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Effect of Soil Aeration and Root Morphology on Yield under Aerated Irrigation

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Abstract: Soil compaction easily causes root hypoxia stress, resulting in poor root growth and the absorption of soil water and nutrients. We hypothesized that aerated irrigation (AI) could enhance nutrient uptake and utilization, thus unlocking the high yield potential by increasing soil aeration and root morphology indicators compared with that in the non-aeration treatment. A greenhouse experiment was conducted to investigate the effect of soil aeration and root morphology on the yield of greenhouse cucumbers. The dissolved oxygen (DO) in irrigation water at 10 mg L^{-1} (A_1), 20 mg L^{-1} (A_2), and non-aeration treatment (A_0) were applied via a subsurface drip irrigation system. The soil respiration rates, DO in soil water, root morphology, and crop yield were measured. The results showed that AI could significantly improve the soil respiration rate, DO in soil water, and root morphology compared with non-aeration treatment. The A_2 significantly increased soil respiration rate by 11.63% and 11.93%, respectively, compared with the A_1 and A_0 treatments. Under A_1 and A_2, the DO in soil water increased by 20.01% and 18.02%, respectively, compared with the A_0. Moreover, during the flowering and fruit set, the mature, and the late stages, the root surface area, root volume, root tip number, root forks, and root dry weight in the A_2 treatment significantly increased than that in the A_0 treatment. The soil respiration rate, DO in soil water, root length, and root forks were the main indexes correlated to the yield, respectively. The DO in soil water and root forks number significantly influenced the yield. The cucumber yield and economic benefits in A_2 peaked at 53.04 t ha^{-1} and 3.95 × 10^4 USD ha^{-1}, increased by 7.86% and 7.30% compared with that in the A_0 treatment, respectively ($p < 0.05$). The results could provide technical support and scientific knowledge for regulating greenhouse cucumbers under AI.

Keywords: canonical correlation analysis; economic benefits; grey correlation analysis; irrigation

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1. Introduction

Subsurface drip irrigation (SDI) is very popular due to its high irrigation efficiency and water use efficiency. However, the rhizosphere saturation wetting fronts [1] lead to a low oxygen diffusion rate and poor soil aeration [2], restricting crop yield increase [3]. Soil hypoxia can adversely affect root vigor by the reduction of the uptake of soil water and nutrients [4,5]. Therefore, the adequate oxygen supply in the rhizosphere was crucially important for high crop yield. The cucumber is a type of shallow-root vegetable crop in greenhouse cultivation. The cucumber root system is very sensitive to hypoxia. So, good aeration in the rhizosphere should be kept to ensure root growth and development, and the uptake of mineral soil nutrients such as nitrogen, phosphorus, and potassium [6]. As a new type of irrigation technique, aerated irrigation (AI) could deliver water, fertilizer, and air mixture to crop root zone through the SDI system, and unlock the high crop yield potential [7–9]. Previous AI studies mainly focused on tomato [5], rice [10,11], soybean [12], and other planting crops, and there is less research work on cucumber.

Soil aeration could promote crop root growth by increasing water use efficiency and nutrient uptake [13,14], and significantly improve crop dry weight, and yield of greenhouse vegetables [15,16]. The effect of AI on soil aeration and root morphology on crop yield was relatively complex. Simple correlation analysis and path analysis are often used to resolve the inter-relationship between crop yield and the related indicators in the soil-crop system under AI, which limited the deepening acquisition of factor-to-factor correlation analysis [17–19]. The influencing factors include multiple indicators of different categories with various criteria, while the evaluation depth of a single indicator was limited [20]. It was hard to resolve the effect of AI on crop yield. Canonical correlation analysis (CCA) was used to extract the overall correlation [21] between the two groups of variables. Compared to a simple correlation analysis, the gray correlation analysis synthesized multiple indicators into a whole and could be used to unravel the comprehensive changes of integrated factors accurately [22].

The AI is an effective technique used in saline, heavy, and clay loam soils [23,24]. Clay loam soil is the most commonly used in greenhouse cultivation. Therefore, clay loam soil was selected as the test soil to investigate the effects of AI on soil aeration, root morphology, and cucumber in various aeration rates. The correlation coefficients between soil respiration rate, dissolved oxygen (DO), root length, root surface area, root volume, root tip number, root fork number, root dry weight, and crop yield under different AI treatments were evaluated using gray correlation analysis. We hypothesized that AI could improve nutrient uptake and utilization, and stimulate crop growth by enhancing soil aeration and root morphology indicators compared with non-aeration treatment. The aims of this study were to (1) clarify the suitable aeration rate for cucumber growth, (2) resolve the coupling relationship between the soil aeration, root morphology, and crop yield under different AI, and (3) identify the key indicators for yield increase.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted from 23 August to 28 November 2020, in a solar greenhouse in Shouguang city Shandong province (36°94′ N, 118°59′ E), China. The region belonged to a warm temperate continental monsoon climate. The average annual rainfall was 708.4 mm, the air temperature was 13.2 °C, and the multi-year evaporation was 1834.0 mm. The greenhouse covered an area of 807.5 m^2 with 95 m in length and 8.5 m in width. It oriented east-west and faced south. The 0.2 mm thick thermal polyethylene sheeting was used in the greenhouse and naturally cooled with roof vents. The temperature and humidity dynamics during the cucumber growth period are shown in Figure 1. The greenhouse appearance and the plot arrangement are shown in Figure 2.

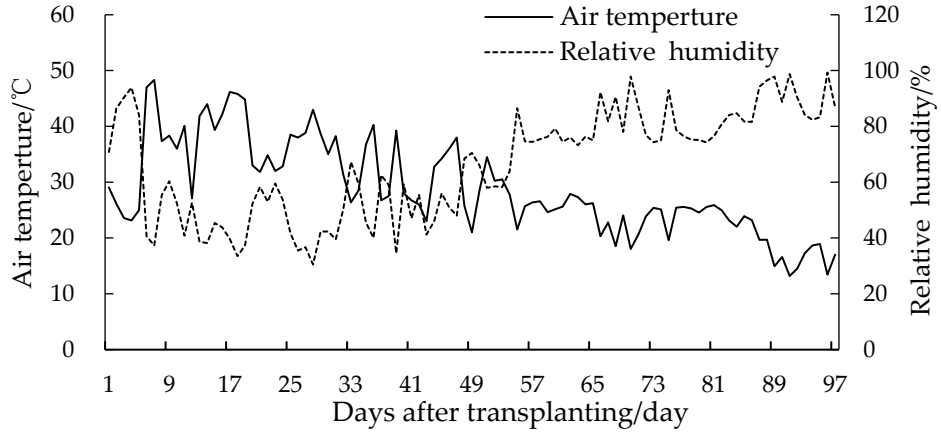


Figure 1. Relative humidity and air temperature in the greenhouse.

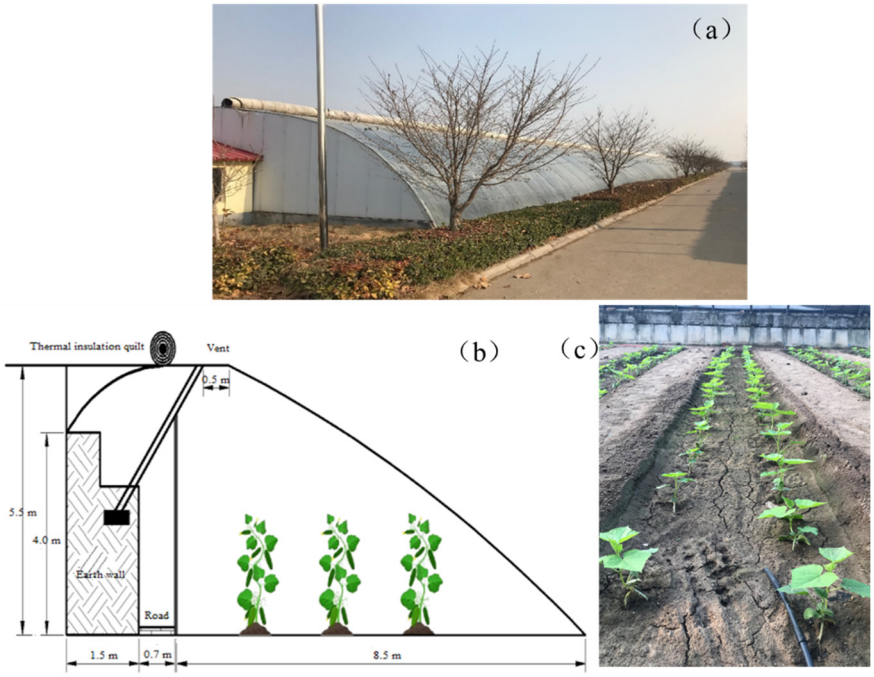


Figure 2. (**a**) The greenhouse appearance. (**b**) Schematic diagram of the greenhouse cross-section. (**c**) Plot layout map in the greenhouse.

2.2. Experimental Materials and Management

The soil used in the experiment was clay loam, and the basic soil's physical and chemical properties are listed in Table 1. The sand (0.02–2 mm), silt (0.002–0.02 mm), and clay (<0.002 mm) fractions of the soil were approximately 32.36%, 29.51%, and 38.13%, respectively. The experiment was arranged in a split-plot design, and the plot size was 8.5 m in length and 1.6 m in width. The cucumber plants were planted in double rows with 80 cm in row space and 35 cm in plant space. The 60 cm plastic film in length was vertically buried between two ridges to prevent the lateral movement of soil water. Subsurface drip irrigation (SDI) was used for irrigation, and the rated flow rate was 2.2 L h^{-1}. Before transplanting, the SDI belt (16 mm in diameter, 20 cm in adjacent dropper space) was laid in the center of each plot, and the buried depth was 15 cm below the soil surface.

Table 1. Basic physical and chemical properties of the test soil.

Soil Layer /cm	pH	Bulk Density /(g cm^{-3})	Field Water Holding Capacity/%	Saturated Water Content/%	Soil Particle Density/(g cm^{-3})	NO_3^--N /(mg kg^{-1})	NH_4^+-N /(mg kg^{-1})
0–20	7.94	1.23	38.51	42.99		82.14	10.81
20–40	8.16	1.51	37.16	43.16	2.72	44.85	11.08
40–60	8.25	1.64	36.57	41.68		19.22	19.28

The cucumber variety *Cucumis sativus* L. was "3966". The plant seedlings were transplanted on 22 August 2020, at the 3–leaf and 1-heart or 4–leaf and 1-heart stage, and the vines were hung when the plant height reached 40–50 cm. The cucumber reproductive period was divided into five stages, including the seedling stage (from 23 August to 13 September), the flowering and the fruiting stage (from 14 September to 13 October), the mature stage (from 14 October to 12 November), and the late stage (from 13 November to 27 November). The fruit was picked from 23 September 2020 to 27 November 2020. The field management practices included fertilization, weeding, pruning, and old leaf removal.

2.3. Experimental Design

The DO concentrations in irrigation water at 10 mg L^{-1} (A_1), 20 mg L^{-1} (A_2), and non-aeration treatment (A_0) [25] were applied via the SDI system. There were 9 plots composed of three treatments and three replicates.

Aerated water for irrigation was produced using a micro-nano bubble generator, and 99.99% ultra-pure oxygen was used as a gas source. The equipment consisted of a circulating aeration unit, a ratio adjustment unit, and a drip irrigation pressure stabilization unit. The DO concentration in irrigation water was monitored using a portable fiber optic oxygen spectrometer. When the target DO in water was reached, the irrigation water was supplied when the head water pressure reached 0.10 MPa, while the tailwater pressure was no less than 0.08 MPa. The principle of the water supply system is shown in Figure 3.

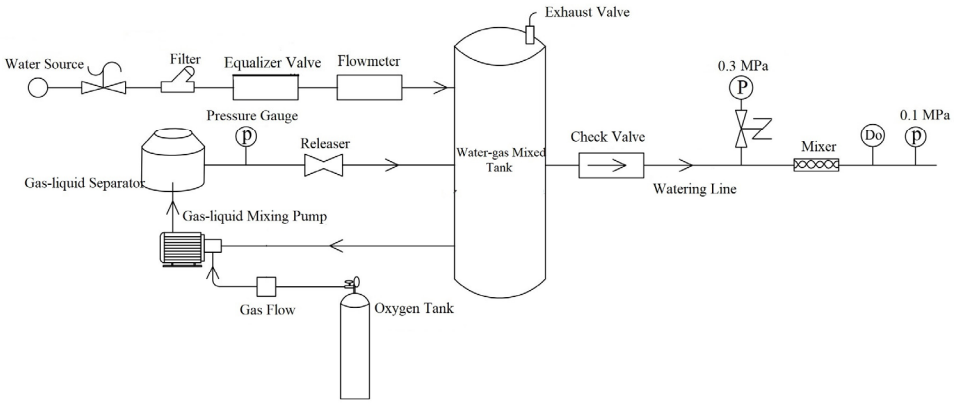


Figure 3. Schematic diagram of the preparation of aerated water for irrigation.

The fertilizers applied in this experiment were urea (N $\geq$ 46%) 240 kg ha^{-1}, calcium superphosphate (P_2O_5 $\geq$ 12%) 150 kg ha^{-1}, and potassium sulfate (K_2O $\geq$ 52%) 200 kg ha^{-1}. All phosphorus and potassium fertilizers were applied as basal fertilizer, 40% urea was used for a basal application, and the remaining 60% of urea was applied in four equals at the 37th, 53rd, 68th, and 84th days after transplanting. The fertilizer pump device was used to mix fertilizer and applied via the SDI system.

2.4. Test Indexes and Methods

2.4.1. Root System Indicators

During the flowering and fruiting stage, the mature stage, and the late stage, three plant root samples of cucumbers from each plot were collected by digging all the roots wrapped in the soil as much as possible, and placed in a mesh bag with a diameter of 0.5 mm, and soaked in water. After separating the roots from the soil with tap water, the roots were dried with absorbent paper and weighed for fresh weight. All the roots in one sample were placed in a transparent tray filled with water to a depth of 10 mm and kept from crossing. The root samples were scanned with an Epson Expression 1600 pro scanner to obtain a grayscale TIF image. The images were analyzed with a WinRHIZO Pro image processing system to obtain the effective root surface area (cm^2), root volume (cm^3), root length (cm), root tip, and root fork.

2.4.2. Soil Water Dissolved Oxygen Content

The DO in soil water was measured using a fiber-optic oxygen meter with the firesting O_2 connected to an oxygen-sensitive probe (Robust Oxygen Miniprobe). The DO probe was embedded in the soil 5 cm laterally and 10 cm vertically from the plant stalk. The measurement was applied every 10-day interval since from the 25th day after transplanting (16 September 2020), while the measurement frequency was expanded after irrigation events. The data were automatically saved after the data were stabilized, and the time duration was about 5 min.

2.4.3. Soil Respiration Rate

Soil respiration rate was measured using an ADC Lci-SD model (Delta-T, Cambridge, UK) photosynthesis meter connected to a soil respiration chamber. The soil respiration chamber base was buried into the soil surface before measurement, and the data were recorded 3–5 min later when the record was stable. Three samples of cucumber from each plot were selected and monitored continuously for 8 days after the irrigation event.

2.4.4. Yield and Economic Benefits

At the fruit ripening stage, the 10 cucumber plants were labeled to calculate the plot yield. The selected plants were healthy and free from diseases and pest attacks. The individual fruit weight and the number of fruits per plant were also recorded.

The economic benefit was calculated as follows [14]:

$$\text{Yield value} = \text{Yield} \times \text{cucumber market price} \quad (1)$$

$$\text{Agricultural inputs} = \text{cucumber seedlings fees} + \text{fertilizers fees} \quad (2)$$

$$\text{Total input} = \text{Agricultural inputs} + \text{Other inputs} \quad (3)$$

$$\text{Net income} = \text{Yield value} - \text{Total input} \quad (4)$$

Agricultural inputs include cucumber seedlings at 0.09 USD plant^{-1}, urea (0.05 USD kg^{-1}), calcium super-phosphate (0.16 USD kg^{-1}), and potassium sulfate (0.59 USD kg^{-1}); other inputs include machinery and management fees. In autumn cultivation, the cucumber market price was 0.89 USD kg^{-1}.

2.5. Grey Correlation Analysis

In this study, the cucumber yield was used as the reference series (M_0), and soil aeration, and root morphology as the comparison series (M_i). The relative relationships among yield, soil aeration, and root morphology of cucumber could be clarified through grey system correlation analysis. The correlation coefficient can be calculated using the following formula [12]:

$$\xi_i(k) = \frac{(\Delta M_{\min} + \rho \Delta M_{\max})}{\Delta M_{i(k)} + \rho \Delta M_{\max}} \quad (5)$$

where $\Delta M_{\min}$ and $\Delta M_{\max}$ are the minimum and maximum absolute differences of all comparison sequences at each time, respectively. $\Delta M_{i(k)}$ is the absolute difference between the two comparison sequences at time k, and ρ is the resolution coefficient with the setting as 0.5.

The degree of relevance is calculated as follows [26]:

$$r_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \quad (6)$$

where r_i is the degree of association between subsequence i and parent sequence 0, and n is the length of the comparison sequence.

2.6. Statistical Analysis

Analysis of variance (ANOVA) and typical correlation was analyzed by the use of SPSS 25.0 Statistics software (SPSS Inc., Chicago, IL, USA) at $p < 0.05$. Gray correlation analysis was done by using SPSSPRO 22.0. Plots and data processing were performed using Excel 2019, PowerPoint 2019, and Origin 2022b (Origin Lab Corp., Microsoft Corp., Redmond, MA, USA).

3. Results

3.1. Dissolved Oxygen (DO) in Soils Water

The dynamic of DO in soil water is shown in Figure 4. Since the beginning of irrigation, the dissolved oxygen concentration in soil water decreased rapidly, and the lowest value appeared at the end of irrigation. It slowly rose with the redistribution of soil water. The DO in soil water under the AI treatment was significantly improved. Under the A_2 treatment, the DO in soil water was the highest one among A_0, A_1, and A_2, peaking at 7.81 mg L^{-1} on the 75th day after planting. Compared to A_0, the DO in soil water under A_2 and A_1 treatment increased by 11.97–21.09% and 13.72–17.55% ($p < 0.05$), respectively. Furthermore, there was a significant difference in soil water DO between AI treatment and non-aeration treatment in the late stage of cucumber, probably because of the entrance of the aging stage, the weakening root respiration, and the microbial respiration rate. The AI treatment enhanced the DO in irrigation water, which extended the contact time between the root system and soil oxygen, and thus improved the root system and microbial respiration.

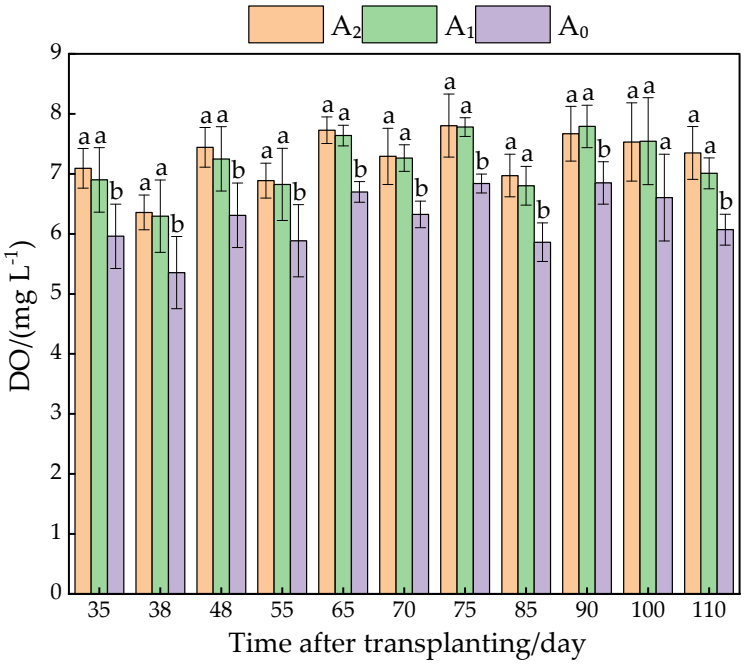


Figure 4. Dynamics of DO content in soil water under different aeration irrigation treatments. A_2, A_1, and A_0 indicate DO in irrigation water at 20 mg L^{-1}, 10 mg L^{-1}, and non-aeration treatment, respectively. Different letters on the same day indicate significance differences at $p < 0.05$.

3.2. The Soil Respiration Rate

The nutrient demand of cucumber increased during the mature stage, while root respiration, soil microorganisms, and soil fauna oxygen consumption also increased. Therefore, the soil respiration rate in one irrigation cycle during the mature stage is listed in Figure 5. After the irrigation event, the soil respiration rate showed a trend of rapid reduction. The soil respiration rate for the A_2 treatment was always the highest, and the soil respiration rate for the A_0 treatment was always the lowest. The mean values of soil respiration rates in A_2, A_1, and A_0 treatments were 3.32, 2.97, and 2.96 μmol $m^{-2}s^{-1}$, respectively (Figure 5). The peak soil respiration rate reached 4.49 μmol $m^{-2}s^{-1}$ on the 4th day after irrigation, with a 17.15% increase in the A_2 treatment compared to the A_0 treatment ($p < 0.05$). Compared with A_1 and A_0 treatments, the mean soil respiration rate in the A_2 treatment increased by 11.63% and 11.93%, respectively ($p < 0.05$). Therefore, the soil respiration rate under AI treatment significantly increased compared to non-aerated treatment.

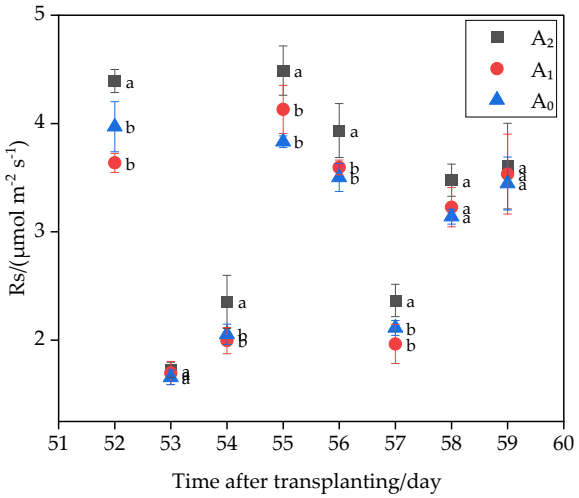


Figure 5. Soil respiration rates during one cycle of irrigation under different aeration irrigation treatments. A_2, A_1, and A_0 indicate DO in irrigation water at 20 mg L^{-1}, 10 mg L^{-1}, and non-aeration treatment, respectively. Different letters on the same day indicate significance differences at $p < 0.05$.

3.3. The Root Morphology

From Figure 6, it is obvious that AI had a significant effect on root morphology, with a more developed root system of high root density, increasing the contact area between the root system and the soil, and facilitating the uptake of soil water and nutrients. The root length, root surface area, root volume, root tip number, root fork number, and root dry weight of cucumber during the flowering and fruiting stage, the mature stage, and the late stage are shown in Figure 7. In the A_2 treatment, the increase of the most root indexes ranked first among the tree treatment. Similarly, the increase rate of root tip number ranked in the top one among A_0, A_1, and A_2. From the mature stage to the late stage, the root length and root fork number increased rapidly.

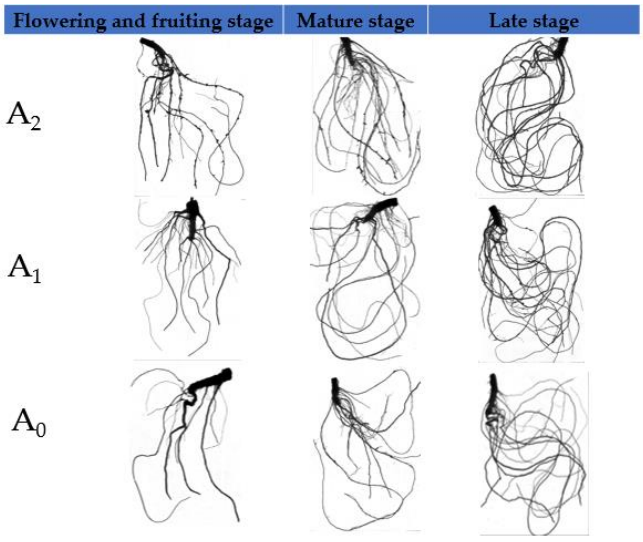


Figure 6. TIF diagram of roots under different aeration treatments. A_2, A_1, and A_0 indicate DO in irrigation water at 20 mg L^{-1}, 10 mg L^{-1}, and non-aeration treatment, respectively.

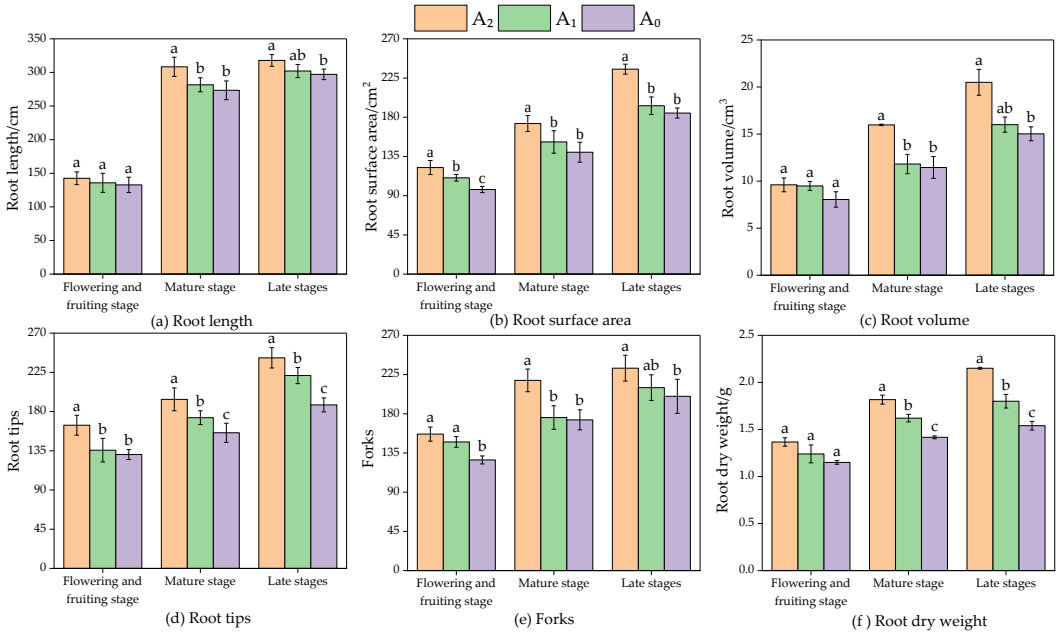


Figure 7. Effect of different aeration treatments on root morphology of cucumber flowering and fruiting stage, mature, and last stage; A_2, A_1, and A_0 indicate DO in irrigation water at 20 mg L^{-1}, 10 mg L^{-1}, and non-aeration treatment, respectively. Different letters in the same growth stage indicate significance difference at $p < 0.05$.

During the flowering and fruiting stage, the root surface area, root volume, root tip number, root fork number, and root dry weight in A_2 increased by 25.96%, 19.28%, 25.77%, 23.36%, and 18.84%, respectively, compared to that in A_0. The cucumber root surface area, root tip number, and root dry weight in A_2 increased by 10.64%, 21.13%, and 10.22%, respectively, compared to A_1. The cucumber root surface area, root volume, and the number of forks in treatment A_1 increased by 13.85%, 17.80%, and 16.27%, respectively, compared to A_0 ($p < 0.05$).

In the mature stage, the root length, root surface area, root volume, root tip number, fork number, and root dry weight in A_2 increased by 12.76%, 23.53%, 39.50%, 24.63%, 26.20%, and 28.24%, respectively, compared to A_1. The root dry weight of A_1 increased by 14.35% compared to A_0 ($p < 0.05$).

During the late stage, the root length, root surface area, root volume, root tip number, root fork number, and root dry weight in A_2 increased by 6.97%, 27.25%, 36.42%, 28.77%, 16.17%, and 39.61%, respectively, compared to A_0. The root surface area, root volume, root fork number, and root dry weight in A_2 increased by 21.75%, 28.10%, 10.63%, and 19.44%, respectively, compared to A_1. The number of root tips and root dry weight in A_1 increased by 17.94% and 16.88%, respectively, compared to A_0 ($p < 0.05$), suggesting that AI had a significant promoting effect on root indexes during the mature and late stage compared to non-aeration treatment.

3.4. Simple Correlation Analysis

The Pearson correlation analysis is applied to cucumber yield, soil respiration rate, soil DO and root morphological indexes (Figure 8). The root volume, root tip number, and root dry weight were all significantly correlated with cucumber yield ($p < 0.05$) and the soil respiration rate, soil DO, root length, root surface area, and root fork number were all extremely and significantly positively correlated with cucumber yield ($p < 0.01$). Soil respiration rate showed an extremely significant positive correlation with soil DO ($p < 0.01$), while an extremely significant positive correlation with root length ($p < 0.01$). Soil DO in soil water was significantly positively correlated with root length, surface area, root volume, and root fork number and was extremely and positively correlated with root

tip number and root dry weight ($p < 0.01$). The correlation between DO, root length, root surface area, root volume, and root fork number were significant. The correlations between root tip number and root dry weight were extremely significant ($p < 0.01$). However, simple correlation analysis can only reflect the correlation between individual variables. It was necessary to conduct a canonical correlation analysis of the two groups of variables to reflect the overall correlation between the two groups of variables.

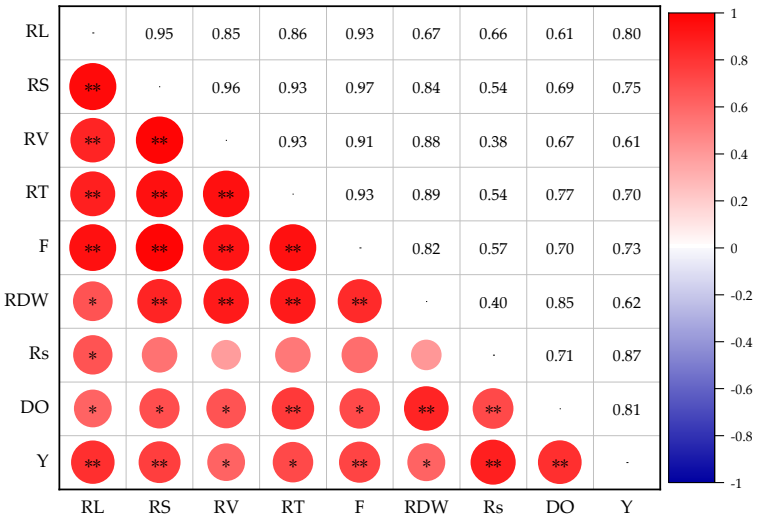


Figure 8. Pearson correlation analysis of cucumber yield, soil respiration, dissolved oxygen, and root morphological indexes. * and ** identify significant differences at $p < 0.05$ and $p < 0.01$, respectively. RL, root length; RS, root surface area; RV, root volume; RT, root tips; F, forks; RDW, root dry weight; Rs, soil respiration rate; DO, dissolved oxygen; Y, yield. Red represents a positive correlation, and blue represents a negative correlation. The deeper the color, the more significant the correlation.

3.5. Canonical Correlation Analysis (CCA)

The canonical correlation between soil aeration indexes (soil respiration rate and DO in soil water) and apparent indexes (yield, root length, root surface area, root volume, root tip number, root fork number, and root dry weight) was analyzed (Table 2). Two typical correlation coefficients (Table 3) were obtained, and the significance test results were $0.009 < 0.01$ and $0.245 > 0.05$, so the first typical correlation coefficient met the requirements. It could be found that the first typical correlation coefficient of 0.994 was greater than the correlation coefficients derived from the simple correlation analyses (Table 4), indicating that the typical correlation analysis could better express the role of the relationship between soil aeration indexes and plant apparent index.

Table 2. Soil aeration (soil respiration rate and soil DO) and apparent index (yield, root length, root surface area, root volume, root tip number, fork number, and root dry weight) variables.

Index Classification	Number	Factor	Index Encoding
soil aeration	1	Soil respiration rate	x_1
	2	DO	x_2
apparent index	3	Yield	y_1
	4	Root length	y_2
	5	Root surface area	y_3
	6	Root volume	y_4
	7	Root tips	y_5
	8	Root forks	y_6
	9	Root dry weight	y_7

Table 3. Typical correlation and significance test among soil aeration and apparent index variables.

	Collection	Eigenvalue	Wilks Statistic	F	Num D. F	Den D. F	Sig.
1	0.994	89.440	0.003	7.889	14.000	6.000	0.009
2	0.872	3.164	0.240	2.110	6.000	4.000	0.245

Note: Num D. F, numerator degrees of freedom; Den D. F, Denominator degrees of freedom; Sig., Significance.

Table 4. Canonical correlation coefficients of soil aeration index.

Variable	Typical Correlation Variables	
	Standardized Typical Coefficients	Correlation Coefficient
x_1	−0.156	0.629
x_2	1.105	0.994

The raw data were first standardized to eliminate the effect of magnitude, and the typical correlation models were obtained in Tables 4 and 5 as follows:

$$\begin{cases} X = -0.156x_1 + 1.105x_2 \\ Y = 1.066y_1 - 0.159y_2 - 2.852y_3 + 1.598y_4 - 0.304y_5 + 1.067y_6 + 0.709y_7 \end{cases} \quad (7)$$

where the X variable is an index of soil aeration, and the Y variable is an apparent index.

Table 5. Canonical correlation coefficients of standardization for apparent metrics.

Variable	Typical Correlation Variables	
	Standardized Typical Coefficients	Correlation Coefficient
y_1	1.066	0.768
y_2	−0.159	0.571
y_3	−2.852	0.686
y_4	1.598	0.685
y_5	−0.304	0.769
y_6	1.067	0.694
y_7	0.709	0.883

According to the typical correlation model equation, it could be seen that x_2 (soil DO) was the dominant factor for X with a correlation coefficient of 0.994; y_1 (yield), y_3 (root surface area), y_4 (root volume), and y_6 (root fork number) were the dominant factors for Y with correlation coefficients of the soil aeration index by 0.768, 0.686, 0.685 and 0.694, respectively. Therefore, the X variable can reflect DO in soil water, while the Y variable could reflect yield, root surface area, root volume, and fork number. According to the typical coefficients, the soil aeration index was positively correlated with the apparent index. The crop yield, root surface area, root volume, and root fork number were significantly positive with DO in soil water, while the root surface area was significantly negatively correlated with DO in soil water. This suggested that when the soil DO in soil water increased, the soil aeration also increased, the root surface area reduced, and the root volume, root fork number, and yield increased subsequently.

3.6. Grey Correlation Analysis

Figure 9 shows the gray correlation analysis between the indicators of different AI treatments and yield, with yield as the parent series (comparison series). The eight indicators including root length, root surface area, root volume, root tip number, root fork number, root dry weight, soil respiration rate, and DO in soil water were used for the evaluation. Firstly, dimensionless processing was carried out on the data to obtain the correlation between 8 evaluation items and yield. The analysis revealed significant differences in the correlations between the indexes of different irrigation treatments and cucumber

yield. Compared to A_1 and A_0 treatments, correlation coefficients of root dry weight, root surface area, and root volume with DO in soil water in A_2 were the highest among the three treatments, as 0.877, 0.803, 0.749, and 0.635, respectively. Also, AI treatment increased the correlation between root length, soil respiration rate, and yield compared to the non-aeration treatment.

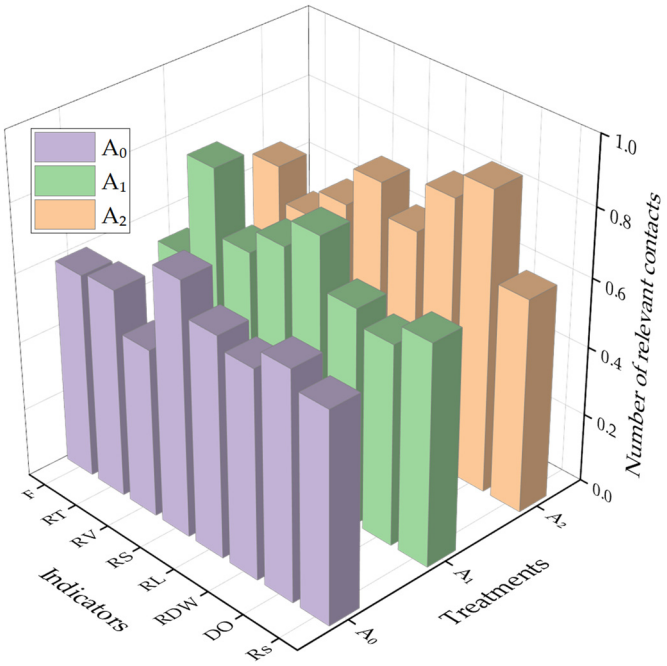


Figure 9. Analysis of grey correlation between soil environmental indicators, root morphology, and crop yield. Note: RL, root length; RS, root surface area; RV, root volume; RT, root tips; F, forks; RDW, root dry weight; Rs, soil respiration rate; *DO*, dissolved oxygen in the water; Y, yield. A_2, A_1, and A_0 indicate DO in irrigation water at 20 mg L^{-1}, 10 mg L^{-1}, and non-aeration treatment, respectively.

3.7. Economic Benefit Analysis of Cucumber under Various AI Treatments

Among the three treatments, the highest yield of 53.04 t ha^{-1} was recorded in the A_2 treatment (Table 6), which increased by 4.27% and 7.86% compared to A_1 and A_0, respectively ($p < 0.05$). The net income of cucumbers increased with the increase in aeration concentration. The highest net income fell in the A_2 treatment at 3.95 × 10^4 USD ha^{-1}, which in the A_2 treatment increased net income by 7.30% compared to the A_0 treatment, indicating that AI can improve the economic benefits of cucumber.

Table 6. Economic profits of cucumber production under different aeration amounts.

Treatment	Yield/ (t ha^{-1})	Yield Value/ 10^4 USD ha^{-1}	Agricultural Inputs/ 10^4 USD ha^{-1}	Other Inputs/ 10^4 USD ha^{-1}	Total Inputs/ 10^4 USD ha^{-1}	Net Income/ 10^4 USD ha^{-1}	Benefit Relative to Control/10^4 USD ha^{-1}
A_2	53.04 a	4.72	0.31	0.46	0.77	3.95	0.27
A_1	50.87 b	4.52	0.31	0.46	0.77	3.75	0.07
A_0	49.18 b	4.37	0.31	0.39	0.70	3.68	0

Note: Agricultural inputs include cucumber seedlings at 0.09 USD $plant^{-1}$, urea (0.05 USD kg^{-1}), calcium super-phosphate (0.16 USD kg^{-1}), and potassium sulfate (0.59 USD kg^{-1}); other inputs include machinery and management fees. In autumn cultivation, the cucumber market price was 0.89 USD kg^{-1}. Different letters indicate significant differences at $p < 0.05$.

4. Discussion

4.1. Effect of Aerated-Irrigation on Soil Aeration and Root Morphology

There was a negative correlation between soil water content and soil respiration [27], and the soil water content directly affected soil respiration and root respiration. The crop

root growth was prone to soil hypoxia and other environmental factors [28,29], which weakened the aerobic respiration of roots, restricted root growth and development, and resulted in a shortage supply of energy metabolism and crop yield reduction. The AI significantly promoted soil respiration rate and the DO in soil water in this study. The most significant effect was observed at an aeration rate of 20 mg L^{-1}, with an average increase of 11.93% and 20.01%, respectively, compared with the non-aeration treatment ($p < 0.05$), which indicated that the AI could accelerate the gas exchange in the soil, thus increasing the DO in soil water. Our results are in line with the findings that soil oxygen content and respiration in AI increased by 2.4–32.6% and 42–100%, respectively, compared with the non-aeration treatment by Chen et al. [30] on pineapple. The reason for that could be that AI transfers a mixture of water and air to the crop rhizosphere, improving the aeration of the clay loam soil and increasing the oxygen content of the soil in the root zone. Previous studies also found that the improvement of soil ventilation improved the root length and surface area [31] of melon, which is consistent with the finding in this study that the root morphology of pepper in AI increased compared to non-aeration treatment. The AI at the mature stage significantly affected root length and bifurcation number (Figure 7a,e). At the late stage, cucumber root surface area and root tip number increased significantly in AI treatment compared to non-aeration treatment, which is consistent with the findings that AI significantly delayed root aging [32]. The reason could be that increased inter-root oxygen content improved the soil bacterial community's diversity, composition, and structure. Meanwhile, root morphology and vigor positively correlated with the soil bacterial community's diversity, composition, and structure [13,33]. Pearson correlation analysis revealed that the root length, root surface area, root volume, and the number of root forks were all positively correlated with the DO in soil water ($p < 0.05$), and root tip number and root dry weight were both extremely significant and positively correlated to the DO in soil water ($p < 0.01$) (Figure 8). The DO in soil water ranked in the top one among A_0, A_1, and A_2 when the aerated amount was at 20 mg L^{-1}. The reason for the high root morphology indexes was probably because of the relatively high DO in soil water. The retention time of air bubbles in the soil increased, which stimulated the contact time and contact area between roots and oxygen, accelerating the gas exchange process in the soil. The soil respiration rate and root respiration increased, which facilitated root growth and lateral root development. Therefore, the balance between soil moisture and soil aeration is essential for root growth.

4.2. Effect of Soil Aeration Index and Root Morphology on Yield

The main factors affecting crop yield are the temperature and humidity, oxygen content, and nutrients of the soil in the root zone [34]. Previous studies showed that AI could increase the concentration of dissolved oxygen in soil water, enhance the respiratory raw material and the soil respiration rate [35], improve the environment in the root zone of plants, and increase microbial abundance and nutrient uptake, thus promoting plant growth and fruit yield [36,37]. Also, AI can effectively increase soil enzyme activity in the root zone, improve the inter-root soil environment, enhance aerobic root respiration, promote crop growth and development, and achieve crop quality and yield increase [38,39]. Whereas, the root system acquires energy from root respiration to maintain its growth and various physiological and metabolic activities to promote nutrient and water uptake and utilization [40]. Root respiratory activity influenced root function, plant growth and development, and crop yield. In this experiment, typical correlation analysis showed that DO in soil water was the dominant factor for soil aeration, and yield, whereas root surface area, root volume, root fork number, and root dry weight were the dominant factors for apparent metric indexes. In addition, root volume, fork number, and root dry weight were positively correlated with yield, indicating that AI increased root respiration rate by increasing DO in soil water, and the increase in root volume and fork number increased root uptake capacity, and area of absorbed nutrients in the soil [13]. Grey correlation analysis showed that the correlations between DO in soil water, root dry weight, root

surface area, and root volume and yield of cucumber were significantly higher at the DO irrigation water at 20 mg L^{-1}, indicating that AI-enhanced the relationships between the effects of soil aeration, root morphology and yield of cucumber. Because AI provided oxygen for the aerobic respiration of cucumber roots, promoted root growth, maintained suitable oxygen content for cucumber growth [36], significantly improved root volume and bifurcation number, promoted root water absorption capacity and nutrient uptake [41] and the distribution ratio of nitrogen in crop organs, resulting in crop yield increase [39].

4.3. Yield and Economic Benefits

In the present study, the effect of AI on cucumber yield was evident. In the experiment of Liu et al. [42], the net income under AI was higher than all drip irrigation treatments. The results of this study revealed that the cucumber yield and economic return in AI increased by 7.86% and 7.30%, respectively, compared to non-aeration treatment. This is consistent with the findings by Du [43]; the net benefit and tomato yield in AI increased by 1.98% to 7.24% and 2.03% to 6.61%, compared with the non-aeration treatment. It was possible to increase both the crop yield and the economic benefit by using AI. Our results also indicated that the 20 mg L^{-1} in the DO of irrigation water reached the best balance, which would improve root growth and physiological activities, enhance water and nutrients uptake [14], and increase dry matter accumulation, crop yield [44], and economic benefits.

5. Conclusions

Aerated irrigation could improve soil respiration rate, the dissolved oxygen DO in soil water, and root morphology. Based on the canonical correlation and gray correlation analysis, it was found that the DO in soil water was the dominant factor for the soil aeration index, and yield, root surface area, root volume, and root fork number were the dominant factors for the apparent index. Compared to non-aeration treatment, the DO at 20 mg L^{-1} in irrigation water increased the correlation between the DO in soil water, root dry weight, root surface area, root volume, yield, and the key influencing indexes on cucumber yield were the DO in soil water and root surface area. The cucumber yield and economic benefit were the highest when the aerated rate was 20 mg L^{-1}, which increased by 7.86% and 7.30% compared to non-aeration ($p < 0.05$).

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References

1. Silberbush, M.; Gornat, B.; Goldberg, D. Effect of irrigation from a point source(trickling) on oxygen flux and on root extension in the soil. *Plant Soil* **1979**, *52*, 507–514. [CrossRef]

2. Bhattarai, S.P.; Midmore, D.J.; Pendergast, L. Yield, water-use efficiencies and root distribution of soybean, chickpea and pumpkin under different subsurface drip irrigation depths and oxygation treatments in vertisols. *Irrigation. Sci.* **2008**, *26*, 439–450. [CrossRef]
3. Shahar, B.; Maya, W.; Evans, J.F.; Anna, B.; Yael, S.; Meni, B.H.; Nirit, B.; Hadas, M. Drip irrigation with nanobubble oxygenated treated wastewater improves soil aeration. *Sci. Hortic.-Amst.* **2022**, *291*, 110550.
4. Bradford, K.J.; Hsiao, T.C. Stomatal behavior and water relations of waterlogged tomato plants. *Plant. Physiol.* **1982**, *70*, 1508–1513. [CrossRef]
5. Horchani, F.; Aloui, A.; Brouquisse, R.; Aschi-Smiti, S. Physiological responses of tomato plants (*Solanum lycopersicum*) as affected by root hypoxia. *J. Agron. Crop. Sci.* **2008**, *194*, 297–303. [CrossRef]
6. Bhattarai, S.P.; Dhungel, J.; Midmore, D.J. Oxygation improves yield and quality and minimizes internal fruit crack of cucurbits on a heavy clay soil in the semiarid tropics. *J. Agric. Sci.* **2010**, *2*, 17–25.
7. Jin, C.C.; Pan, H.W.; Lei, H.J.; Xiao, Z.Z.; Sun, K.P. Effects of aerated irrigation and nitrogen application on tomato yield and nitrogen absorption in greenhouse environment. *Fresenius. Envron. Bull.* **2022**, *31*, 8150–8160.
8. Liu, Y.X.; Zhou, Y.P.; Wang, T.Z.; Pan, J.C.; Zhou, B.; Muhammad, T.; Zhou, C.F.; Li, Y.K. Micro-nano bubble water oxygation: Synergistically improving irrigation water use efficiency, crop yield and quality. *J. Clean. Prod.* **2019**, *222*, 835–843. [CrossRef]
9. Zhu, Y.; Miles, D.; Cai, H.j.; Song, L.b.; Chen, H. The effects of aerated irrigation on soil respiration, oxygen, and porosity. *J. Integr. Ag.* **2019**, *18*, 2854–2868. [CrossRef]
10. Sang, H.; Jiao, X.; Wang, S.F.; Guo, W.H.; Salahou, M.K.; Liu, K.H. Effects of micro-nano bubble aerated irrigation and nitrogen fertilizer level on tillering, nitrogen uptake and utilization of early rice. *Plant. Soil. Environ.* **2018**, *64*, 297–302. [CrossRef]
11. Zhu, L.; Yu, S.; Jin, Q. Effects of aerated irrigation on leaf senescence at late growth stage and grain yield of rice. *Rice. Sci.* **2012**, *19*, 44–48. [CrossRef]
12. Bhattarai, S.P.; Huber, S.; Midmore, D.J. Aerated subsurface irrigation water gives growth and yield benefits to zucchini, vegetable soybean and cotton in heavy clay soils. *Ann. Appl. Biol.* **2004**, *144*, 285–298. [CrossRef]
13. Li, Y.; Niu, W.Q.; Zhang, M.Z.; Wang, J.W.; Zhang, Z.X. Artificial soil aeration increases soil bacterial diversity and tomato root performance under greenhouse conditions. *Land. Degrad. Dev.* **2020**, *31*, 1443–1461. [CrossRef]
14. Cui, B.J.; Niu, W.Q.; Du, Y.D.; Zhang, Q. Response of yield and nitrogen use efficiency to aerated irrigation and N application rate in greenhouse cucumber. *Sci. Hortic.-Amst.* **2020**, *265*, 109220. [CrossRef]
15. Zang, O.Y.; Tian, J.C.; Yan, X.F.; Shen, H. Effects of different concentrations of dissolved oxygen or temperatures on the growth, photosynthesis, yield and quality of lettuce-Science Direct. *Agric. Water Manag.* **2019**, *228*, 105896.
16. Du, Y.D.; Cao, H.X.; Liu, S.Q.; Gu, X.B.; Cao, Y.X. Response of yield, quality, water and nitrogen use efficiency of tomato to different levels of water and nitrogen under drip irrigation in Northwestern China. *J. Integr. Agric.* **2017**, *16*, 1153–1161. [CrossRef]
17. Baram, S.; Evans, J.F.; Berezkin, A.; Ben-Hur, M. Irrigation with treated wastewater containing nanobubbles to aerate soils and reduce nitrous oxide emissions. *J. Clean. Prod.* **2020**, *280*, 124509. [CrossRef]
18. Zang, M.; Lei, H.J.; Pan, H.W.; Liu, H.; Xu, J.X. Aerated subsurface drip irrigation improving soil aeration and tomato growth. *Trans. Chin. Soc. Agric. Mach. Eng.* **2018**, *34*, 109–118. (In Chinese)
19. Du, Y.D.; Zhang, Q.; Cui, B.J.; Sun, J.; Wang, Z.; Ma, L.H.; Niu, W.Q. Aerated irrigation improves tomato yield and nitrogen use efficiency while reducing nitrogen application rate. *Agric. Water Manag.* **2020**, *235*, 106152. [CrossRef]
20. Zhang, Z.; Li, M.N.; Yang, Z.; Cai, Z.L.; Hong, T.T. Comprehensive regulation of water and fertilizer coupling based on multi-index collaboration of strawberry. *Trans. Chin. Soc. Agric. Mach.* **2020**, *51*, 267–276. (In Chinese)
21. Wang, C.H.; Zhang, Y.Z.; Wang, H.; Zheng, W.J.; Zhao, J.M. Canonical correction analysis on relationship between yield traits and main quality traits of japonica hybrid rice in north China. Southwest Chin. *J. Agric. Sci.* **2012**, *25*, 781–785. (In Chinese)
22. Zou, J.; Zhang, J.Q.; Long, Y.; Chen, K.; Long, J. Grey relational analysis based on the production and main agronomic traits in 20 freshly edible cron varieties. *Seed* **2019**, *38*, 138–142. (In Chinese)
23. Bhattarai, S.P.; Pendergast, L.; Midmore, D.J. Root aeration improves yield and water use efficiency of tomato in heavy clay and saline soils. *Sci. Hortic.-Amst.* **2006**, *108*, 278–288. [CrossRef]
24. Zhou, Y.P.; Bastida, F.; Zhou, B.; Sun, Y.F.; Gu, T.; Li, S.Q.; Li, Y.K. Soil fertility and crop production are fostered by micro-nano bubble irrigation with associated changes in soil bacterial community. *Soil. Biol. Biochen.* **2020**, *141*, 107663. [CrossRef]
25. Qiu, R.J.; Du, T.S.; Kang, S.Z.; Chen, R.Q.; Wu, L.S. Assessing the SIMDualKc model for estimating evapotranspiration of hot pepper grown in a solar greenhouse in Northwest China. *Agric. Syst.* **2015**, *138*, 1–9. [CrossRef]
26. Adams, S.; Cockshull, K.; Cave, C. Effect of temperature on the growth and development of tomato fruits. *Ann. Bot.* **2001**, *88*, 869–877. [CrossRef]
27. Zhu, J.J.; Niu, W.Q.; Zhang, Z.H.; Siddique, K.H.M.; Sun, D.; Yang, R.Y. Distinct roles for soil bacterial and fungal communities associated with the availability of carbon and phosphorus under aerated drip irrigation. *Agric. Water Manag.* **2022**, *274*, 107925. [CrossRef]
28. Pendergast, L.; Bhattarai, S.P.; Midmore, D.J. Evaluation of aerated subsurface drip irrigation on yield, dry weight partitioning and water use efficiency of a broad-acre chickpea (*Cicer arietinum*, L.) in a vertosol. *Agric. Water Manag.* **2019**, *217*, 38–46. [CrossRef]
29. Armstrong, W.; Beckett, P.M.; Colmer, T.D.; Setter, T.L.; Greenway, H. Tolerance of roots to low oxygen: 'anoxic' cores, the phytoglobin-nitric oxide cycle, and energy or oxygen sensing. *J. Plant. Physiol.* **2019**, *239*, 92–108. [CrossRef]

30. Chen, X.M.; Dhungel, J.; Bhattarai, S.P.; Torabi, M.; Pendergast, L.; Midmore, D.J. Impact of oxygation on soil respiration, yield and water use efficiency of three crop species. *J. Plant. Ecol.* **2011**, *4*, 236–248. [CrossRef]
31. Botta, G.F.; Tolón, B.A.; Bienveni, D.F.; David, R.; Daniel, A.L.; Alejandar, E.C.; Enrique, E.C. Sunflower (*Helianthus annuus* L.) harvest: Tractor and grain chaser traffic effects on soil compaction and crop yields. *Land. Degerad. Dev.* **2018**, *29*, 4252–4261. [CrossRef]
32. Wei, C.L.; Zhu, Y.; Zhang, J.Z.; Wang, Z.H. Evaluation of Suitable Mixture of Water and Air for Processing Tomato in Drip Irrigation in Xinjiang Oasis. *Sustainability* **2021**, *13*, 7845. [CrossRef]
33. Li, Y.; Niu, W.Q.; Dyck, M.; Wang, J.W.; Zou, X.Y. Yields and nutritional of greenhouse tomato in response to different soil aeration volume at two depths of subsurface drip irrigation. *Sci. Rep.* **2016**, *6*, 39307. [CrossRef] [PubMed]
34. Boyer, J.S. Plant Productivity and Environment. *Science* **1982**, *218*, 443–448. [CrossRef]
35. Yu, Z.Z.; Wang, C.; Zou, H.F.; Wang, H.X.; Li, H.L.; Sun, H.T.; Yu, D.S. The Effects of Aerated Irrigation on Soil Respiration and the Yield of the Maize Root Zone. *Sustainability* **2022**, *14*, 4378. [CrossRef]
36. Li, Y.; Niu, W.Q.; Wang, J.W.; Liu, L.; Zhang, M.Z.; Xu, J. Effects of artificial soil aeration volume and frequency on soil enzyme activity and microbial abundance when cultivating greenhouse tomato. *Soil. Sci. Soc. Am. J.* **2016**, *80*, 1208–1221. [CrossRef]
37. Zhou, Y.P.; Zhou, B.; Xu, F.P.; Muhammad, T.; Li, Y.K. Appropriate dissolved oxygen concentration and application stage of micro-nano bubble water oxygation in greenhouse crop plantation. *Agric. Water Manag.* **2019**, *223*, 105713. [CrossRef]
38. Li, Y.; Jia, Z.X.; Niu, W.Q.; Wang, J.W. Impact of post-infiltration soil aeration at different growth stages of sub-surface trickle-irrigated tomato plants. *Int. Agrophys.* **2016**, *30*, 331–337. [CrossRef]
39. Zhu, Y.; Cai, H.J.; Song, L.B.; Chen, H. Impacts of oxygation on plant growth, yield and fruit quality of tomato. *Trans. Chin. Soc. Agric. Mach.* **2017**, *48*, 199–211. (In Chinese)
40. Guo, S.R.; Wang, T.; Ma, Y.H. The relationships between respiratory activity and low dissolved O_2 tolerance of cucumber and tomato root systems. *Proc. Fifth Youth Sym. Chin. Hor. Soc.* **2002**, *5*, 593–598. (In Chinese)
41. Niu, W.Q.; Fan, W.T.; Persaud, N.; Zhou, X.B. Effect of post-irrigation aeration on growth and quality of greenhouse cucumber. *Pedosphere* **2013**, *23*, 790–798. [CrossRef]
42. Liu, H.B.; Chen, H.; Fu, L.B.; Yin, M.; Chen, J.F.; Hong, L.F. Effect of nitrogen and phosphorus Fertilizer Application rate on yield and Economic benefit of cucumber under drip irrigation and irrigation. *Jiangsu Agric. Sci.* **2014**, *42*, 123–124. (In Chinese)
43. Du, Y.D. *Effects of Aerated Irrigation and Nitrogen Application on Greenhouse Tomato Soil Environment and Nitrogen Use Efficiency*; Northwest A&F University: Yangling, China, 2020.
44. Hu, D.Y.; Yao, B.G.; Su, N.H. Effect of aerated irrigation on physiological and biochemical characteristics of autumn cucumber root. *J. Irri. Drai.* **2015**, *34*, 65–68. (In Chinese)

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