

Micro-nano aerated subsurface drip irrigation and biochar promote photosynthesis, dry matter accumulation and yield of cucumbers in greenhouse

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ABSTRACT

The combination of micro-nano bubble water (MNBW) with subsurface drip irrigation (SDI) is an effective and water-saving aerated irrigation technique. Biochar is a biomass resource with high porosity, alkalinity, and specific surface area. The effects of SDI with MNBW and biochar on crop photosynthetic characteristics, dry matter accumulation, and red soil (clay) aeration are not well understood. Three levels concentrations of dissolved oxygen (DO) in MNBW: O1 (4–5 mg/L), O2 (9–10 mg/L), and O3 (14–15 mg/L), as well as three levels amount of biochar application (BA): B1 (20 t/hm²), B2 (40 t/hm²), and B3 (60 t/hm²), and one control group (CK, O: 4–5 mg/L, B: 0 t/hm²) were the subjects of this study, followed by a two-factor randomized block design. The study examined the aeration practices of the red soil (clay) and the responses of greenhouse-grown cucumbers to SDI over the first and second growing seasons. The concentration of DO in MNBW and the amount of BA had a substantial impact on yield, dry matter accumulation, key quality indicators, photosynthetic characteristics, and soil aeration ($P < 0.05$). Compared to CK, in the two-season experiment, the average soil aeration porosity (SAP) increased by 0.53–44.00 %, the soil oxygen content (SO) increased by 0.47–31.80 %, the net photosynthetic rate (Pn) increased by 1.91–50.78 %, the dry matter accumulation increased by 10.53–69.19 %, the yield increased by 1.72–44.23 %, and the water use efficiency (WUE) improved by 0.42–76.57 %. Plant dry weight, cucumber yield, irrigation water use efficiency, vitamin C, and the sugar-acid ratio all have a substantial positive correlation ($P < 0.05$) with the photosynthetic rate. Soil aeration porosity, soil oxygen, photosynthetic rate, plant dry weight, and irrigation water use efficiency all have a substantial positive correlation with yield ($P < 0.05$). Micro-nano bubble water enhanced the oxygen content and soil aeration porosity, while biochar increased the porosity and lowered the bulk density of the soil. The "oxidation-porous" qualities of micro-nano bubble water and biochar combined to enhance clay soil aeration, promote cucumber development, accelerate photosynthetic rate and dry matter buildup, and enhance yield and quality. O3B3 (O3 14–15 mg/L, B3 60 t/hm²) was the optimal treatment when factors like yield and quality were taken into consideration. The research findings provide theoretical basis and feasible approaches for improving the aeration of clay and enhancing the quality and efficiency of greenhouse crops.

1. Introduction

Red soil (clay) is a zonal soil found in the humid subtropical regions of China, primarily distributed in the low mountain and hilly areas south of the Yangtze River in China. Red soil is thick and sticky, clumps easily,

has a moderate acidity, and retains water and nutrients poorly (Zhang et al., 2023). Furthermore, greenhouse growers overapply fertilizers to boost yields due to market demand and financial gains, which causes issues like soil compaction and decreased porosity. The production potential of greenhouse crops was limited because traditional irrigation

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methods such as flooding, furrow irrigation, and drip irrigation inevitably lead to the expulsion of soil air from the root zone (Bhattarai et al., 2015; Silberbush et al., 1979). Additionally, in intensively irrigated or slowly drained wet soils during heavy rainfall, soil O₂ concentration was negatively correlated with irrigation intensity and precipitation (Friedman and Naftaliev, 2012; Silver et al., 2013), which decreased soil aeration (Pendergast et al., 2013; Zang et al., 2018).

Soil aeration has been regarded as one of the main limiting variables of irrigation in crop yield for more than 70 years (Wiersma and Mortland, 1953). Many techniques have been tested to improve soil aeration, including the injection of atmospheric air into the soil via SDI using either a compressor (Abuarab et al., 2013; Bhattarai et al., 2015) or a venturi apparatus (Bhattarai et al., 2013), injection of oxygen releasing chemicals via SDI (Wang et al., 2022a), cyclic aeration drip irrigation (Lei et al., 2016; Wang et al., 2022b), inclusion of surfactants (Cheng et al., 2013). It has been demonstrated that aerated irrigation enhances soil aeration conditions (Ben-Noah and Friedman, 2018; Zhu et al., 2017b) and generates superior crop yield and quality (Ben-Noah and Friedman, 2016; Islam et al., 1998; Niu et al., 2013). Aerated irrigation raises overall quality (Zhu et al., 2017a) and dramatically increases crop output and water use efficiency when compared to non-aerated drip irrigation (Bhattarai et al., 2005; Chen et al., 2018; Du et al., 2018; Pendergast et al., 2019). Although researchers have achieved numerous advancements and enhancements to the Venturi aeration drip irrigation system, the uniform and long-distance transfer of gas continues to be a major problem that impacts the soil aeration effect and the effectiveness of aeration drip irrigation in practice. A novel irrigation technology that has progressively gained traction in recent years is micro-nano aeration irrigation. Micro-nano bubble water offers clear benefits over conventional aeration techniques, including a high rate of oxygen dissolution, a powerful mass transfer capacity, and a high aeration efficiency. By reducing the water-gas anomaly caused by conventional irrigation, it gives crop root systems a healthy soil oxygen environment. The productivity and quality of greenhouse tomatoes, cucumbers, and lettuce have significantly increased due to micro-nano bubble water irrigation (Liu et al., 2019; Ouyang et al., 2020, 2021; Zhou et al., 2019). Fewer research studies have examined the physiological effects of aerated irrigation on crop photosynthetic traits and dry matter accumulation, specifically the effects of micro-nano bubble water on these traits and dry matter accumulation of crops and cucumbers in subtropical red soil (Li et al., 2016; Ouyang et al., 2023; Pendergast et al., 2019; Tanure et al., 2019).

Biochar is recognized to possess properties including high adsorption capacity, high specific surface area, and porousness. It can increase the production and quality of greenhouse crops (Zheng et al., 2018) in addition to improving soil structure and aeration conditions (Obia et al., 2016; Qian et al., 2020; Tanure et al., 2019). Biochar improves groundwater use, lowers water consumption in greenhouse tomatoes (Shao et al., 2019a), and preserves moisture relations and leaf gas exchange rates in nitrogen-reducing and water-saving environments (Guo et al., 2021). Additionally, it raises the amount of organic acids, soluble solids, soluble sugars, and vitamin C in tomatoes (Shao et al., 2019b; Zheng et al., 2023). Under moderate deficit irrigation, tomato growth is inhibited, resulting in a slight decrease in yield (Zhang et al., 2020), significantly improving the yield and water use efficiency of greenhouse tomatoes (Akhtar et al., 2014; Fan et al., 2021). Zeeshan et al. (2020) indicated that adding 20 t ha⁻¹ of wood biochar to contaminated soil with a particle size of less than 3 mm can increase tomato yield by 68.57 %. However, depending on many experimental conditions, including crop characteristics, biochar type, biochar amount, and soil parameters, the behavior of soil biochar can change due to combined water-salt stress in dry and semi-arid environments (Wu et al., 2022). It is uncertain how biochar enhances the aeration of sticky red soil, and how it impacts cucumber development, photosynthetic features, yield, and quality in subtropical sticky red-yellow soil areas used for greenhouse agriculture.

There is growing interest in the problem of air permeability in clayey soils. It is still unknown how the combined application of micro-nano bubble water and biochar would affect the permeability of subtropical red soil and cucumber growth. This study expands on earlier research (Ouyang et al., 2020, 2021; Ouyang et al., 2023) that proposes combining biochar with a rich porous structure and MNBW by subsurface drip irrigation (SDI), which has effective water-saving qualities, aiming to clarify the interaction effect and the impact patterns of the photosynthetic traits and cucumber yield, as well as the relationship between soil aeration indicators and cucumber growth, in order to greatly increase the aeration of red soil through the "oxidation-porous" synergistic effect. The research results provide a scientific basis for improving the hypoxic conditions in the root zone of subtropical red soil and enhancing the yield and fruit quality of greenhouse vegetables.

2. Materials and methods

2.1. Experimental overview

The study area is located at the Hunan Irrigation Experiment Station in Changsha, Hunan Province, China (28°19' N, 113°17' E), at an altitude of 51.6 m. It has a subtropical monsoon climate, with a multi-year average atmospheric pressure of 1007.5 hPa, an average temperature of 18 °C, an average maximum temperature of 22.5 °C, an average minimum temperature of 14.7 °C, relative humidity of 80.1 %, an average wind speed of 2.1 m/s, annual precipitation of 1488.5 mm, annual evaporation of 1315.6 mm, and a total sunshine duration of 1585.5 h. The test red soil is clay, with clay particles (0–0.002 mm), silt particles (0.002–0.02 mm), and sand particles (0.02–2 mm) content of 56.50 %, 32.60 %, and 10.90 %, respectively, and a porosity of 40.92 %, a soil bulk density of 1.56 g/cm³, and the irrigation water source comes from local groundwater. The pH of the 0–20 cm soil layer is 5.8, organic matter is 8.16 g/kg, alkali-hydrolyzable nitrogen is 87.16 mg/kg, available phosphorus is 8.7 mg/kg, and readily available potassium is 352.51 mg/kg. Fig. 1 illustrates the variations in temperature, humidity, and light intensity during the greenhouse's two growing seasons.

2.2. Experimental design

The two-factor randomized block design method was used in this study. Three concentrations of dissolved oxygen (DO) in micro-nano bubble water (MNBW): O1 (4–5 mg/L), O2 (9–10 mg/L), O3 (14–15 mg/L), three amounts of biochar application (BA): B1 (20 t/hm²), B2 (40 t/hm²), B3 (60 t/hm²), and one control group CK (O: 4–5 mg/L, natural state dissolved oxygen of irrigation water; B: 0 t/hm², no biochar applied) were set up, with each treatment repeated three times, totaling 30 treatments. Under the conditions of this experiment, without micro-nano aeration, the DO in irrigation water in its natural state is 4–5 mg/L. With micro-nano aeration, the saturated DO in irrigation water can reach approximately 14–15 mg/L. Table 1.

2.3. Experiment implementation

At the time of planting, the test cucumber (*Cucumis sativus* L.) variety "Kangmi" (Hunan Xiangyan Seed Industry Co., Ltd., Changsha, China) was at the three-leaf stage. The first crop and second crop experiments of cucumbers lasted for 61 days (from April 3, 2024, to June 5, 2024) and 60 days (from June 21, 2024, to August 19, 2024), respectively. A planting density of 35,732 plants/hm² was achieved by planting two rows of plants in each experimental plot, which had an area of 16.8 m² (12 m long and 1.4 m wide). The plant spacing was 0.40 m and the row spacing was 0.50 m. Each experimental plot was arranged with two parallel in-line drip irrigation pipes by SDI with plastic film, the drip irrigation tubes were placed close to the crop planting row, with a tube diameter of 16 mm, a drip emitter spacing of 0.2 m, and a drip emitter flow rate of 2 L/h. The treatments did not affect each other when drip

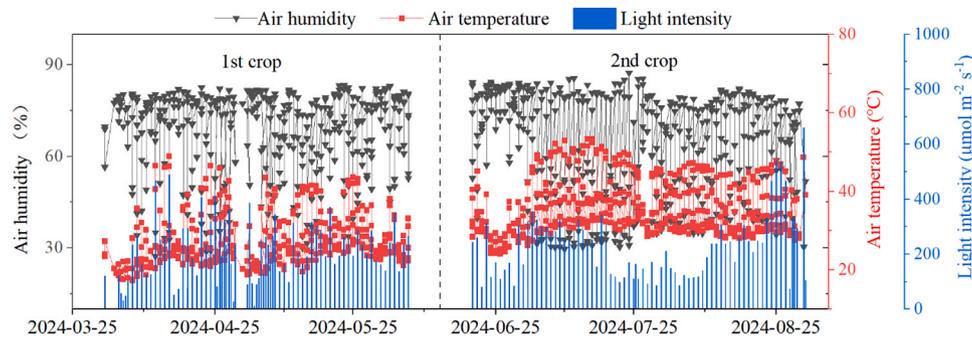


Fig. 1. Shows the changes in air temperature, air humidity, and light intensity in the greenhouse. "1st crop" represents the first growing season, and "2nd crop" represents the second growing season.

Table 1
Design of micro-nano bubble water (MNBW) and biochar experiment in the greenhouse.

Treatment	Dissolved oxygen concentration of MNBW	Amount of biochar application (BA)
O1B1	O1 (4–5 mg/L)	B1 (20 t/hm ²)
O1B2	O1 (4–5 mg/L)	B2 (40 t/hm ²)
O1B3	O1 (4–5 mg/L)	B3 (60 t/hm ²)
O2B1	O2 (9–10 mg/L)	B1 (20 t/hm ²)
O2B2	O2 (9–10 mg/L)	B2 (40 t/hm ²)
O2B3	O2 (9–10 mg/L)	B3 (60 t/hm ²)
O3B1	O3 (14–15 mg/L)	B1 (20 t/hm ²)
O3B2	O3 (14–15 mg/L)	B2 (40 t/hm ²)
O3B3	O3 (14–15 mg/L)	B3 (60 t/hm ²)
CK	O1 (4–5 mg/L)	B1 (0 t/hm ²)

irrigation was utilized, and adjacent experimental plots were separated by 0.6 m (Fig. 2).

The Nine instances of subsurface drip irrigation (SDI) with micro-nano bubble water (including seedling period irrigation) were carried out in the first season, with an irrigation quota of 990 m³/hm², fifteen instances of subsurface drip irrigation with micro-nano bubble water (including seedling period irrigation) were carried out in the second season, with an irrigation quota of 1440 m³/hm². The organic base fertilizer (amino acid chelated type, N + P₂O₅+K₂O≥6 %, organic matter≥30 %) was applied at a rate of 5400 kg/hm² before planting for all experimental treatments by local fertilization practices, and top-dressing with K₂SO₄ compound fertilizer (N:P₂O₅:K₂O=15:15:15, total

nutrients ≥45 %) was carried out during the critical period of crop nutrient demand, after the compound fertilizer was dissolved in water, it was evenly delivered to the crop root zone using an integrated water and fertilizer drip irrigation system. In the first season, the compound fertilizer was applied 5 times at a rate of 375 kg/hm², totaling 1875 kg/hm², in the second season, the compound fertilizer was applied 10 times at a rate of 187.5 kg/hm², also totaling 1875 kg/hm², converted to pure N, P₂O₅, and K₂O content, each at 281.25 kg/hm². Before planting, biochar was evenly applied to the soil surface and uniformly mixed into the 0–20 cm soil layer with a rotary tiller during tillage. Biochar was placed evenly to the soil surface and dispersed evenly into the 0–20 cm soil layer during plowing before to planting the first-season crops (no biochar is applied for the second-season crops). The micro-nano bubble water (MNBW) was created by a micro-nano bubble machine (XZCP-K, Yunnan Xiazhi Spring Company, China), the bubble widths ranged from 200 nm to 4 μm, the device power was 1.5 kW, its air content was 84–90 %, and its bubble creation rate was 3–3.5 m³/h. To accommodate varying dissolved oxygen concentration requirements, the design additionally incorporates a circulation aeration system to progressively raise the dissolved oxygen in the irrigation water, and then it was delivered to the crop root zone through an integrated water and fertilizer underground drip irrigation system (Fig. 2).

2.4. Measurement items and methods

2.4.1. Plant growth, photosynthetic characteristics

At the end of the seedling stage, three randomly selected healthy plants from each treatment were marked. The plant height (PLH) was

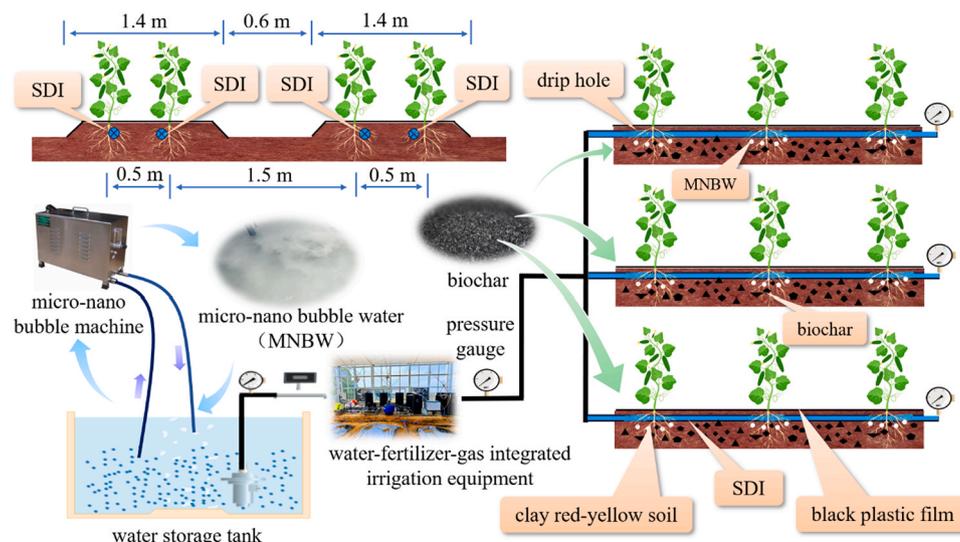


Fig. 2. Schematic diagram of the experimental process in greenhouse.

measured by a steel tape measure, the stem diameter (SD) at the base of the main stem was measured by a digital caliper, and the relative chlorophyll content (SPAD) and nitrogen (N) content of the leaves were measured by a portable plant nutrient analyzer (LD-YD, Shandong Lanende Intelligent Technology Co., Ltd, China), approximately every 10 days. The leaf photosynthetic characteristic parameters were measured by a portable photosynthesis measurement system (LI-6400, LI-COR, USA), generally conducted on clear days between 9:00–11:00 AM. Directly measured indicators include net photosynthetic rate (Pn), stomatal conductance (Cond), intercellular CO₂ concentration (Ci), transpiration rate (Tr), leaf temperature (T_{leaf}), air temperature (T_{air}), saturated vapor pressure deficit (VpdL), and stomatal limitation (Ls) and leaf water use efficiency (WUE_{leaf}) were calculated by these measurements, with observations taken once during each reproductive period (before, during, and after growth), a total of 3 times.

2.4.2. Soil aeration, moisture, temperature, electrical conductivity, soil aeration and surface morphology

The soil volumetric water content (SVWC), soil temperature (ST), and soil electrical conductivity (SEC) were tracked in real-time by the TERO12 sensor (METER, USA) set up with the EM50 data logger, data was collected every 30 min, and the sensor was buried 20 cm below the surface. Soil oxygen (SO) content and soil redox potential (SORP) were measured by a FireSting-O₂ fiber optic oxygen meter (PyroScience, Germany) and a portable soil OPR meter (TR-901, INESA Scientific Instrument Co., Ltd, China), respectively, with observations taken every 10 days. The Soil bulk density (SBD) was determined by the ring knife method at the beginning and end of the experiment. Dissolved oxygen in irrigation water was monitored by a portable dissolved oxygen analyzer (JPB-607A, INESA Scientific Instrument Co., Ltd, China). The undisturbed soil in the experimental plot was obtained by a 100 cm³ ring knife, and the imaging of the apparent morphology was obtained by a stereomicroscope.

Soil porosity (f) and soil aeration porosity (F_a) were calculated by the following formulas (Zang et al., 2018; Zhu et al., 2017b):

$$SP = 1 - \frac{\rho_b}{\rho_s}$$

$$SAP = f - \theta_v$$

In the formula, SP represents soil porosity, %; SAP represents the average soil aeration porosity at 0–40 cm, %; ρ_s represents soil particle density, g/cm³, with the vast majority of mineral soils ranging between 2.6 g/cm³ and 2.7 g/cm³, taken as 2.65 g/cm³; ρ_b represents soil bulk density (SBD), g/cm³; θ_v represents soil volumetric water content (SVWC), %.

2.4.3. Yield, dry matter accumulation, and fruit quality

The overall yield of the cucumber at the end of each growing season trial was the sum of the yields from each harvest. For each treatment, the aboveground parts of the plants were cut off, and the plant roots were obtained by digging a pit around the stem that was about 40 cm in diameter and 40 cm deep. After carefully shaking off the soil surrounding the root zone and giving it a thorough rinse, the stems, leaves, and roots were scorched for 15 min at 105 °C in an oven, and they were then dried at 75 °C until their weight remained constant, the fresh weight (F_w) and dry weight (D_w) of the plants were recorded, and the tissue moisture content (T_w), root-crown ratio (RCR), and fresh-to-dry ratio (RFD) were calculated. The vitamin C (VC), soluble sugars (SSU), organic acids (OA), and soluble solids (SSO) of the quality of cucumber fruit were determined according to the 2,6-dichlorophenol indophenol titration method, 3,5-dinitrosalicylic acid colorimetric method, acid-base titration method, and refractometer method, respectively.

2.4.4. IWUE, WUE, and ET_c

The water consumption of crops (ET_c) was calculated based on the

principle of water balance, groundwater recharge was minimal because the experimental area's groundwater depth was more than 3 m. The rainfall had no effect because the experiment was carried out in a greenhouse, there was no surface runoff or deep percolation, and the drip irrigation intensity was lower than the soil penetration rate. During any period t within the entire growing season, the change in water storage within the soil planned wet layer (H) can be demonstrated by the following water balance equation:

$$ET_c = M - (W_t - W_0)$$

In the formula, ET_c was the crop water consumption during period t, mm; W₀ and W_t were the soil moisture storage in the planned wetting layer at the start and end of period t (H was taken as 20 cm), mm; M was the irrigation quota during period t, mm.

Irrigation water use efficiency (IWUE) = Y/I, where Y was yield (kg) and I was irrigation quota (m³), Water use efficiency (WUE) = Y/ET_c, Leaf instantaneous water use efficiency (WUE_{leaf}) = Pn/Tr.

2.4.5. Statistics and analysis

Data was organized using Excel 2019 software, and variance analysis and Duncan's multiple range test were conducted on the results of the two-season experiments by Data Processing System 18.10 (DPS, Hangzhou Ruifeng Information Technology Co., Ltd., China). This included soil aeration, moisture conditions, cucumber growth, photosynthetic characteristics, dry matter accumulation, yield, and quality indicators. In the figures, different lowercase letters within the same growing season indicate significant differences between treatments (p < 0.05). In the results of the ANOVA, "*" indicates a highly significant difference (p < 0.01), "*" indicates a significant difference (p < 0.05), and "ns" indicates no significant difference (p > 0.05). The Origin 2021 software (OriginLab Corporation) was used for Pearson correlation analysis and plotting.

3. Results

3.1. Soil aeration and surface morphology

The primary indicators for measuring potential of soil aeration were soil bulk density (SBD), soil porosity (SP), soil aeration porosity (SAP), soil redox potential (SRP), and soil oxygen (SO). As illustrated in Fig. 3, the concentration of dissolved oxygen (DO) in micro-nano bubble water (MNBW) and the amount of biochar application (BA) had different effects on soil aeration performance. The SBD significantly decreased with the increase in BA (P < 0.05), the concentration of DO in MNBW had no significant effect on SBD (P > 0.05), and the interaction of the two had no significant effect on SBD (P > 0.05), compared to the CK, during the two growing seasons, the average SBD of each treatment decreased by 4.32–29.97 %. The SP increased considerably with the BA (P < 0.05), but not significantly with the concentration of DO in MNBW (P > 0.05) or with the interaction of both (P > 0.05), the average SP of each treatment increased by 4.01–27.81 %. The amount of BA significantly increases SAP (P < 0.05), the concentration of DO in MNBW had no significant effect on SAP (P > 0.05), and the interaction of the two had no significant effect on SAP (P > 0.05), the average SAP of each treatment increased by 0.53–37.01 % and 4.05–44.00 %, respectively. The amount of BA and the concentration of DO in MNBW both significantly enhanced the SRP (P < 0.01), and the interaction of two factors had a significant effect on the SRP (P < 0.05), the average SRP of each treatment increased by 0.54–34.74 %. The amount of BA and the increase in the concentration of DO in MNBW both significantly raised the SO (P < 0.01), and the interaction of both had a significant effect on SO (P < 0.05), the average SO of each treatment increased by 0.47–31.80 %. The black color of the biochar particles became increasingly noticeable on the soil surface as the amount of BA increased from B1 (20 t/hm²) to B3 (60 t/hm²), even while the DO concentration in MNBW remained constant (Fig. 4).

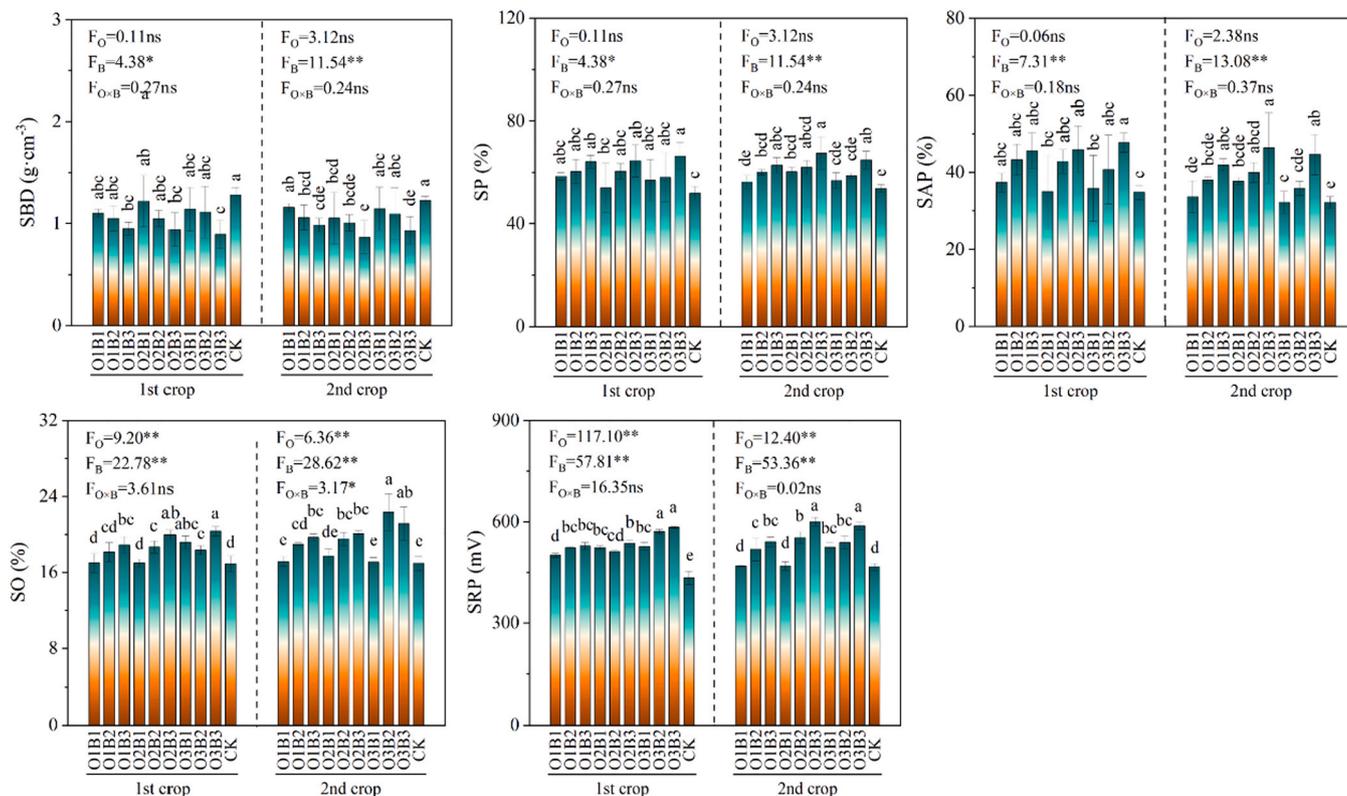


Fig. 3. illustrates the changes in soil bulk density (SBD), soil porosity (SP), soil aeration porosity (SAP), soil redox potential (SRP), and soil oxygen (SO). The terms "1st crop" and "2nd crop" denote the first and second growing seasons, respectively. Different lowercase letters within the same growing season indicate significant differences between treatments ($P < 0.05$), * denotes significant changes ($P < 0.05$), ** denotes extremely significant differences ($P < 0.01$), and ns denotes no significant differences ($P > 0.05$).

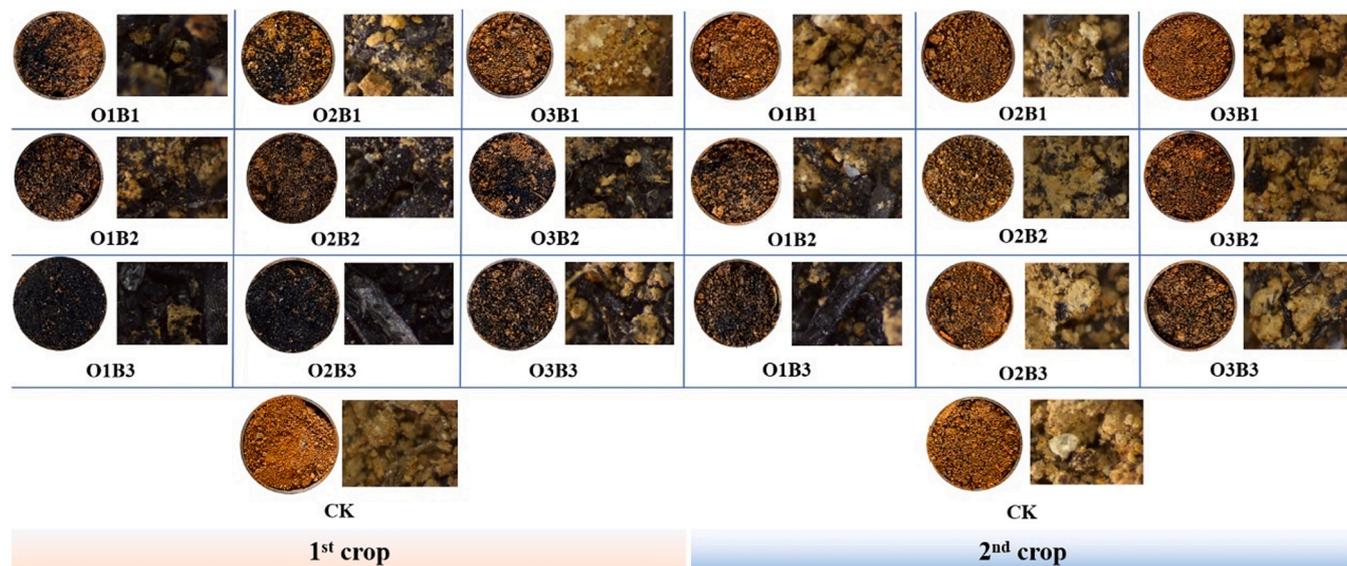


Fig. 4. shows the changes in the apparent morphology of soil under a stereomicroscope. The image on the left side of each number is the image of undisturbed soil by a ring knife, and the image on the right side is the image magnified 50 times under a stereomicroscope. The terms "1st crop" and "2nd crop" denote the first and second growing seasons, respectively.

3.2. Soil aeration, moisture, temperature, and electrical conductivity

Before biochar was added, the average SBD of the 0–40 cm soil layer in the analyzed soil was 1.56 g/cm³, the soil moisture content (SVWC) at different field capacity (θ_f) ratios can be converted from the SBD. As can be observed from the analysis of Fig. 5, it can be seen that irrigation

begins when the SVWC of all treatments falls below 0.60 θ_f , and each irrigation lasts 90 m³ /hm². The SVWC ($P < 0.01$) was impacted by the amount of BA, but neither the DO concentration in MNBW ($P > 0.05$) nor their interaction ($P > 0.05$) were affected. While there was no significant change ($P > 0.05$) when the concentration of DO in MNBW increased, the SVWC considerably dropped when the amount of BA

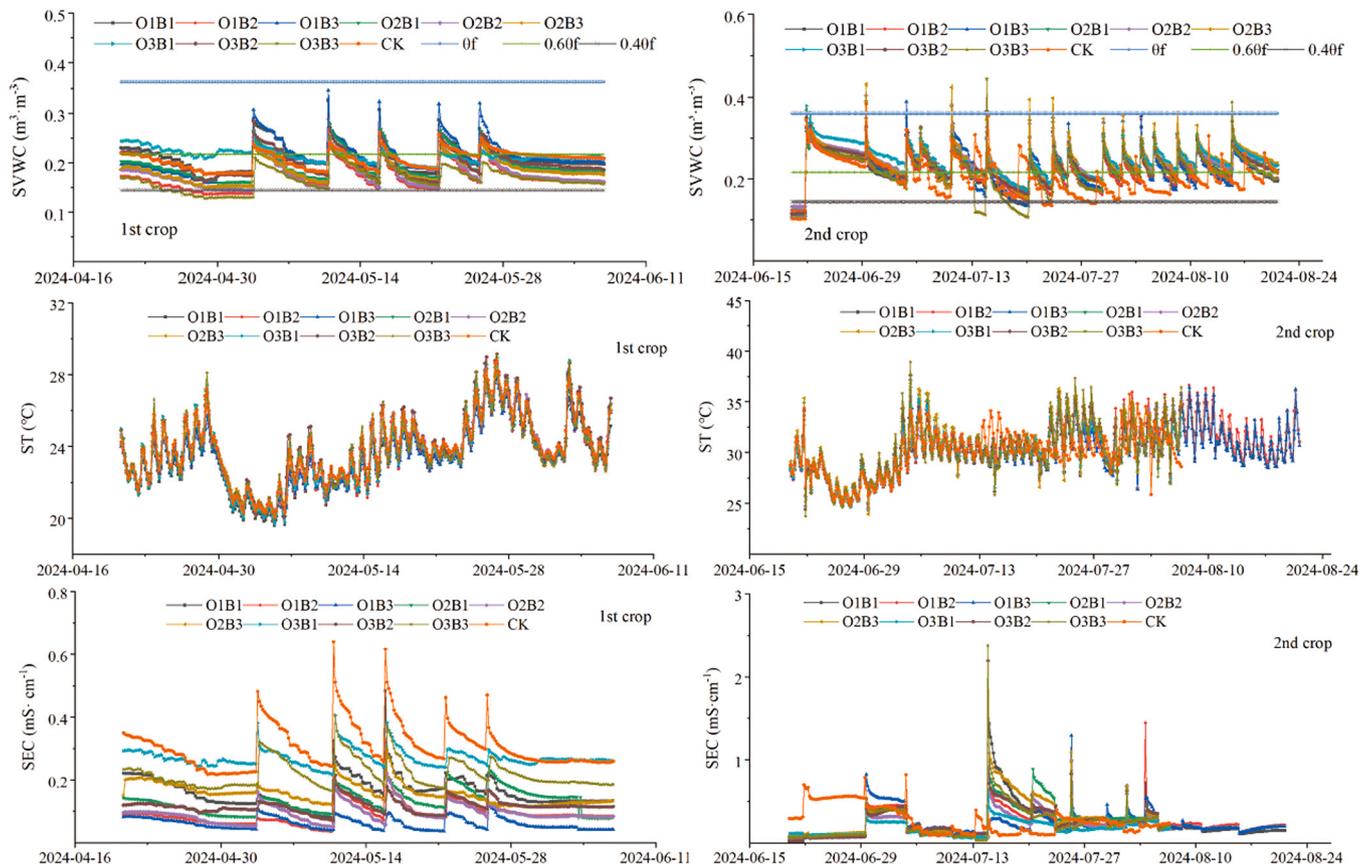


Fig. 5. shows the variations in soil volumetric water content (SVWC), soil temperature (ST), and soil electrical conductivity (SEC). The terms "1st crop" and "2nd crop" denote the first and second growing seasons, respectively.

increased ($P < 0.05$), the average SVWC of each treatment rose by 0.09~31.73 %, in comparison to the CK. The soil temperature (ST) was significantly impacted by the amount of BA and the concentration of DO in MNBW ($P < 0.05$), but not by the interaction of these two variables ($P > 0.05$). The ST exhibited a trend of first rising and then falling as the amount of BA and DO concentration in MNBW increased, the average ST of each treatment between 20 °C~38 °C, respectively. Additionally, the ST of the second crop was significantly higher than that of the first, indicating that ST was mostly impacted by air temperature, the average ST of each treatment fell by 0.05~2.60 %. The soil electrical conductivity (SEC) was strongly impacted by the quantity of BA in the first crop ($P < 0.05$), but not by the amount of BA in the second crop ($P > 0.05$), the SEC was not significantly impacted by the interaction of both crops ($P > 0.05$). The SEC significantly decreased as the amount of BA grew; for the first crop, it ranged between 0.05 and 0.6 mS/cm, and for the second crop, it ranged between 0.02 and 2.0 mS/cm. The application of irrigation and fertilization techniques also had an impact on SEC, as evidenced by the sudden variations in conductivity those practices cause.

3.3. Plant growth

Analysis of Fig. 6 shows that the BA and the dissolved oxygen concentration in the MNBW had varied effects on plant development circumstances. Overall, plant height (PLH) was considerably impacted by the BA and the dissolved oxygen concentration of the MNBW ($P < 0.01$), and this effect was also significantly impacted by their interaction ($P < 0.05$). Initially rising and then falling as the dissolved oxygen concentration rose, plant height grew significantly ($P < 0.05$). In comparison to the CK, the average plant height of each treatment increased by 0.38~27.86 %. The stem diameter (SD) of the second crop was

significantly impacted by the DO concentration in MNBW and the amount of BA ($P < 0.01$), and the interaction of the two factors also significantly impacted SD ($P < 0.05$), the average stem diameter of each treatment rose by 3.25~45.17 %. The amount of leaf N content in MNBW was not significantly impacted by the DO concentration ($P > 0.05$), but it was significantly impacted by the BA concentration ($P < 0.05$), and the two factors together had no significant impact ($P > 0.05$). As the amount of BA increased, the leaf N content first increased and subsequently reduced. In both treatments, the PLH increased greatly as the number of transplanting days increased.

3.4. Photosynthetic characteristics

According to the analysis of Fig. 7, the net photosynthetic rate (Pn) was significantly impacted by the amount of BA and the concentration of DO in MNBW ($P < 0.01$), the Pn was likewise significantly impacted by the interaction of both parameters ($P < 0.01$) when the concentration of DO in MNBW and the amount of BA increased, the Pn increased significantly ($P < 0.05$), the average Pn of each treatment increased by 1.91~50.78 %, in comparison to the CK. The stomatal conductance (Cond) was significantly impacted by the concentration of DO in MNBW and the amount of BA ($P < 0.05$), the relationship between the two factors had a significant effect on Cond ($P < 0.01$), and the Cond significantly decreased as the concentration of DO in MNBW and the amount of BA increased ($P < 0.05$), the average Cond of each treatment increased by 8.35~64.14 %. The intercellular CO₂ concentration (Ci) was significantly impacted by the amount of BA ($P < 0.01$), the Ci first rose and then fell as the concentration of DO in MNBW and the amount of BA increased, the average Ci of each treatment fell by 0.09~5.87 %. The amount of BA and the dissolved oxygen content of the MNBW had a substantial impact on the transpiration rate (Tr) ($P < 0.05$). The Tr was

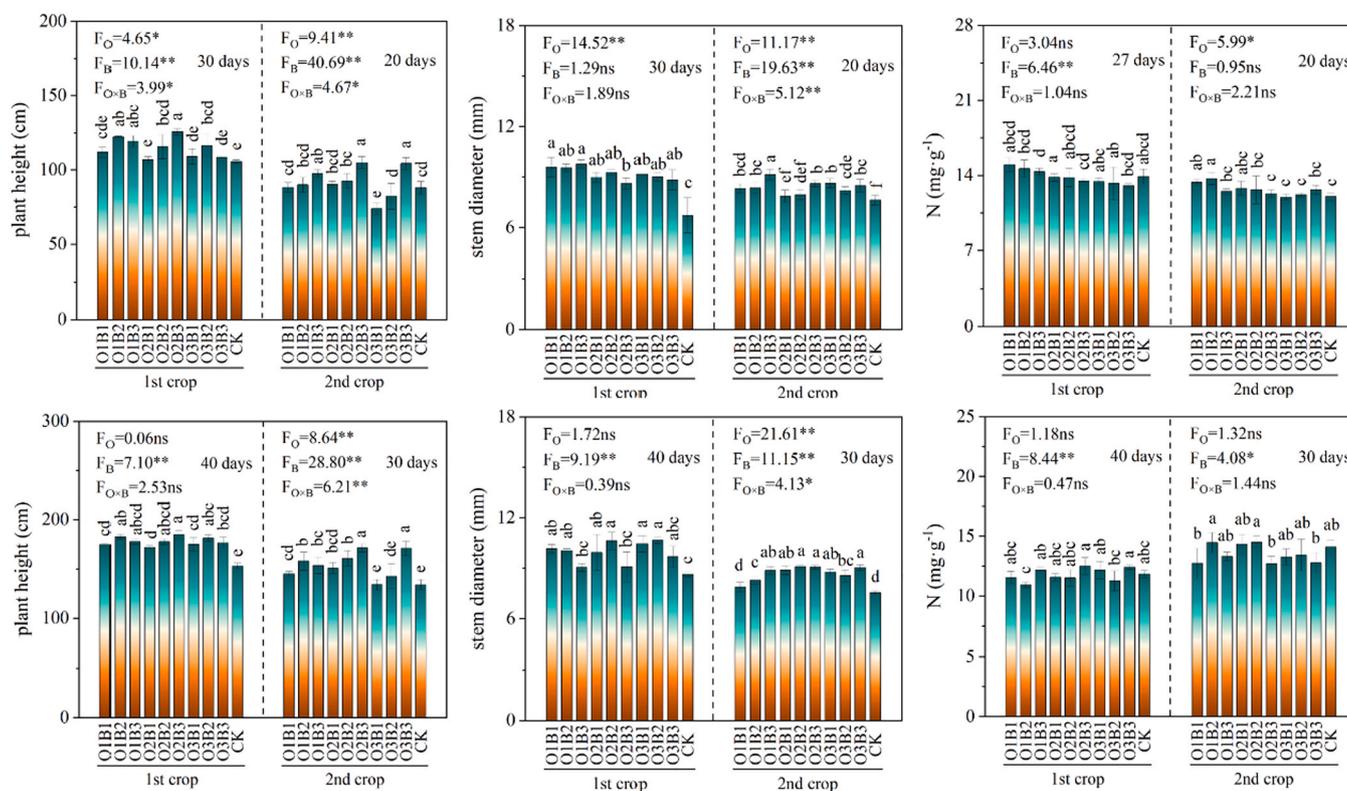


Fig. 6. Variations in plant height (PLH), stem diameter (SD), and nitrogen (N) for several days following transplanting. The terms "1st crop" and "2nd crop" denote the first and second growing seasons, respectively. Different lowercase letters within the same growing season indicate significant differences between treatments ($P < 0.05$), * denotes significant changes ($P < 0.05$), ** denotes extremely significant differences ($P < 0.01$), and ns denotes no significant differences ($P > 0.05$).

significantly impacted by the interaction between the two ($P < 0.01$). The amount of BA and the dissolved oxygen content both significantly reduced the Tr ($P < 0.05$); however, the Tr was on average raised by 3.55–39.34 % when compared to CK.

The saturation vapor pressure deficit (V_{pdL}) was significantly impacted by the concentration of DO in MNBW and the amount of BA ($P < 0.05$), a couple of these factors had a highly significant effect on the V_{pdL} of the first crop ($P < 0.01$), and the V_{pdL} significantly increased as the concentration of DO in MNBW and the amount of BA increased ($P < 0.05$), in comparison to the CK, the average V_{pdL} of each treatment decreased by 5.61~16.40 %. The air temperature (T_{air}) was significantly impacted by both the amount of BA and the concentration of DO in MNBW ($P < 0.01$), and the combination of the two factors also significantly impacted T_{air} ($P < 0.01$). The T_{air} significantly increased with the increased amount of BA ($P < 0.05$) and decreased with the increased concentration of DO in MNBW, the average T_{air} of each treatment decreased by 0.17~2.98 %. The Leaf temperature (T_{leaf}) was significantly influenced by the amount of BA and the DO content in MNBW ($P < 0.05$), with T_{leaf} rising as BA levels rose. The amount of BA and the concentration of DO in MNBW had a substantial effect on the stomatal limitation value (Ls) ($P < 0.05$), and the two factors' interaction had a significant effect on Ls as well ($P < 0.05$). The Ls significantly dropped ($P < 0.05$) when the amount of BA and the DO content in MNBW increased, the average Ls of each treatment decreased by 1.34~16.67 %. The amount of BA and the DO concentration in MNBW had a substantial impact on the SPAD ($P < 0.05$). Overall, when the amount of BA and DO concentration in MNBW grew, the SPAD first rose and subsequently fell. The level of BA and the concentration of DO in MNBW had a highly significant effect on the leaf water use efficiency (WUE_{leaf}) ($P < 0.01$), the average WUE_{leaf} of each treatment increased by 5.29~31.69 %.

3.5. Dry matter accumulation

Fig. 8 Analysis showed that the concentration of DO in MNBW and amount of BA had a highly significant effect on root dry weight (Root-Dw) ($P < 0.01$) and that the interaction of the two also had a highly significant effect on Root-Dw ($P < 0.01$). When the concentration of DO in MNBW rose, the Root-Dw first increased and subsequently decreased, and when the amount of biochar applied increased, it also rose, the average Root-Dw of each treatment rose by 1.68~151.46 % in comparison to CK. The stem weight (Stem-Dw) was highly significantly impacted by the amount of BA and the concentration of DO in MNBW ($P < 0.01$), and the Sem-Dw increased significantly with the increase in DO concentration in MNBW and amount of BA ($P < 0.05$), in comparison to the CK, the average Stem-Dw of each treatment increased by 0.18~93.14 %. The leaf dry weight (Leaf-Dw) was significantly impacted by the DO concentration in MNBW ($P < 0.05$), and it increased significantly as the DO concentration in MNBW and the amount of BA increased ($P < 0.05$), the average Leaf-Dw of each treatment increased by 34.46~181.29 %. Both the DO concentration in MNBW and the amount of BA had a significant impact on the total dry weight (Dw) ($P < 0.05$), and the Dw increased significantly as the DO concentration in MNBW and the amount of BA increased ($P < 0.05$), the average Dw of each treatment increased by 10.53~69.19 %.

Fresh weight (Fw) was significantly impacted by the concentration of DO in MNBW and the amount of BA ($P < 0.05$). The Fw increased significantly as the concentration of DO in MNBW and the amount of BA increased ($P < 0.05$). In comparison to the CK, the average Fw of each treatment increased by 4.72~82.66 %. The root-to-crown ratio (RCR) was significantly impacted by the concentration of DO in MNBW and the amount of BA ($P < 0.01$), the RCR first rose and then fell as the concentration of DO in MNBW and the amount of BA increased, the O2B2 treatment, which had intermediate levels of DO in MNBW and BA, corresponded to the maximum RCR, in comparison to the CK, the RCR in

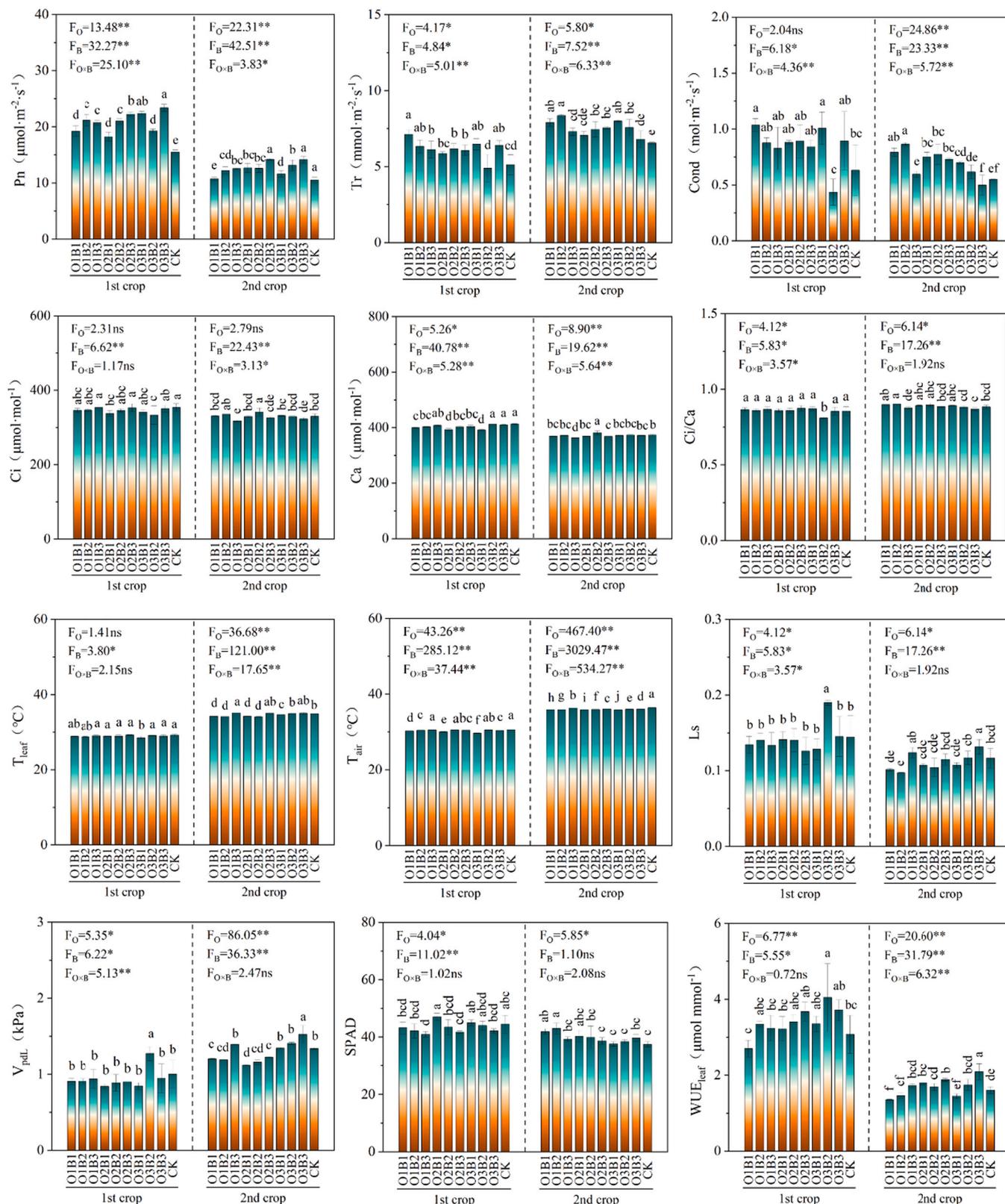


Fig. 7. The changes in photosynthetic characteristic parameters: net photosynthetic rate (Pn), stomatal conductance (Cond), intercellular CO₂ concentration (Ci), transpiration rate (Tr), leaf temperature (T_{leaf}), stomatal limitation (Ls), saturated vapor pressure deficit (V_{pdl}), air CO₂ concentration (Ca), and leaf water use efficiency (WUE_{leaf}). The terms "1st crop" and "2nd crop" denote the first and second growing seasons, respectively. Different lowercase letters within the same growing season indicate significant differences between treatments ($P < 0.05$), * denotes significant changes ($P < 0.05$), ** denotes extremely significant differences ($P < 0.01$), and ns denotes no significant differences ($P > 0.05$).

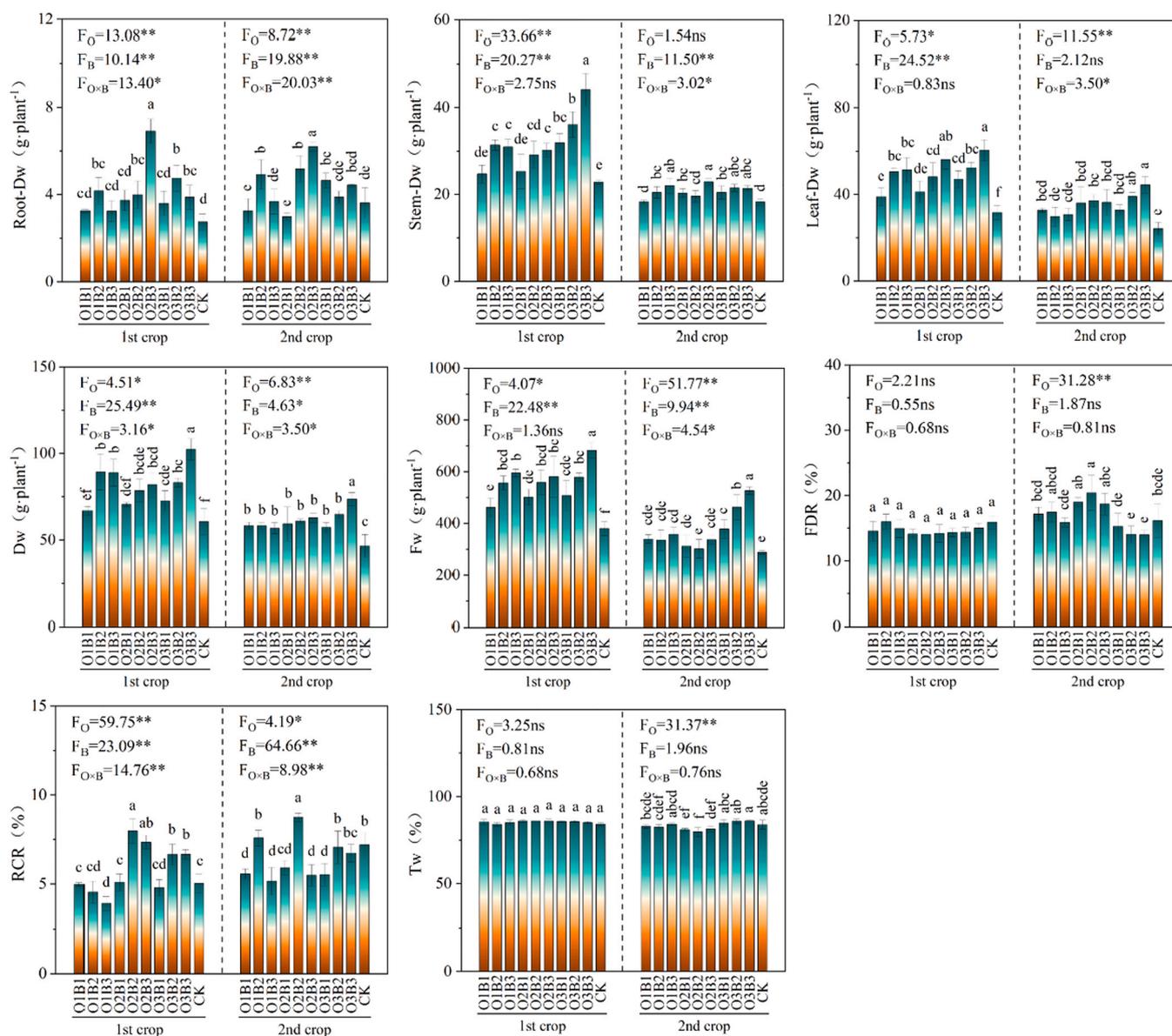


Fig. 8. The variations in the plants' fresh weight (Fw), dry weight (Root), dry weight of root (Root-Dw), dry weight of stem (Stem-Dw), dry weight of leaf (Leaf-Dw), tissue moisture content (Tw), root-crown ratio (RCR), and fresh-dry ratio (FDR) of the plants. The terms "1st crop" and "2nd crop" denote the first and second growing seasons, respectively. Different lowercase letters within the same growing season indicate significant differences between treatments ($P < 0.05$), * denotes significant changes ($P < 0.05$), ** denotes extremely significant differences ($P < 0.01$), and ns denotes no significant differences ($P > 0.05$).

the first and second crops under the O2B2 treatment increased by 59.14 % and 21.35 %, respectively. The fresh-to-dry ratio (FDR) and tissue water content (Tw) were not significantly impacted by the amount of BA or the DO concentration in MNBW ($P > 0.05$).

3.6. Yield, fruit quality, and irrigation water use efficiency

The amount of BA and the DO content in MNBW had a highly significant effect on cucumber yield ($P < 0.01$), according to the study in Fig. 9. The combination of both factors also had a significant impact on cucumber yield ($P < 0.05$). Cucumber yield rose significantly as DO concentration in MNBW and BA amount increased ($P < 0.05$). Compared to the CK, during the two growing seasons, the average yield of each treatment increased by 1.72~44.23 %. The number of cucumbers (NC) was significantly impacted by the amount of BA and the DO content in MNBW ($P < 0.01$), the interaction of both factors did not significantly affect the NC ($P > 0.05$), the NC increased significantly with the increase in the concentration of DO in MNBW and the amount

of BA ($P < 0.05$), the average NC of each treatment increased by 5.00~44.23 %. The concentration of DO in MNBW and the amount of BA had no significant effect on the average weight of a cucumber (AWAC) ($P > 0.05$), and the interaction of the two had no significant effect on the AWAC ($P > 0.05$). The concentration of DO in MNBW and the amount of BA had a highly significant impact on irrigation water use efficiency (IWUE) ($P < 0.01$), the interaction of both factors significantly affected IWUE ($P < 0.05$), and the IWUE increased with the increase in DO in MNBW and amount of BA ($P < 0.05$), the average IWUE of each treatment increased by 1.72~44.23 %. The amount of BA and the DO concentration in MNBW significantly affected the water use efficiency (WUE) ($P < 0.01$), the interaction of both factors also had a highly significant effect on WUE ($P < 0.01$). The WUE rose significantly as the amount of BA and the concentration of DO in MNBW increased ($P < 0.05$), and the average WUE of each treatment increased by 0.42~76.57 %. All things considered, when the amount of BA and DO concentration in MNBW grew, crop water consumption (ETc) fell, overall, ETc dropped with increasing biochar application when

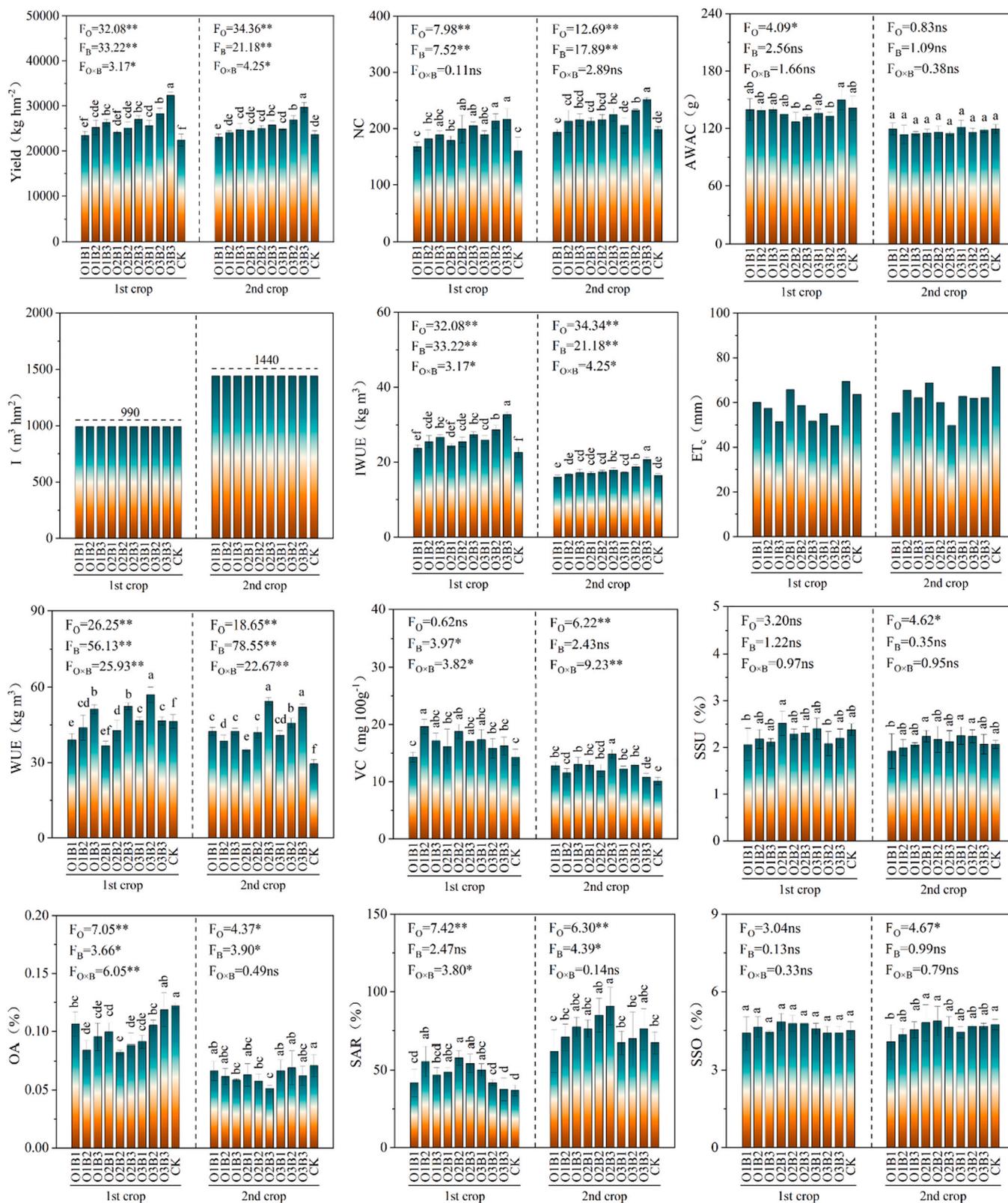


Fig. 9. shows the changes in cucumber yield (Yield), number of cucumbers (NC), average weight of a cucumber (AWAC), irrigation quota (I), irrigation water use efficiency (IWUE), water use efficiency (WUE), crop water consumption (ET_c), vitamin C (VC), soluble sugar (SSU), soluble solids (SSO), organic acid (OA), and sugar-acid ratio (SAR). "1st crop" indicates the first growing season, and "2nd crop" indicates the second growing season. Different lowercase letters within the same growing season indicate significant differences between treatments ($P < 0.05$); ** indicates extremely significant differences ($P < 0.01$), * indicates significant differences ($P < 0.05$), and ns indicates no significant differences ($P > 0.05$).

dissolved oxygen (O2) was at a moderate level, ETC exhibited a trend of initially rising and then falling with dissolved oxygen when biochar was applied at a low level (B1).

The vitamin C (VC) was significantly impacted by the interaction of DO concentration in MNBW and BA amount ($P < 0.05$). The VC trended upward and then downward as the concentration of DO in MNBW and BA increased. Compared to the CK, during the two growing seasons, the average VC of each treatment increased by 0.23~46.71 %. The organic acid (OA) was considerably impacted by the amount of BA and the DO content in MNBW ($P < 0.05$). In comparison to the CK, the average OA of each treatment dropped by 2.67~30.85 %, as the concentration of DO in MNBW and the amount of BA increased. The sugar-acid ratio (SAR) was strongly impacted by the amount of BA and the DO concentration in MNBW ($P < 0.05$). As the concentration of DO in MNBW and the amount of BA grew, the SAR generally showed a tendency to initially increase and then decrease. In comparison to the CK, the average SAR of each treatment increased by 2.03~56.83 %. The amount of BA and the DO concentration in MNBW did not significantly affect the amount of soluble sugars (SSU) or soluble solids (SSO) ($P > 0.05$).

3.7. The correlation between soil aeration and cucumber growth, photosynthetic characteristics, dry matter accumulation, yield, and quality

All of the important indicators' correlations were examined by the Pearson correlation analysis approach (Fig. 10). Overall, the SBD had a strongly negative correlation ($P < 0.01$) with SP, SAP, SORP, and SO in the two growing season studies. The PLH, Pn, Fw, Dw, yield, IWUE, WUE, and SAR were considerably positively connected with soil general indicators such as SP, SAP, SORP, and SO ($P < 0.05$), whereas SEC, SPAD, and OA were strongly adversely correlated ($P < 0.05$). The SVWC had a negative correlation with ST, Ls, and T_{air}, but a substantial positive correlation with SEC, Cond, and Tr ($P < 0.05$). The Fw, Dw, Yield, IWUE, WUE, VC, and SAR all showed a strong positive correlation with the Pn ($P < 0.05$). There was a substantial negative correlation ($P < 0.05$) between the Cond and Ls, but a strong positive correlation ($P < 0.05$) with Tr. The plants' yield, IWUE, and WUE showed a substantial positive correlation with both their Fw and Dw ($P < 0.05$). While yield had a strong negative correlation ($P < 0.05$) with SBD and SEC, it had a substantial positive correlation ($P < 0.05$) with SP, SAP, SORP, SO, Pn, Fw, Dw, NC, and IWUE. There was a substantial positive correlation between SSU and SSO ($P < 0.05$), a significant negative

correlation between VC and OA ($P < 0.01$), and a significant positive correlation between SAR and SSU ($P < 0.05$).

4. Discussion

4.1. Soil aeration, moisture, temperature, and electrical conductivity

The increase in biochar application resulted in a considerable drop in soil bulk density in both growth seasons; the average reduction in bulk density across all treatments ranged from 4.32% to 29.97 %, the research findings were in line with Wang et al. (2019). This study also found that the amount of BA significantly increased SAP and SP. The SAP increased by 0.53~37.01 % and 4.05~44.00 % for the first crop and second crop treatments, respectively, while the SP increased by 4.01~27.81 % and 4.82~25.45 %, Because biochar has a porous structure and a large specific surface area (Ajayi et al., 2016; Tanure et al., 2019), when evenly mixed with soil, it increased porosity, reduced SBD, improved gas exchange and circulation capacity within the soil, and improved soil aeration. That's why there was no noticeable impact of DO concentration in MNBW on SBD, SP, or SAP. On the other hand, MNBW had little effect on SBD and SP. As the concentration of BA and DO in MNBW increased, the SO and SORP also increased dramatically. The SO and SORP were significantly impacted by the interaction of both, the SORP grew by 15.58~34.74 % and 0.54~28.60 % in the first crop and second crop treatments, respectively, while the SO increased by 0.47~20.37 % and 0.72~31.80 %. This primarily referred to oxygen-rich micro-nano bubble water used for irrigation; because of their small size, the micro-nano bubbles had a long half-life in water and soil (Yang, 2002), a high mass transfer efficiency (Li et al., 2013), and a stable nature (Yang, 2002). They also had a high reactivity and readily adhered to soil and root systems when interacting with biochar. Both improved the SO and SORP through their synergistic effects. Under the same concentration of DO in MNBW, the two-season experiment showed substantial variations in soil surface morphology. The black hue of the biochar particles on the soil surface becomes more apparent as additional BA is added from B1 to B3. Color changes and visible biochar particles on the soil surface did not alter considerably under the same amount of BA when the DO content in MNBW increased from O1 to O3. When compared to the surface morphology of the first crop, the black areas of the original soil have become less noticeable in the second crop. Although no more biochar was applied to the second crop, the growth of

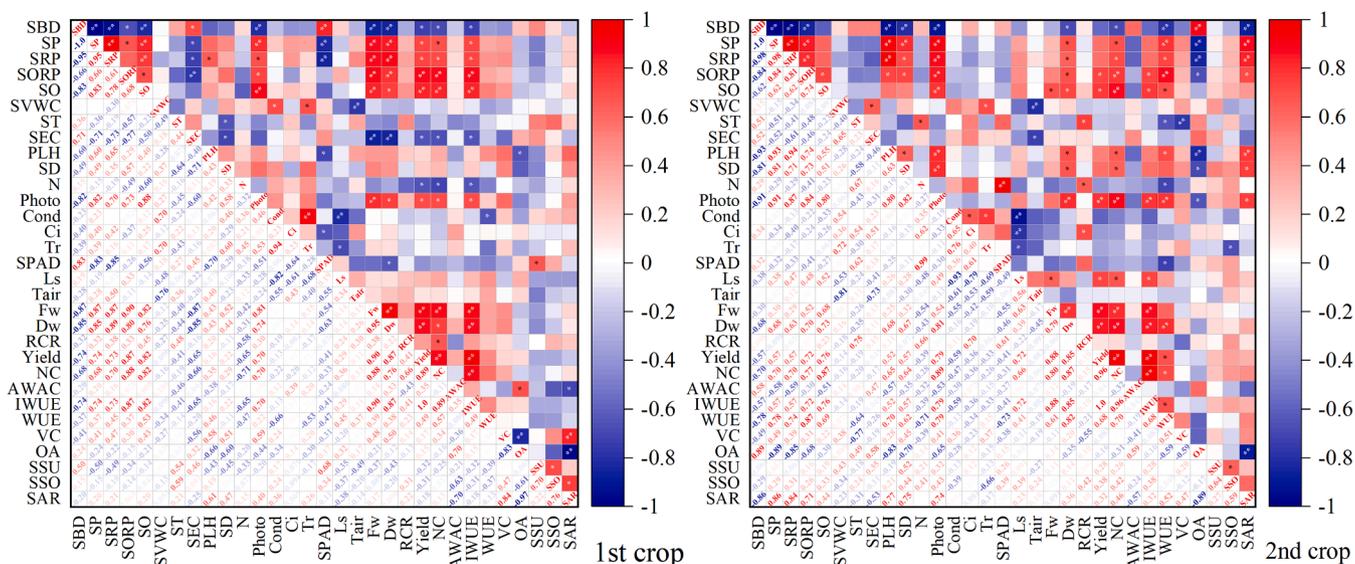


Fig. 10. Correlation analysis between main indicators. "1st crop" indicates the first growing season, and "2nd crop" indicates the second growing season. ** indicates extremely significant differences ($P < 0.01$), * indicates significant differences ($P < 0.05$).

the crops, the breakdown of the biochar, and other factors such as soil tillage, resulted in this change, indicating that the amount of BA can significantly affect the surface morphology of the soil.

As the amount of BA rose, the SVWC dramatically reduced; however, the SVWC was improved by the interaction treatment of micro-nano bubble water and biochar, with the average SVWC of each treatment increased by 0.09–31.73 %. This was because the porous nature of biochar not only improved its capacity to absorb moisture and nutrients, but also increased soil aeration, microbial activity, and soil enzyme activity (Liu et al., 2019; Morard and Silvestre, 1996). This encouraged crop roots to absorb and use soil moisture (Zhang et al., 2024), which in turn decreased SVWC. Following the addition of biochar, the soil's porosity and aggregation changed, its specific surface area rose, and eventually, its capacity for soil water retention was impacted (Cornelissen et al., 2004; Schulz and Glaser, 2012). The results were comparable to those of Li et al. (2014), with the exception that red soil was utilized in this investigation. Micro-nano bubble water that was rich in oxygen was absorbed by the biochar, which partially preserved and eventually raised the SVWC. Additionally, depending on the relative changes in soil-specific surface area, soil texture, structure, and organic matter content all affect the soil's ability to retain water (Zeng et al., 2013). A tendency of initially increasing and then decreasing was seen in the ST when the amount of BA and the concentration of DO in MNBW rose. This occurred because biochar's large specific surface area and porous structure allow it to absorb solar radiation energy, reducing soil heat loss. Its high carbon content also contributes to its comparatively high heat capacity, all of which create ideal conditions for regulating soil temperature (ST). Oxygen-rich micro-nano bubble water had helped to raise ST, improved the soil gas exchange rate, and raised SO to some degree. Conversely, when it comes to a single irrigation, the soil temperature drops from the start to the finish as the amount of irrigation water increased. Furthermore, the daily and seasonal variations in ST were most influenced by the temperature of the irrigation water and the ambient air. The more BA there was, the lower the SEC. This was because biochar decreased SBD, enhanced soil permeability, and encouraged irrigation-induced soil salinity leaching, all of which decreased SEC. Although their investigation was based on saline-alkali land, Qu et al. (2021) found similar results. Simultaneously, irrigation and fertilization had an impact on the SEC. The use of fertilizer and irrigation techniques was the cause of all the sudden variations in conductivity.

4.2. Growth, photosynthetic characteristics, and dry matter accumulation

Overall, plant height and leaf nitrogen content increased in tandem with increased in dissolved oxygen concentration (DO) and biochar application (BA). This was mostly due to the fact that roots can breathe more efficiently in an oxygen-rich environment, which further enhanced soil conditions and promoted root development and nutrient absorption, all of which improved the growing conditions for cucumbers. The majority of research findings also showed that adding biochar can boost crop growth (Tanure et al., 2019), enhance crop yields (Agbna et al., 2017; Zeeshan et al., 2020), and have varying effects on soil qualities and plant growth depending on the attributes of the soil and the biochar itself (Purakayastha et al., 2019). This was explained by increased soil fertility, efficient nutrient use, improved soil structure, and increased water-retention capacity (Ajayi et al., 2016).

The amount of BA and the increase in DO concentration in MNBW caused a large increase in Pn, WUE_{leaf} , V_{pdL} , and T_{leaf} . On the other hand, when the amount of BA and DO concentration in MNBW increased, Cond, Tr, Ls, and SPAD all dramatically dropped. As the concentration of DO in MNBW and the amount of BA increased, the Ci first showed an upward trend before declining. The reason for this could be that the quantity of BA enhanced SP, supplying nutrients like N, P, and K, and adsorbing a significant amount of oxygen-rich micro-nano bubble water, which partially preserved SVWC and nutrients, produced ideal

conditions for crop photosynthesis, and enhanced Pn. However, SVWC had an impact on biochar's ability to retain water (Agbna et al., 2017), and it also changed the structure of soil aggregates and pores (Akhtar et al., 2014). The Pn of each treatment rose by 1.91–50.78 %, in the two-season studies, which was essentially in line with the findings of Bao et al. (2018). Additionally, Studies have also shown that when biochar is applied under adequate irrigation, it fills soil pores with pore water and fine-particle biochar, which hinders the extension of root systems, preventing them from absorbing additional water and nutrients and lowering the Pn of leaves (Tanure et al., 2019). Climate, biochar type, soil physicochemical characteristics, and soil texture could all be factors in this discrepancy.

The Dw and RCR were greatly impacted by the amount of BA and the DO concentration in MNBW. With a rise in the amount of BA and the DO concentration in MNBW, the Dw rose significantly. In the first and second crops, the Dw of each treatment rose by 10.53–69.19 %. The first crop's RCR rose by 59.14 percent in the O2B2 treatment, whereas the second crop's RCR rose by 21.35 %. This study found a substantial positive correlation ($P < 0.05$) between the Pn and indicators like Fw and Dw. This occurred as a result of oxygen-rich micro-nano bubble water supplying water and oxygen to the root zone and biochar boosting the soil's porosity. It enhanced soil aeration and water retention, boosted root vitality, and prompted the roots to take up and utilize soil moisture and nutrients (Baram et al., 2022) when mixed with oxygen-rich micro-nano bubble water.

4.3. Yield, quality, and water use efficiency

Cucumber yield, IWUE, and WUE were significantly impacted by the amount of BA and the DO concentration in MNBW ($P < 0.01$). Cucumber yield, IWUE, and WUE are all strongly impacted by the interaction of both parameters ($P < 0.05$). As the amount of BA and DO concentration in MNBW rose, there was a substantial rise in cucumber yield, IWUE, and WUE ($P < 0.05$). In general, the ET_c dropped as the amount of BA and DO concentration in MNBW rose. This agreed with Liu et al. (2019) findings, which show that MNBW not only improved SO but also influenced the activity of soil enzymes including urease and catalase, altered the soil microenvironment (Morard and Silvestre, 1996), and encouraged plant and animal biological activities (Ushikubo et al., 2010). In contrast, this study results from the interaction effects of micro-nano bubble water and biochar. Biochar has a rich porous structure, which increased the porosity of clay and reduced soil bulk density. Meanwhile, the oxygen-rich micro-nano bubble water used in subsurface drip irrigation has oxidative properties, enhanced the soil's redox potential and oxygen content. The interaction between the two synergistically improved soil aeration porosity, enhanced soil aeration potential, provided good oxygen conditions for root growth, promoted photosynthesis and dry matter accumulation, improved yield and quality. This was mostly due to the fact that each treatment had identical irrigation quotas, soil texture, fertilizer, and climate conditions; also, the higher yield indirectly improved the IWUE, but the WUE was primarily based on the ET_c and yield.

Although consumers have always wanted higher yields and quality, the majority of research has shown that the best quality is not always correlated with the largest yield. In other words, allowing for a certain yield drop during real production can result in fruit of the highest quality. The amount of BA and the DO concentration in MNBW had a substantial impact on VC, OA, and SAR. The amount of BA and the DO concentration in MNBW coupled had a substantial impact on the SAR, VC, and OA. While the OA fell as the concentration of DO in MNBW and the amount of BA grew, the VC and SAR first climbed and subsequently declined. A study by Liu et al. (2019) found that cucumbers irrigated with MNBW had increased in VC and SSU by 40.9 % and 20.8 %, respectively. However, according to the study's findings, neither SSU nor SSO were significantly impacted by the combination of MNBW and BA. The influence mechanisms of micro-nano bubble water and biochar

on acidic soil aeration, yield, and quality are complicated, and more research will enhance our understanding of them.

5. Conclusions

Red soil's porosity and bulk density were much boosted by porous biochar, while the soil's redox potential and oxygen content were greatly raised by oxygen-rich micro-nano bubble water. Biochar and micro-nano bubble water both worked in concert to increase soil aeration and aeration porosity. The average soil oxygen concentration rose by 0.47–31.80 % and the average soil aeration porosity increased by 0.53–44.00 % in comparison to CK. With a net photosynthetic rate improvement of an average of 1.91–50.78 % and a dry matter accumulation increase of 10.53–69.19 %, the interaction of micro-nano bubble water with biochar greatly increased soil moisture content, encouraged cucumber root growth and photosynthesis, and increased dry matter accumulation. Simultaneously, it enhanced water use efficiency and yield, increased yield by an average of 1.72–44.23 % and water use efficiency by 0.42–76.57 %. When considering factors like yield and quality, O3B3 (O3 14–15 mg/L, B3 60 t/hm²) is the treatment with the highest yield and superior quality.

CRedit authorship contribution statement

Zan Ouyang: Writing – original draft, Supervision, Investigation. **Xueli Liang:** Data curation. **Jie Zhang:** Investigation. **Yong Zhang:** Investigation. **Qihua Yu:** Visualization. **Rong Tang:** Formal analysis. **Zhengfeng Yang:** Software. **Hui Wang:** Writing – review & editing, Resources.

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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Data availability

Data will be made available on request.

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