plants using a root drill with a diameter of 5 cm. The sampling depth was 30 cm, and the sampling interval was 10 cm. After sampling, the root samples were washed with a sieve with a pore diameter of 0.5 mm, and root scanning was performed using a scanner (Epson V700, Epson Co., Ltd., China). Root analysis software (WinRHIZO version 5.0) was used for analysis, and the *FRLD* (diameter less than 2 mm), *RSAD*, *RVD*, *RD* and *RDM* of tomato in each soil layer were calculated.

2.4.4. Tomato yield, ET, WUE

After leaving four ears of fruit for each tomato plant, the ripe tomato of the whole experimental plot were picked every 7 days after the first ear was ripe. The fresh fruit weight was measured using an electronic balance with an accuracy of 0.05 kg and recorded. The total yield ($t \cdot ha^{-1}$) of tomato was obtained by summing the recorded data after all fruits were picked. At the same time, the number of fruits per plant of each treatment was recorded at Stage IV, and the weight per fruit was calculated using the ratio of the yield per plant to the number of fruits per plant. The *ET* (mm) is calculated based on the water balance equation. Simplified, it is the irrigation water amount plus the soil moisture storage at planting minus the soil moisture storage at harvest. The *WUE* is the ratio of tomato yield to *ET*.

2.4.5. Coupling coordination degree model

The coupling coordination degree model was used to evaluate the coordinated development level of soil structure ($R > 0.25$, *MWD*, *BD* and *TP*), hydraulic characteristics (*GWC*, *FWC*, *WP*, *SAWC* and *SMC*) and tomato root growth (*FRLD*, *RSAD*, *RVD, RD* and *RDM*) systems of the biochar addition layer.

First, the comprehensive evaluation indices of soil structure, hydraulic characteristics and tomato root growth system were calculated.

$$f(y) = \sum_{j=1}^{4} \alpha_{1j} y_{1j} \quad (4)$$

$$g(y) = \sum_{j=1}^{5} \beta_{2j} y_{2j} \quad (5)$$

$$h(y) = \sum_{j=1}^{5} \gamma_{3j} y_{3j} \quad (6)$$

where $f(y)$ is the comprehensive evaluation index of the soil structure system, α_{1j} is the weight of each index of the system and y_{1j} is the normalized value of the *j* index of the system. $g(y)$ is the comprehensive evaluation index of the hydraulic characteristics system, β_{2j} is the weight of each index of the system and y_{2j} is the normalized value of the *j* index of the system. $h(y)$ is the comprehensive evaluation index of the root growth system, γ_{3j} is the weight of each index of the system and y_{3j} is the normalized value of the *j* index of the system.

Second, the *C* and *T* of the soil–water–root system are calculated:

$$C = 3 \times \frac{(f(y) \times g(y) \times h(y))^{1/3}}{f(y) + g(y) + h(y)} \quad (7)$$

$$T = af(y) + bg(y) + ch(y) \quad (8)$$

where *a*, *b* and *c* are the weights of the soil structure system, hydraulic characteristics system and root growth system, respectively. This study considers that the three systems have equally essential roles. Therefore, 1/3 is used for *a*, *b* and *c*.

Finally, the D of the soil–water–root system is calculated:

$$D = \sqrt{C \times T} \quad (9)$$

When $0 < D \leq 0.3$, it is the low coordinated coupling level. When $0.3 < D \leq 0.5$, it is the moderate coordinated coupling level. When $0.5 < D \leq 0.8$, it is a highly coordinated coupling level. When $0.8 < D \leq 1$, it is the extremely coordinated coupling level (Gao et al., 2023).

2.5. Statistical analysis

IBM SPSS Statistics 26 was used for two-factor analysis of variance, and Duncan's method was used for significance analysis at $P < 0.05$ level. With variance expansion factor greater than 3 as the standard, the collinearity diagnosis of each index of the soil–water–root system was performed. The structural equation model was constructed using IBM SPSS AMOS 26.

3. Results

3.1. Effects of biochar on soil physical structure

3.1.1. Soil aggregates

With an increase in biochar application days, soil micro-aggregates gradually transformed into small aggregates and large aggregates (Fig. 2a). Compared with Stage I, the average value of the micro-aggregates decreased by 26.3%–31.2% at Stage IV, and the average values of the small aggregates and large aggregates increased by 2.5%–21.7% and 32.8%–50.4%, respectively. No significant difference in soil aggregate content among different treatments at Stage I and Stage II were observed in 2021 ($P > 0.05$). From the beginning of Stage III in 2021 (93 d after the application of biochar), the addition of biochar reduced the proportion of soil micro-aggregates by 1.7%–21.1%. The proportion of small aggregates and large aggregates increased by 0.9%–19.2% and 0.9%–50.3%, respectively. With an increase in biochar addition, the proportion of small aggregates and large aggregates increased gradually, and the proportion of micro-aggregates was opposite.

Compared with the Stage I, $R > 0.25$ and *MWD* at Stage IV (Fig. 2a–b) increased by 8.5%–31.3% and 9.6%–41.4%, respectively. In the same growth stage, $R > 0.25$ and *MWD* in 2022 increased by 12.1%–35.1% and 5.8%–42.3%, respectively, compared with those in 2021. Results showed that the stability of the soil aggregates increased with an increase in biochar application days. No significant difference in the values of $R > 0.25$ and *MWD* at each biochar application level at Stage I and Stage II was observed in 2021, and the values of $R > 0.25$ and *MWD* at other growth stages in 2021 and the whole growth stage in 2022 showed an increasing trend with an increase in biochar application level. T4, T3, T2 and T1 increased $R > 0.25$ by 18.1%–22.8%, 16.3%–21.4%, 10.5%–13.5% and 1.4%–3.01% compared with T0, respectively. The *MWD* was increased by 21.6%–34.5%, 19.4%–32.8%, 14.1%–21.1% and 1.2%–3.7%, respectively.

3.1.2. Soil BD and TP

With an increase in biochar application days, soil *BD* gradually increased (Fig. 3a–b), and the average soil *BD* at Stage IV was 5.3% higher than that at Stage I. The average soil *TP* at Stage II, Stage III and Stage IV decreased by 2.0%, 2.6% and 4.9% compared with that at Stage I, respectively (Fig. 3c–d). Soil *BD* in the second year of biochar application was significantly lower than that in the first year, with an average decrease of 3.8%. Compared with no biochar addition (T0), the average soil *BD* of T4, T3, T2 and T1 biochar addition decreased by 12.5%, 8.9%, 6.2% and 3.6%, respectively. The average soil *TP* increased by 11.6%, 8.5%, 6.1% and 3.6%, respectively, indicating that compared with no biochar addition, the addition of biochar makes the soil more porous and increases soil aeration.

3.2. Effects of biochar on soil hydraulic characteristics

Fig. 4a shows the change law of the soil water characteristic curve under various biochar additions in the 0–30 cm soil layer at the end of growth period in 2022. The determination coefficients (R^2) of the soil

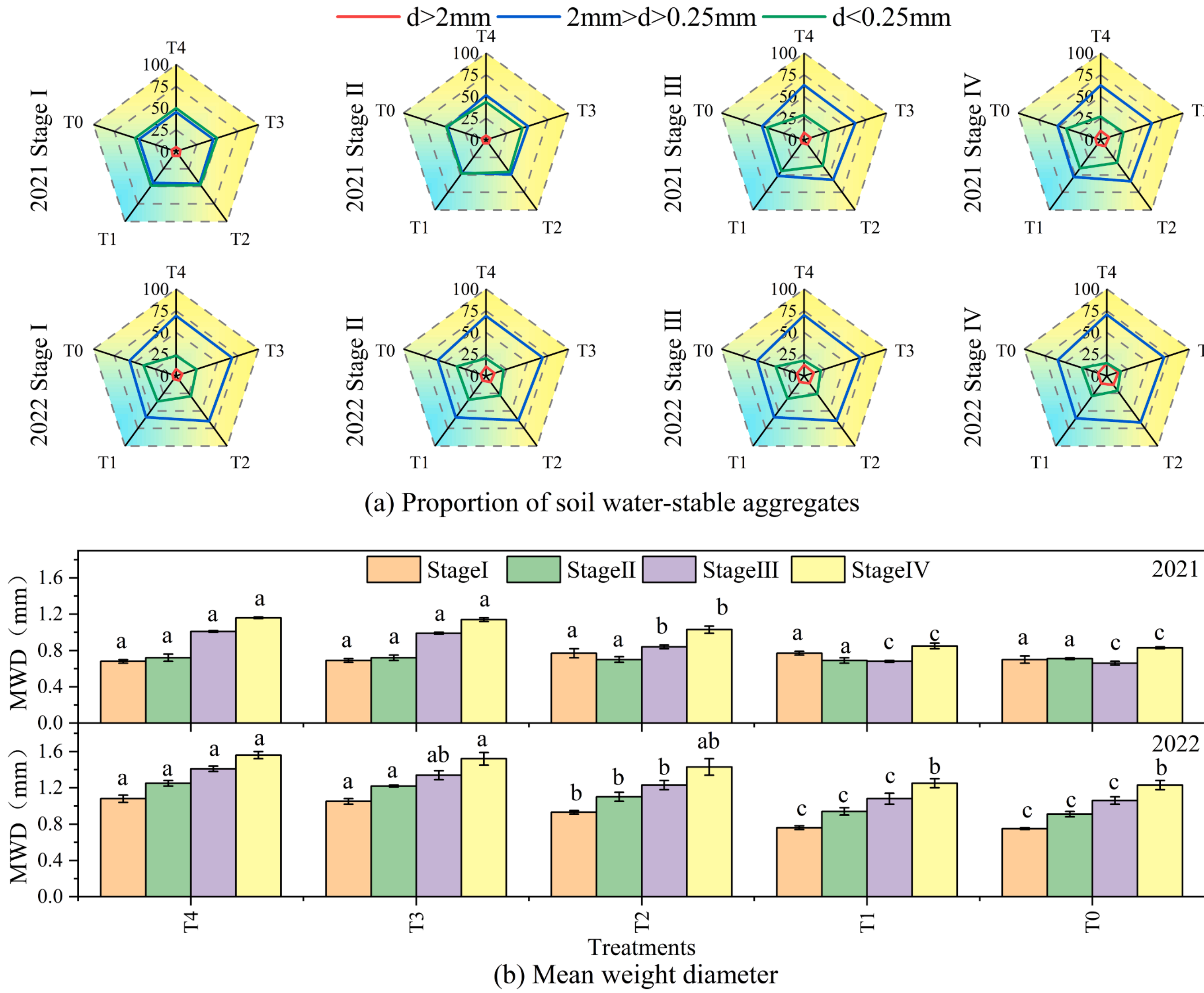

Fig. 2. Effects of biochar on the proportion of soil water stable aggregates (a) and the *MWD* of soil (b). Different lowercase letters in the figure indicate significant differences in *MWD* between different treatments in the same growth period (P < 0.05), and the same lowercase letters indicate no significant differences between treatments (P > 0.05).

water characteristic curve fitted by the Van Genuchten (V-G) model are all above 0.96, which indicates that the V-G model can simulate the soil water characteristic curve well under the test condition. In the low-suction stage (the value of soil water potential $PF < 2.52$, and the *SMC* is higher than the *FWC*), the *SMC* of each biochar addition amount under the same suction is T4, T3, T0, T1 and T2 in descending order. In the medium-suction stage ($2.52 < PF < 4.18$, *SMC* ranged from the *WP* to the *FWC*), the *SMC* of each biochar addition was T3, T4, T1, T2 and T0 in descending order, and there was no significant difference between T3 and T4 and between T1 and T2, indicating that the addition of biochar at this suction stage could increase *SMC*. In the high-suction stage ($PF > 4.18$, *SMC* less than the *WP*), compared with T0, the difference in *SMC* among other biochar addition amounts was not significant, except that T2 treatment reduced *SMC* slightly.

The soil *FWC*, *WP*, *GWC* and *SAWC* of each treatment were calculated using the fitted soil water characteristic curve, and results are shown in Fig. 4b–e. The soil *FWC* of T4, T3, T2 and T1 was 24.5%, 28.1%, 9.0% and 7.7% higher than that of T0, respectively. Except that the soil *WP* of T2 addition was 35.3% lower than that of T0, the soil *WP* of other biochar addition was increased compared with that of T0, but the soil *WP* was not significantly different among different biochar addition amounts. The addition of biochar reduced the soil *GWC* by 17.1%–80.1% compared with T0 and increased the *SAWC* by 6.9%–35.7%. The *SAWC* showed an increasing trend with an increase in the amount of biochar.

The application of biochar in soil can change the soil water status in tomato root zones by improving the soil physical structure and water retention. Fig. 5 shows the effect of biochar on the average *SMC* of the 0–30 cm soil layer in each growth stage of tomato. As shown in the figure, the average *SMC* shows an increasing trend with an increase in the amount of biochar added. The addition of 60, 45, 30 and 15 $t \cdot ha^{-1}$ biochar increased the average *SMC* of the 0–30 cm soil layer by 12.7%–26.4%, 8.3%–19.5%, 4.9%–13.3% and 1.7%–7.8%, respectively.

3.3. Effects of biochar on tomato root growth

Fig. 6 shows the effects of biochar on the root growth indexes in the 0–30 cm soil layer of facility tomato in 2021 (a–d) and 2022 (e–h). The *FRLD*, *RSAD*, *RVD* and *RDM* of tomato all increased first and then decreased with the advancement of the growth period. The average value of each treatment reached the maximum at Stage III (the *FRLD* at Stage II was slightly higher than that at Stage III in 2021), and the *FRLD*,

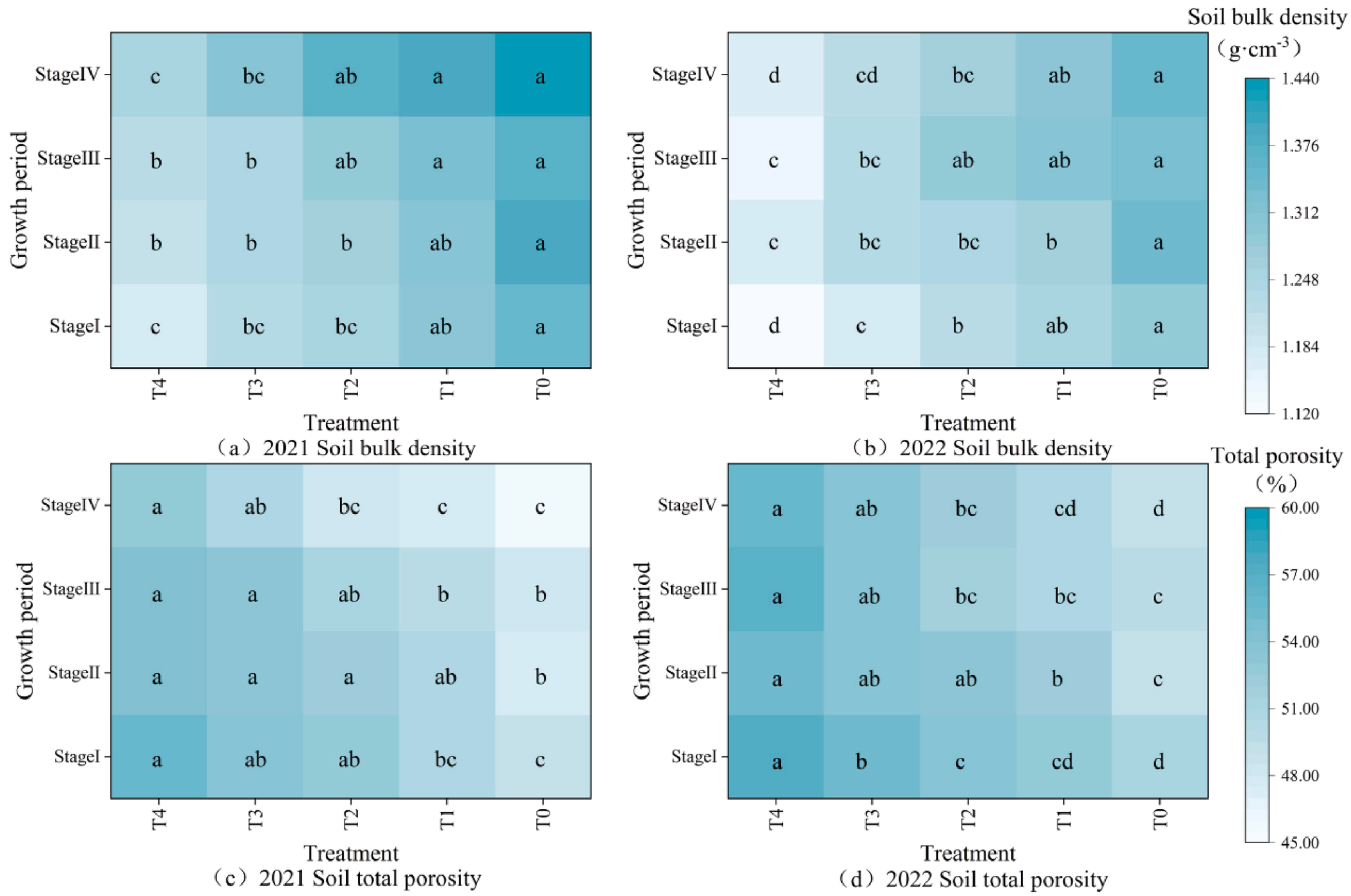

Fig. 3. Effects of biochar on soil bulk density and porosity.

RSAD, *RVD* and *RDM* at Stage III were 25.7%–32.9%, 46.7%–54.3%, 38.1%–56.6% and 52.3%–63.2% higher than that at Stage I (minimum value), respectively. At Stage I and Stage II in 2021, the *FRLD*, *RSAD* and *RVD* of tomato increased first and then decreased with an increase in biochar addition. In other growth periods in 2021 and the whole growth stage in 2022, all of them showed an increasing trend with an increase in biochar addition, and the addition of biochar increased the *FRLD*, *RSAD* and *RVD* by 21.4%–63.3%, 38.2%–76.3% and 36.0%–75.4%, respectively, compared with no biochar addition. Except for the fact that there was no significant difference in *RDM* among the treatments at Stage I in 2021, the *RDM* of tomato all other growth stages showed an increasing trend with an increase in biochar addition. The addition of biochar increased the *RDM* by 18.1%-73.4% compared with no biochar addition. With the advancement of the growth stage, the *RD* gradually became thicker, and the average *RD* of tomato root at Stage IV in 2021 and 2022 increased by 54.2% and 29.9% compared with Stage I, respectively. The *RD* of T4, T3, T2 and T1 was reduced by 22.9%–48.8%, 20.8%–38.8%, 13.6%–32.8% and 10.0%–22.9% respectively compared with that of T0.

3.4. The D of soil–water–root compound system

The effects of biochar addition in 2021 and 2022 on the *D* of the soil–water–root compound system of tomato at each growth stage are shown in Fig. 7. As the application days of biochar increased, the *D* values of each treatment gradually stabilized. In Stages I and II in 2021, the *D* values of T2 and T3 were the highest, reaching an extremely coupled level. However, the *D* values of T0 were the lowest at 0.39 and 0.42 respectively, indicating a moderately coupled level. The *D* value shows an increasing trend with the increase of the addition amount of biochar in other growth periods in 2021 and the whole growth stage in 2022. The average coupling coordination degrees of different growth stages in 2021 and 2022 were both shown as T4 > T3 > T2 > T1 > T0. Among which the *D* values of T4 and T3 were between 0.81–0.87, reaching an extremely coordinated coupling level. T2 and T1 were at a highly coordinated coupling level, and T0 had the smallest *D* value, ranging from 0.12 to 0.21, and was at a low coordinated coupling level. In addition, compared with no biochar addition, adding biochar increased the *D* value by 25.7%-85.5% and 64.5%-86.0% respectively in 2021 and 2022. This indicates that adding biochar is conducive to the coordinated development of the soil–water–root compound system.

3.5. Effects of biochar on tomato yield components and WUE

The effects of biochar on the weight per fruit and yield reached extremely significant levels ($P < 0.001$). No significant effect on the number of fruits per plant was observed ($P > 0.05$), indicating that the yield difference between different treatments was mainly caused by weight per fruit (Fig. 8). Compared with T0, the addition of biochar increased tomato yield, *ET* and *WUE* by 28.8%–33.3%, 1.9%–11.0% and 21.4%–29.6%, respectively. The yield and *WUE* increased first and then decreased with an increase in biochar addition, both reached the maximum under T2. In addition, the yield of tomato treated with biochar in 2022 was 0.9%–3.9% higher than that in 2021, and the yield of tomato treated with T0 in 2022 was 1.7% lower than that in 2021.

3.6. Comprehensive evaluation results of the CRITIC-TOPSIS

The CRITIC weighting method was employed to determine the weights of soil structure (*R* > *0.25*, *MWD*, *BD* and *TP*), hydraulic characteristics (*GWC, FWC, WP, SAWC and SMC*), tomato root growth (*FRLD, RSAD, RVD, RD and RDM*), yield and *WUE*. Subsequently, the TOPSIS method was applied to comprehensively evaluate these

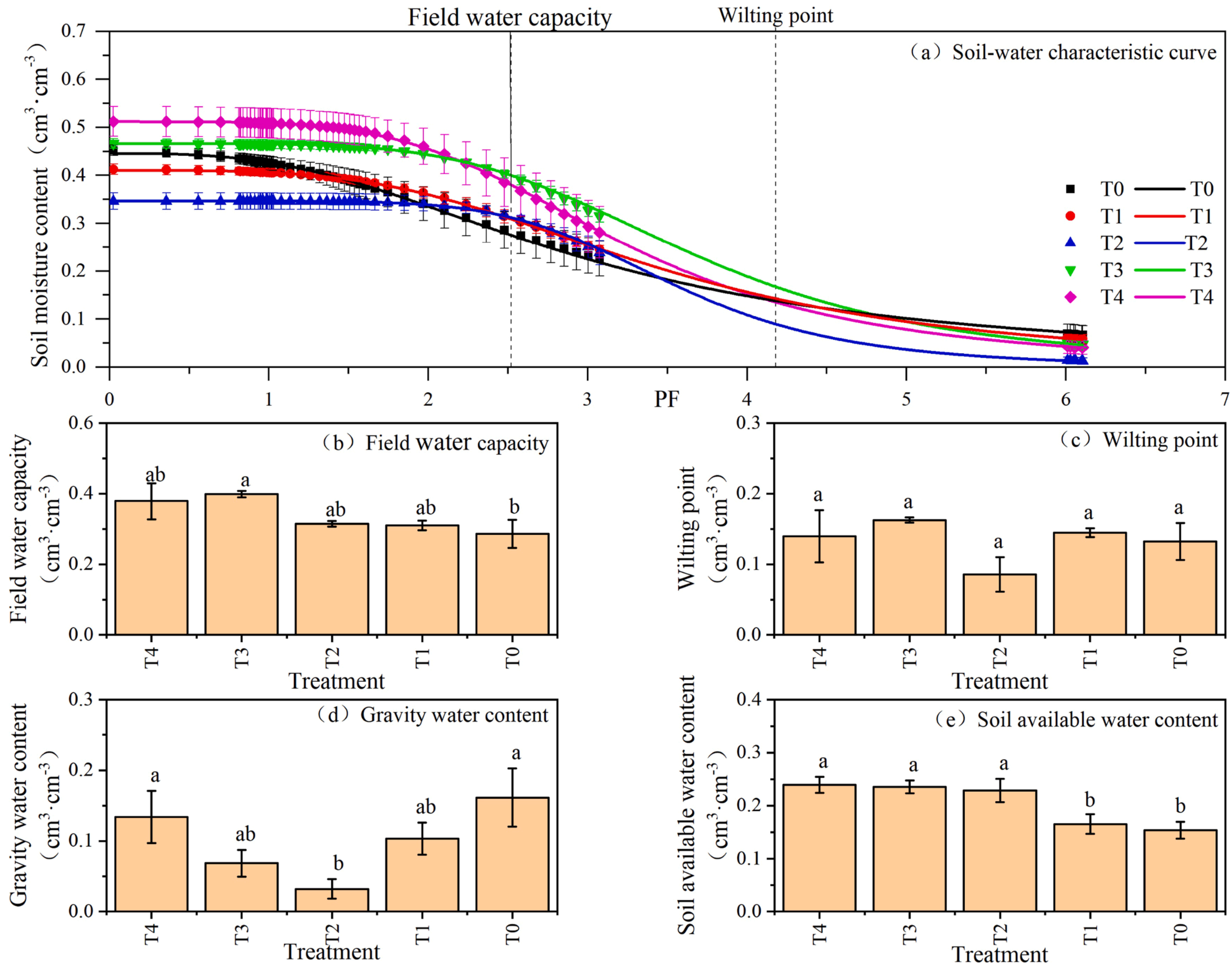

Fig. 4. Effect of biochar on soil water retention.

indicators and identify the optimal biochar application rate for facility tomato (Table 2). The results showed that the comprehensive evaluation value initially increased and then decreased with an increase in biochar addition. T2 achieved the highest values in 2021 and 2022, followed by T3, the lowest value was achieved by T0. These findings indicate that 30 $t{\cdot}ha^{-1}$ represents the optimal biochar application rate for integrated enhancement of soil structure, hydraulic properties, root growth, yield and *WUE*.

3.7. Relationship between tomato yield and soil–water–root system

Correlation analysis of soil structure, hydraulic characteristics, root growth and tomato yield (Fig. 9a) showed that tomato yield was significantly positively correlated with *R > 0.25*, *TP*, *FWC*, *SAWC*, *SWC*, *FRLD*, *RSAD*, *RVD* and *RDM* ($P < 0.05$). It was negatively correlated with *BD*, *GWC* and *RD* ($P < 0.05$). Soil aggregate stability (*R > 0.25*, *MWD*) was significantly positively correlated with *FRLD*, *RSAD*, *RD*, *RVD* and *RDM* ($P < 0.05$), indicating that the growth and development of tomato roots could promote the enhancement of soil aggregate stability. In addition, *SAWC* was positively correlated with *R > 0.25*, *MWD* and *TP* ($P < 0.05$), indicating that the improvement of soil aggregate stability and porosity contributed to the increase in *SAWC*.

On this basis, the collinearity diagnosis of soil physical structure, hydraulic characteristics and tomato root growth indexes was performed, and the structural equation model was constructed (Fig. 9b). The results showed that the model fit well ($\chi^2/df = 0.56$, P $= 0.83$, GFI $= 0.99$, NFI $= 0.99$). The yield of tomato was mainly affected by the *D* of soil–water–root system ($r = 0.989$, $P < 0.01$). Biochar mainly affects the *D* value through *SAWC* (the indirect path coefficient is 0.489), followed by the *RD* and *RDM* (the indirect path coefficients are 0.198 and 0.125 respectively). However, the influence of *TP* on *D* is not significant. In addition, biochar had a negative effect on *RD* ($r = -0.512$) and *RD* on *D* value ($r = -0.386$). In conclusion, biochar mainly affects the *D* of the soil–water–root system by improving the *SAWC* and root growth indicators, and thereby indirectly influences tomato yield.

4. Discussion

4.1. Changes in soil–water–root system processes driven by biochar

This study shows that the differences in soil aggregate content and stability among different amounts of biochar gradually become apparent as the biochar is applied to the soil over time. Previous studies have also found that approximately 60 days after the application of amendments, compared with the control group, the content of large aggregates and *MWD* treated with amendments begin to increase significantly (He et al., 2019). The reason is that primary minerals form secondary clay minerals after weathering. It forms micro-aggregates under the cementation of organic colloid and mineral colloid, the condensation of cations and the adsorption of microorganisms, and then combines to form large

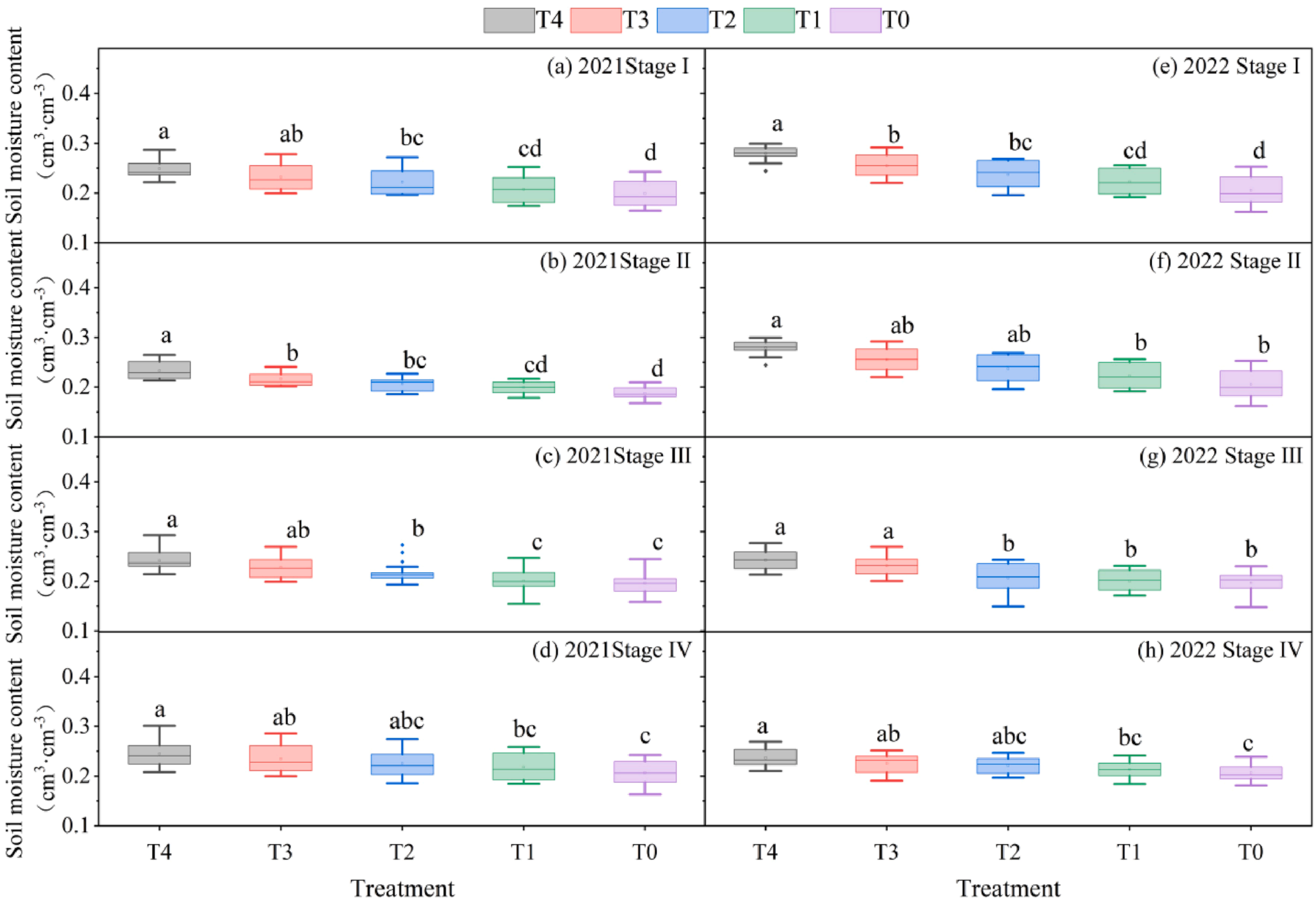

Fig. 5. Effect of biochar on soil moisture content.

aggregates under biological actions (Liu et al., 2023). Owing to the different generation and bonding processes of different cementing materials, and the formation mechanisms of aggregates with different particle sizes are also different. The mechanism of biochar's promotion to the stability of soil aggregates may include: (1) biochar has the characteristics of large specific surface area, rich functional groups and high cation exchange capacity, which can adsorb mineral particles and form soil aggregates with them (Gul et al., 2015). (2) the high carbon content and porosity of biochar provide a favorable habitat for the survival of microorganisms, promoting their growth and decomposition, and thereby generating more organic matter, which is conducive to the formation and stability of soil aggregates(Peng et al., 2013; Situa et al., 2022).

The soil equivalent pore size under different biochar treatments was calculated based on the soil water characteristic curve (Figure S1). With the increase in the amount of biochar added, the storage pore showed an increasing trend, indicating that adding biochar can increase the *SAWC* by increasing the storage pore. While adding biochar reduced the crack pore and transmission pore in the soil, and had no significant effect on the residual pore of the soil. In addition, this study concluded that *SAWC* was significantly positively correlated with $R> 0.25$, *MWD* and *TP*, but negatively correlated with *BD*. The application of biochar in soil increased the proportion of small aggregates, large aggregates, aggregate stability and *TP* and reduced soil *BD*. As a result, water in soil changes in terms of permeability, residence time and movement path, which improves the water retention ability of biochar soil layer (Chen et al., 2010). Ultimately, compared with that without biochar, the application of biochar can increase *SMC* by 1.7%-26.4%. Previous studies have shown that biochar affects soil water-holding capacity mainly through its porous characteristics and huge surface area in the early application stage, and the hydrophilicity of biochar plays an essential role in the later application stage (Suliman et al., 2017).

The response of crop roots to biochar is related to the time after the application of biochar. After biochar is applied to soil, nutrients from organic fertilizer become tightly adsorbed to its surface. This makes it difficult for young roots to absorb and utilize these nutrients during the early growth stage. As a result, root growth is inhibited (Ghezzehei et al., 2014; Ghorbani and Amirahmadi, 2024). However, starting from the Stage III in 2021, the addition of biochar made tomato roots thinner and longer. Olmo et al. (2016) found that the addition of biochar in soil increased the specific root length of wheat and reduced the *RD* and mass density of root tissue, which was conducive to the interaction between biochar and roots and promoted the absorption and utilization of soil nutrients by crops. These findings are consistent with the results of this study.

4.2. The evolution and regulatory mechanism of the D of the soil–water–root system

The stability of the *D* of the soil–water–root system gradually increases as the time of applying biochar to the soil. The main reasons are as follows: (1) the stability of soil aggregates was relatively weak at the beginning of the application of biochar to the soil. The results of this study showed that at the end of Stage I in 2021, the differences in aggregate content of each grain grade under different treatments were small, but from the end of Stage II in 2021, the differences in aggregate content of each grain grade under different treatments gradually appeared. In addition, it was found that after Stage II in 2021, the stability of soil aggregates was gradually enhanced with an increase in biochar addition. (2) the excessive biochar addition at Stage I and Stage

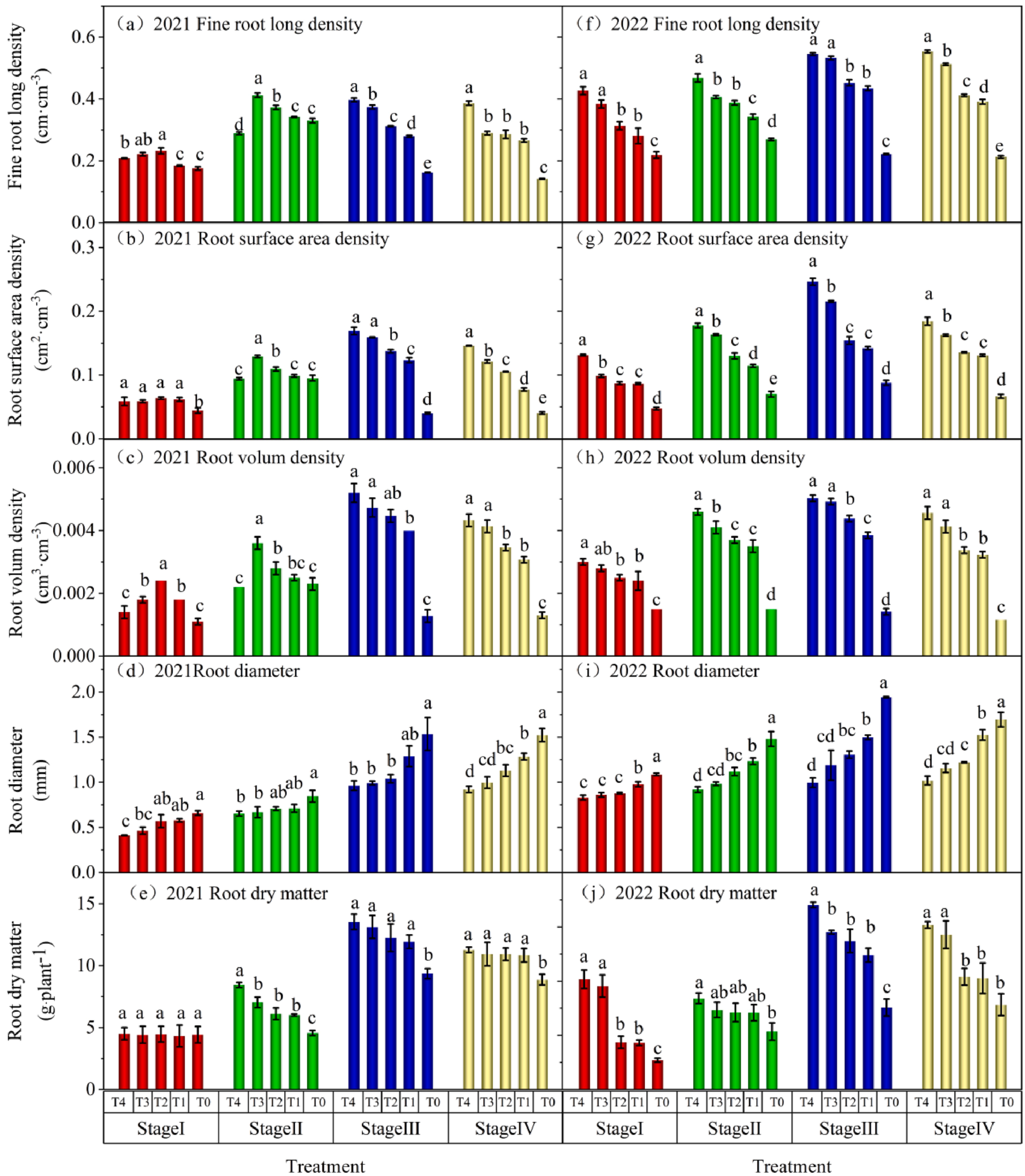

Fig. 6. Effect of biochar on root growth of facility tomato.

II had a certain inhibitory effect on tomato root growth in 2021. It may be due to the strong adsorption effect of biochar.

External factors affecting crop root growth mainly include soil mechanical resistance, aeration, water and nutrient status (Bengough et al., 2011). This study showed that the application of biochar reduced soil *BD* and increased *TP*, which would reduced the mechanical resistance of root growth. Compared with no addition of biochar, the addition of biochar can also improve the water-holding capacity of soil and increase the *SMC* in the main root zone (0–30 cm). Therefore, the addition of biochar creates a good soil environment for the growth of crop roots and makes the roots become thinner and longer, thus promoting the absorption and transport of nutrients by crops (Li et al., 2024a). Meanwhile, this study indicates that there is a significant positive correlation between root growth indicators (*FRLD*, *RSAD*, *RD*, *RVD* and *RDM*) and

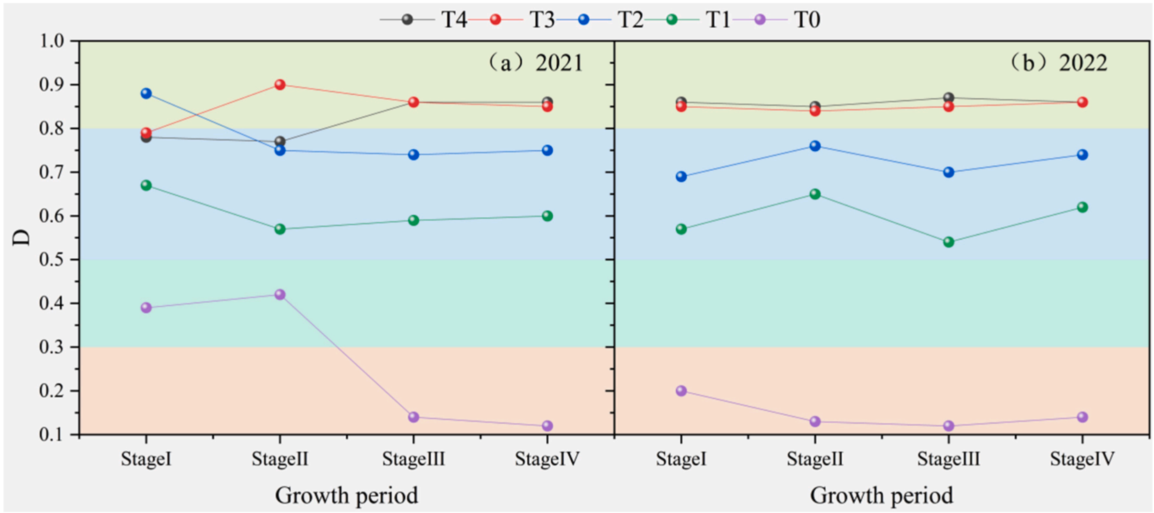

Fig. 7. Coupling coordination degree of the soil–water–root compound system under different treatments.

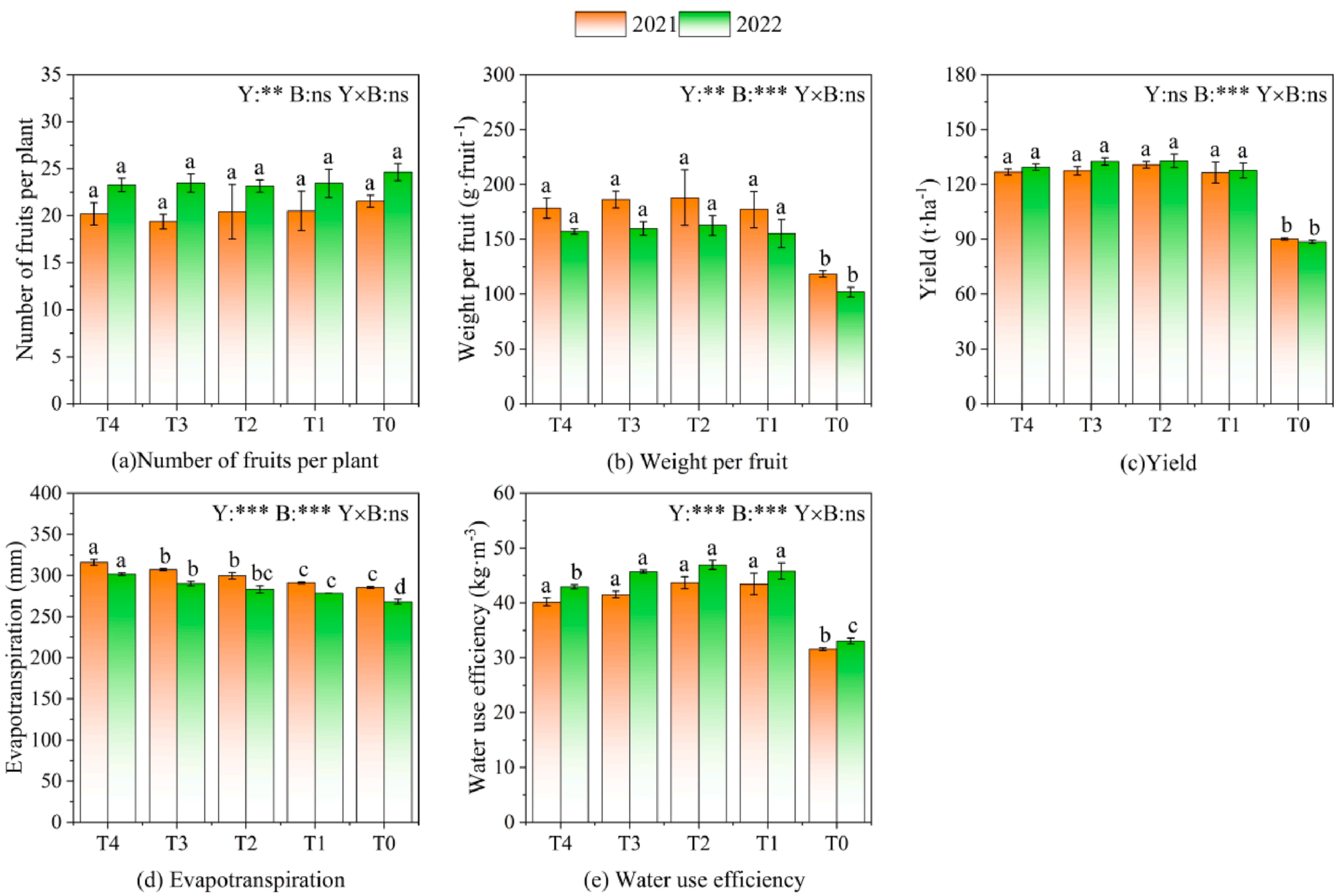

Fig. 8. Tomato yield components, evapotranspiration and water use efficiency under different treatments. Note: Y represents planting year, B represents biochar addition amount and Y×B represents the interaction between planting year and biochar addition amount. '*', '**' and '***' indicate that significance was reached at P < 0.05, P < 0.01 and P < 0.001, respectively.

aggregate stability indicators (*R* > *0.25*, *MWD*). The reason is that the continuous tangle of roots in the soil and the increase in root exudates can produce a large amount of cementing material, which is conducive to the formation of soil aggregates (Xiao et al., 2024). As a result, the *D* of the soil–water–root compound system in the later stage tends to increase with an increase in biochar addition amount. In this study, equal weights were assigned to the soil–water–root subsystems when constructing the coupling coordination degree model. The reason for this is that, with the exception of a few indicators (*MWD* and *WP*), tomato yield showed a strong correlation with all indicators across the soil-water-root subsystems (Fig. 9). Furthermore, our approach aims to achieve synergy and balance among soil–water–root. Soil structure and moisture should align with root growth, while roots in turn improve soil structure and water-holding capacity. To avoid overemphasizing any

Table 2
Comprehensive evaluation results based on CRITIC-TOPSIS.

—	2021		2022	
	Evaluation value	Ranking	Evaluation value	Ranking
T4	0.87	3	0.88	3
T3	0.89	2	0.94	2
T2	0.91	1	0.95	1
T1	0.86	4	0.86	4
T0	0.04	5	0.04	5

single parameter when constructing the coupling coordination degree model, we adopted an equal-weighting approach.

4.3. The relationship between the D of the soil-water root system and tomato yield

The improvement in the *D* of the soil–water–root system indicates an enhanced interaction among the three components, as well as a coordinated optimization and a virtuous cycle. The soil–water–root compound system is an essential link between biochar and crop yield. This study found that soil hydraulic characteristics had no direct influence on tomato yield, the single factor of soil physical structure and root growth index had little influence on tomato yield, and tomato yield was mainly affected by the *D* of the soil–water–root system coupling. Biochar affects the *D* of the soil–water–root system mainly by affecting *SAWC*. On the basis of the structural equation model, Zhang et al. (2020) showed that biochar can be used as an effective soil amendment, which is conducive to improving soil structure and promoting high yield and efficient utilization of nutrients in rice–wheat rotation system. It has also been found that compared with no biochar addition, the application of biochar in soil can increase the *FWC*, the volume of micropores and roots, and ultimately increase the thousand-grain weight of quinoa (Daraei et al., 2024). The addition of biochar increased the content of macro-aggregates larger than 5 mm in diameter, the stability of the aggregates, the water retention capacity of soil and the yield of the first season crop (rice) by 6.3%–13.3%. The influence of biochar on the crop yield of the second (rape) and third (maize) mainly depended on the type and amount of biochar (Yang and Lu, 2021).

Herein, it was found that tomato yield increased first and then decreased with an increase in biochar addition, and reached the highest value under T2, which was similar to the results of Guo et al. (2021). On one hand, the excessive addition of biochar resulted in soil water and nutrient levels exceeding the threshold value that could be absorbed by crops, resulting in excessive nutrient growth in the early stage of crop growth, reproductive growth decreased in the late growth period (Li et al., 2023c). On the other hand, excessive biochar may lead to nutrient fixation, which reduces nutrient accumulation in plants and weakens tomato photosynthesis, thus reducing tomato yield (Wang et al., 2021). The tomato yield of the T2-T4 in 2022 was higher than that in 2021, with an increase of 0.9%–3.9%. The yield of tomato treated without biochar in 2022 is lower than that in 2021, which may be caused by the different meteorological conditions in the two years and the time effect after biochar application (Rong et al., 2023). However, the two-year meteorological data showed that, except that the atmospheric temperature and ET_0 at Stage II in 2021 were higher than those in 2022 and the relative humidity was lower than that in 2022, the two-year meteorological conditions in other growth stages had little difference. Therefore, it could be inferred that the second year of biochar addition had a more significant promoting effect on tomato yield. This study shows that the addition of biochar can increase the *ET* of tomato, the reason for this is that the addition of biochar raises the *SMC*, thereby increasing the amount of water that the tomato roots can absorb. In addition, this study also indicates that the *D* of the soil–water–root system and the total dry matter show an increasing trend with the increase in the amount of biochar added. However, the tomato yield does not follow this pattern. The reason for this is that an excessively high amount of biochar reduces the harvest index of tomato, but has no significant effect on the root-shoot ratio of tomato (Table S1). This study only constructed the coupling coordination degree among some indicators of the soil–water–root system. In future research, indicators such as soil chemistry, biological characteristics, root vitality, as well as analysis of the canopy system (growth and physiological indicators) can be considered to explore the mechanism of their effects on tomato yield.

5. Conclusions

Our results revealed that the addition of biochar enhanced the stability of soil aggregates, maked the soil more loose and increased the proportion of storage pores in the soil. Consequently, *FWC* and *SAWC* increased by 7.7%–28.1% and 6.9%–35.7%, respectively. At Stage I and Stage II in 2021, the *D* value of the soil–water–root system first increased and then decreased with an increase in biochar addition, and then, it gradually increased. T4 and T3 were at an extremely coordinated coupling level, T2 and T1 were at a highly coordinated coupling level and T0 was at a low coordinated coupling level. The yield of the T2 was the highest, increasing by 28.9%–31.6% compared to T0. Based on the CRITIC–TOPSIS comprehensive evaluation, the optimal biochar application rate under the experimental conditions was determined to be 30 t·ha^{-1} (T2). The structural equation model further revealed that tomato

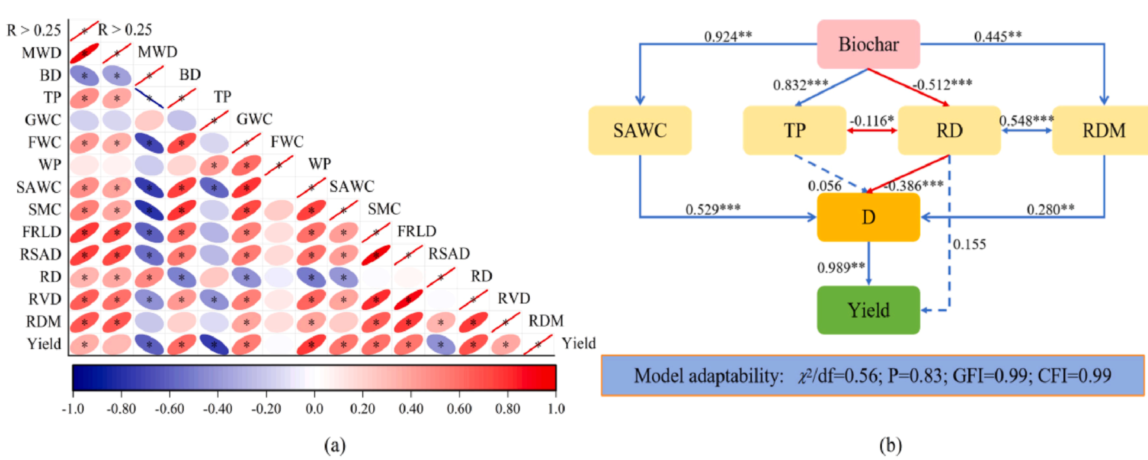

Fig. 9. Correlation analysis and structural equation model between tomato yield and soil–water–root system. The blue line represents the positive influence relationship, and the red line represents the negative influence relationship; the solid line indicates that the relationship is significant, and the dashed line indicates the opposite. '*', '**' and '***', respectively, $P < 0.05$, $P < 0.01$ and $P < 0.001$ level, the impact or correlation is significant.

yield is mainly affected by the *D* value, while biochar mainly regulated the *D* value indirectly by increased *SAWC*. In addition, the *D* value of the soil-water root system was not in a linear relationship with the tomato yield. This is mainly due to the fact that excessive biochar addition reduced the tomato harvest index. The conclusions of this study were limited by specific experimental conditions. In the future, long-term field experiments can be conducted under various conditions to comprehensively study the interaction between soil–roots–canopy, and calculate its overall economic benefits over the years, thereby making the research results more applicable.

CRediT authorship contribution statement

Lijian Zheng: Writing – review & editing, Funding acquisition. **Juanjuan Ma:** Writing – review & editing, Project administration, Funding acquisition. **Xufeng Li:** Writing – original draft, Investigation, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2026.110354.

Data availability

The authors do not have permission to share data.

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