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Impact of Aerated Irrigation Duration on the Growth of Greenhouse Grape Seedlings and Rhizosphere Soil Microorganisms

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Abstract: This study investigates the effects of varying durations of aerated irrigation, administered at a consistent frequency, on the growth of greenhouse grape seedlings and the structure of the rhizosphere soil microbial community. Using two-year-old 'Flame Seedless' grape seedlings as the test material, we established a control group with no aeration (CK) and three treatment groups with aeration durations of 10 min (T1), 20 min (T2), and 30 min (T3), respectively. We determined grape seedling growth under different aerating durations. Additionally, changes in the rhizosphere soil microbial community of the plants were analyzed using 16S and ITS high-throughput genome sequencing to further explore the correlation between microbial diversity and plant growth. The results revealed that: (1) Aerated irrigation significantly enhanced plant growth, with the T2 treatment yielding superior increases in plant height, above-ground dry weight, below-ground dry weight, total root length, and root volume compared to T1 and T3 treatments. (2) Aeration treatments notably elevated the Shannon and Chao1 indices of the rhizosphere soil fungal community, with the T2 treatment exhibiting the most substantial effects, and the Shannon index of the bacterial community was also significantly higher under the T2 treatment. (3) The T2 treatment significantly increased the relative abundance of beneficial aerobic bacterial genera such as *Flavobacterium*, *Ellin6067*, and *Coniochaeta*, while decreasing the relative abundance of detrimental fungal genera like *Fusarium* and *Gibberella*. In conclusion, a 20 min aeration duration can effectively promote grape seedling growth, enhance the diversity of rhizosphere soil microbial communities, increase beneficial aerobic microorganisms, and reduce harmful ones. This study provides a theoretical basis for optimizing aerated irrigation practices in facility grape cultivation.

Keywords: grapes; aerated irrigation duration; growth; Illumina sequencing; microbial community

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1. Introduction

Facility agriculture is a specialized cultivation technology designed to enhance the productivity of plants and animals under relatively controlled environmental conditions. It represents an important advancement in modern agriculture [1] and plays an increasingly vital role in the global food system [2,3]. In China, the facility grape industry has experienced rapid growth, with the area dedicated to facility grape cultivation reaching 230,700 hectares by the end of 2016, positioning the country as the second largest producer worldwide [4]. Soil, as an important resource in agricultural production systems, can

provide the necessary water and nutrients for crop growth and development, and soil conditions such as nutrient effectiveness, porosity, and aeration can significantly affect crop root structure [5]. Key environmental factors, such as water, fertilizer, air, and heat, are crucial for plant growth and maintaining soil fertility [6]. However, in many facility agriculture systems, practices such as excessive irrigation; over-fertilization; prolonged mechanization; inadequate tillage; and imbalances in water, heat, and air can lead to a substantial decline in soil oxygen levels. Consequently, crop roots become increasingly sensitive to hypoxic stress [7].

Subsurface drip irrigation technology is widely adopted in agricultural production due to its high irrigation efficiency and effective water utilization [8]. However, traditional subsurface drip irrigation methods can lead to water saturation in soil pores [9], resulting in decreased soil aeration and stagnant water conditions [10]. This decline in soil oxygen can cause hypoxia in plant roots, leading to hypoxic stress [11] that adversely affects plant growth, development, yield, and quality [1]. Enhancing soil aeration is critical for improving soil fertility [12], which in turn promotes plant health. Aerated irrigation represents an innovative solution to address these challenges by integrating underground cavity storage with drip irrigation. This technique employs air pumps and ventilation devices to deliver air directly to the crop root zone. Additionally, Venturi aerating equipment can inject micro-bubbles or a water–gas mixture into the underground drip irrigation pipeline [13], ensuring that oxygen is continuously supplied to the root zone [14]. The micro-bubbles possess a large surface area and long lifespan, making them effective for mitigating soil hypoxia [15] and satisfying the oxygen demands of both the crop root system and the surrounding microbial community [16,17]. This can greatly promote crop growth and development and improve water utilization efficiency and overall yield [18]. Aerated irrigation technology has been widely implemented in crops such as cotton [19] and tomatoes [20]. Bhattarai et al. [21] demonstrated that tomatoes under aerated treatment exhibited a 21% increase in fresh weight compared to non-aerated treatments.

Microbial communities are vital components of soil ecosystems, playing a key role in regulating ecosystem functions and soil biogeochemistry [22]. They are integral to nutrient cycling and maintenance of soil structure, and their diversity can effectively respond to changes in soil quality [23,24]. Factors such as climatic conditions and irrigation practices can directly impact the structure of these microbial communities [25]. Variations in soil oxygen content significantly affect the diversity and composition of microbial communities [26]. For example, Chen et al. [27] showed that aerated irrigation increased the abundance and diversity of soil microorganisms in tomato rhizosphere soil, thereby enhancing soil respiration rates. Li Yuan et al. [9] found that aerated irrigation significantly affected microbial populations in melons. Research by Chen [28] and others indicated that increased oxygen levels could boost the relative abundance of aerobic microbes and facultative anaerobic microbes while reducing the prevalence of strictly anaerobic species. The rhizosphere is home to a diverse array of microorganisms that are essential parts of the soil–plant ecosystem, with the composition and diversity of these communities directly influencing plant growth and development [29].

Although aerated irrigation technology effectively addresses oxygen deficiency in the crop root zone, there is limited research on how different aerated irrigation durations affect plant growth and the structure of rhizosphere soil microbial communities. Our experiment focuses on two-year-old own-rooted 'Flame Seedless' grape seedlings, adopting aerated irrigation technology while using conventional non-aerated treatment as a control. The study aims to evaluate the effects of different aeration durations on grape seedling growth and the microbial community structure in the rhizosphere, ultimately identifying the optimal duration for aerated irrigation. This research seeks to provide a theoretical basis for the scientific and rational application of aerated irrigation in agricultural production, facilitating further optimization and improvement.

2. Materials and Methods

2.1. Plant Material and Experimental Design

Our experiment was carried out from April to December 2023 in a solar greenhouse at the College of Agriculture, Shihezi University, located in Shihezi City, New Uygur Autonomous Region (44°19′ N, 85°58′ E). During the experiment, greenhouse temperatures ranged from 16 to 32 °C, and relative humidity varied between 60% and 80%. A potting experiment was employed using topsoil collected from the vineyard of the Experimental Station at Shihezi University, specifically at a depth of 0–30 cm. The soil, classified as gray desert soil, was sieved through a 40-mesh screen prior to use. The soil's nutrient composition was analyzed, revealing a total nitrogen content of 1.22 g·kg^{-1}, ammonium nitrogen of 2.63 mg·kg^{-1}, nitrate nitrogen of 2.01 mg·kg^{-1}, quick-acting phosphorus of 43.6 mg·kg^{-1}, and quick-acting potassium of 305 mg·kg^{-1}. The soil's bulk density was measured at 1.40 g·cm^{-1}, the particle density at 2.65 g·cm^{-1}, and the pH was recorded at 6.56. The experimental pots used were cylindrical, with a mouth diameter of 30 cm, a base diameter of 25 cm, and a height of 45 cm.

Uniformly grown two-year-old own-rooted 'Flame Seedless' grape seedlings were planted in the center of each pot after acclimatization on 16 May 2023 (Figure 1), Inject oxygen gas that does not contain pollutants. A subsurface cavity storage drip irrigation system was used for drip irrigation and air injection treatment (Figure 1). The experimental design included a control group with no aeration (CK) and three treatments with different aeration durations: 10 min (T1), 20 min (T2), and 30 min (T3) per day. Each treatment consisted of nine plants in a single-plant replication. Aerated irrigation treatments commenced 30 days post-planting, with irrigation performed daily at 9 a.m. for a duration of 30 days. The irrigation water volume was kept consistent across treatments. An air compressor was used for aeration, maintaining a pressure of 0.04 MPa and a gas flow rate of 55 L·min^{-1}. The aeration volume was determined according to the formula $V = 0.0003 (rR + r^2 + R^2) (1 - \rho_b/\rho_s) \pi h$ [30], where V represents the aeration volume (L), r is the radius of the pot mouth (15 cm), R is the radius of the pot bottom (12.5 cm), ρ_s is the soil density (2.65 g·cm^{-3}), ρ_b is the soil bulk density (1.40 g·cm^{-3}), and h is the pot height (45 cm). This resulted in an aeration volume of 11.38 L per pot per filling. A rigid PVC pipe, 10 cm in height and 5 cm in diameter, was used as the underground gas injection bucket for drip irrigation. This pipe was sealed at the top with openings at the bottom, featuring evenly distributed small holes (0.5 cm in diameter) along the pipe wall. The gas injection bucket was placed 30 cm deep, with a distance of 5 cm between the plant and the bucket. Valves connected the main tube to the branch tubes, and a gas solenoid valve linked to a control center was used to regulate the opening and closing of each valve, allowing for precise control over the duration of gas filling for each treatment.

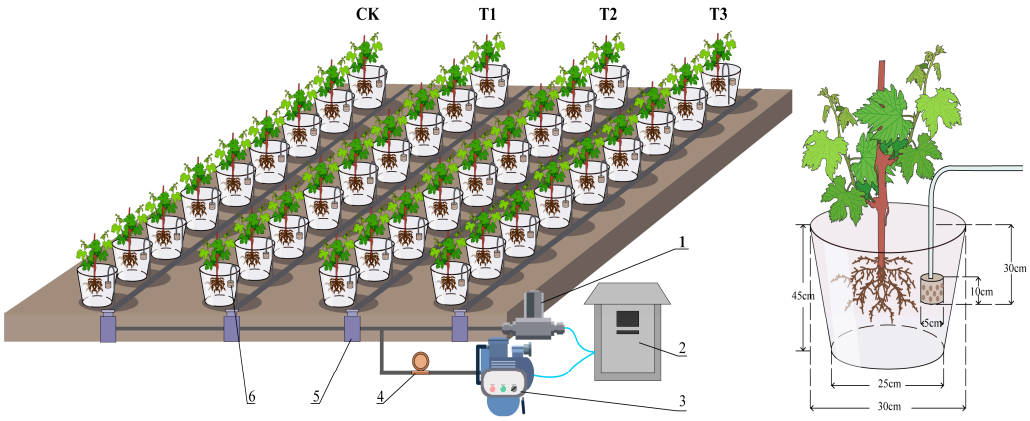


Figure 1. Schematic diagram of experimental design. Note: 1. water storage; 2. control center; 3. air compressor; 4. gas flow meter; 5. switch; 6. gas injection bucket for drip irrigation in underground cavity.

2.2. Measurement Items and Methods

2.2.1. Determination of Growth Indicators of Grape Seedlings

Growth indicators, including plant height, stem thickness, and SPAD values, were measured at 15, 18, 21, 24, and 27 days after the initiation of aerated irrigation treatments. Plant height was determined using a tape measure, stem thickness was assessed with a vernier caliper, and SPAD values were recorded using a SPAD-502 Plus chlorophyll meter.

2.2.2. Determination of Biomass and Root Activity in Grape Seedlings

After 30 days of aerated irrigation treatments, five uniformly growing grape seedlings were randomly selected from each treatment for destructive sampling.

Root activity was estimated using the modified triphenyl tetrazolium chloride (TTC) method following root removal [31]. The fresh roots were washed with dH_2O thrice, blotted on filter paper, and then stored at 4 °C to be used the same day. The standard curve was plotted based on the spectrophotometric absorption (λ = 485 nm) of different amounts of TTC (1 g·0.1 L^{-1}) solution with $Na_2S_2O_4$ and ethyl acetate. Roots were then sliced into one-centimeter pieces and immersed in 10 mL of an equally mixed solution of TTC (0.4%) and phosphate buffer (0.1 mol·L^{-1}, pH 7.0), then kept in the dark for 3 h at 37 °C. Subsequently, 2 mL of H_2SO_4 (1 mol·L^{-1}) was added to stop the reaction. The immersed root tips were dried with filter paper and extracted with ethyl acetate. The extracted solution was transferred into a tube with ethyl acetate cleaning solution to a total volume of 10 mL, and absorbance was read at 485 nm. Root activity was calculated from the standard curve and expressed as TTC reduction intensity: μg·g^{-1}·h^{-1}.

The dry weights (g) of both above-ground and below-ground plant parts were determined separately. The plant samples were dried in an oven preheated to 105 °C for 30 min, and then the temperature was adjusted to 80 °C until the weight was constant.

2.2.3. Determination of Morphological Indicators of Plant Roots

After 30 days of aerated irrigation treatments, three uniformly growing grape plants, free from pests and diseases, were selected for each treatment. The soil from the top 0–30 cm layer was collected, and the root systems were quickly extracted and rinsed with sterile water. The root systems were then scanned with a root scanner, and the scanned images were analyzed by WinRHIZO software purchased in Beijing (Regent, Vancouver, BC, Canada) [32]. This analysis provided morphological indicators of the root systems, including effective root surface area (cm^2), effective root volume (cm^3), total root length (cm), and the number of root tips. Following scanning, the roots were dried at 80 °C until a constant weight was achieved, and the dry weight of the root systems was subsequently recorded.

2.2.4. Rhizosphere Soil Sampling

Rhizosphere soil sampling was conducted using a soil auger method after 30 days of aerated irrigation treatments. For each cultivation pot, four sampling points were established evenly at a horizontal distance of 5 cm from the grape plant. Soil samples of 100 g were collected at a vertical depth of 20–30 cm from the soil surface. The soil from the four sampling points was thoroughly mixed, and this process was repeated five times. The collected soil samples were immediately sieved through a 40-mesh sieve, mixed again, and stored in a freezer at −80 °C for subsequent 16S and ITS high-throughput genome sequencing.

2.3. Soil DNA Extraction and Sequencing

Total soil DNA was extracted using the Fast DNATM SPIN Kit for Soil (MP Biomedicals, Irvine, CA, USA). The purity and concentration of the extracted DNA were assessed via 1.2% agarose gel electrophoresis. An appropriate volume of the sample taken in a centrifuge tube was diluted to 1 ng·μL^{-1} with sterile water and stored in a refrigerator at −80 °C for backup. The diluted DNA genome served as a template for PCR amplification, employing

Phusion® High-Fidelity PCR Master Mix with GC from New England Biolabs (Ipswich, MA, USA). Specific primers with Barcode Buffer and high-efficiency, high-fidelity enzymes targeting the V3-V4 regions of the bacterial 16S rRNA gene (primers: CCTAYGGGRBGCASCAG and GGACTACNNGGGTATCTAAT) and the intra-fungal transcriptional spacer (ITS) genes (primers: CTTGGTCATTTAGAGGAAGTAA and TGCGTTCTTCATCGATGC) were used. The PCR amplification procedure included pre-denaturation at 98 °C for 1 min, followed by 30 cycles of denaturation at 98 °C for 10 s, annealing at 50 °C for 30 s, and extension at 72 °C for 30 s, concluding with a final extension at 72 °C for 5 min. The PCR products were then mixed, purified, and prepared for library construction and on-board sequencing.

2.4. Bioinformatics Analysis and Data Processing

The data for each sample were separated based on the Barcode sequences and PCR amplification primers. The sequences of the Barcode and primers were extracted using FLASH to splice the sequences for each sample, yielding high-quality raw data. These data were then filtered to remove chimeric sequences, resulting in valid sequences. Amplicon Sequence Variants (ASVs) were generated through noise reduction using DADA2 based on the validated data, and the representative sequences of each ASV underwent species annotation and abundance analysis, revealing the species composition and abundance distribution of the samples.

2.5. Statistical Analysis

Data organization was performed using Excel 2010. Statistical analyses were conducted using SPSS 27, Duncan's multiple comparisons was used as a post hoc test after a significant difference was found in ANOVA ($p < 0.05$). Graphs were created using Origin 2021 and Graphpad Pism 9.5 software. Pearson correlation coefficients were calculated to analyze the relationship between microorganisms and growth indicators, with a significance level set at $p < 0.05$.

3. Results

3.1. Effects of Aerated Irrigation Duration on Growth Indicators of Grape Seedlings

3.1.1. Impact on Plant Height, Stem Thickness, and SPAD Value of Grape Seedlings

As illustrated in Figure 2, a moderate increase in the duration of aerated irrigation significantly enhanced grape plant height. The heights of grape seedlings exhibited an initial increase followed by a decrease with prolonged aerated irrigation duration. Notably, 24 days after aerated irrigation, the height of the plants under T2 treatment was significantly greater than that under other treatments, showing increases of 78.3%, 27.7%, and 31.9% compared to CK, T1, and T3 treatments, respectively. At 27 days post-aeration, the plant height rankings were T2 > T3 > T1 > CK, with significant differences observed. In contrast, stem thickness did not exhibit significant variation across treatments. At each measurement period, the SPAD values under CK and T2 treatments were significantly higher than those under T1 and T3 treatments. Specifically, at 24 days post-aeration, the SPAD values were reduced by 6.2%, 22.8%, and 19.2% under CK, T1, and T3 treatments, respectively, in comparison to T2 treatment.

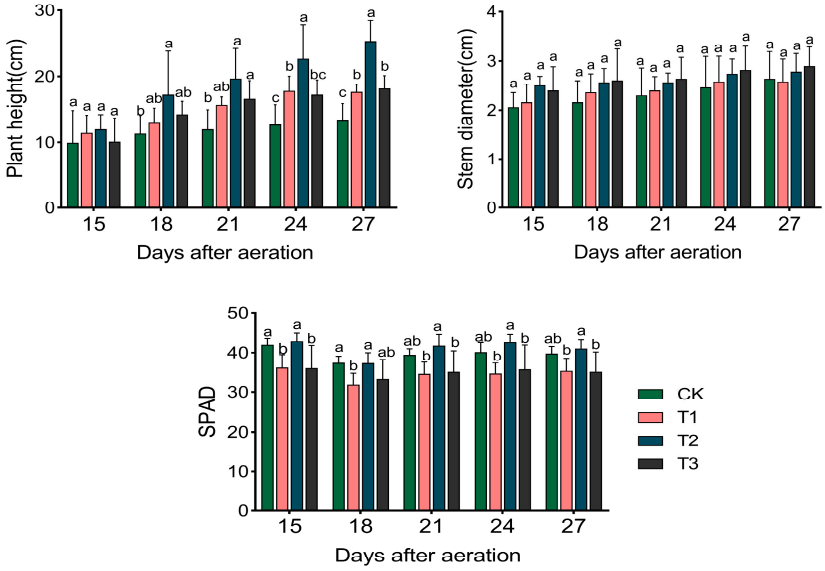


Figure 2. Impact of aerated irrigation duration on plant height, stem diameter, and SPAD value of grape seedlings, aeration durations are 0 min (CK), 10 min (T1), 20 min (T2), and 30 min (T3) per day. Note: Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

3.1.2. Impact on Biomass and Root Activity of Grape Seedlings

As shown in Table 1, both above-ground and below-ground dry biomass exhibited increasing trends followed by decreases with increasing durations of aerated irrigation, with the highest values recorded under T2 treatment. There were no significant differences in above-ground dry biomass between T1 and T2 treatments; however, both were significantly greater than CK and T3. For below-ground dry biomass, T2 treatment resulted in increases of 49.0%, 34.9%, and 25.7% compared to CK, T1, and T3 treatments, respectively, with these differences being significant. Root activity under different treatments showed, in descending order, T2 (0.0520 $\mu g \cdot g^{-1} \cdot h^{-1}$) > CK (0.0482 $\mu g \cdot g^{-1} \cdot h^{-1}$) > T1 (0.0458 $\mu g \cdot g^{-1} \cdot h^{-1}$) > T3 (0.0455 $\mu g \cdot g^{-1} \cdot h^{-1}$), with the T2 treatment yielding the highest value, which was 7.9%, 13.8% and 13.5% higher than the CK, T1, and T3 treatments, respectively.

Table 1. Impact of aerated irrigation duration on dry biomass and root activity of grape seedlings, aeration durations are 0 min (CK), 10 min (T1), 20 min (T2), and 30 min (T3) per day.

Treatment	Above-Ground Dry Biomass (g)	Below-Ground Dry Biomass (g)	Root System Activity ($\mu g \cdot g^{-1} \cdot h^{-1}$)
CK	8.71 ± 0.13 b	4.69 ± 0.09 c	0.0482 ± 0.00 a
T1	10.28 ± 0.47 a	5.18 ± 0.27 bc	0.0458 ± 0.00 a
T2	10.38 ± 0.10 a	6.99 ± 0.38 a	0.0520 ± 0.01 a
T3	9.84 ± 0.52 ab	5.56 ± 0.13 b	0.0455 ± 0.00 a

Note: Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

3.1.3. Impact on Root Morphology of Grape Seedlings

As shown in Figure 3, the T1, T2, and T3 treatments significantly increased the root volume and the number of root tips of grape seedlings compared to CK treatment, and positively affected the total root length. The T2 treatment exhibited the highest increases, with the total root length enhanced by 19.1%, 4.7%, and 11.9% compared to CK, T1, and T3 treatments, and the root volume increased by 16.6%, 12.5%, and 22.6%. Noteworthily, the number of root tips was significantly greater under T1 treatment compared to other treatments. While the root surface area did not show significant differences across treatments in comparison with CK, it displayed varying degrees of increase, peaking under T2 treatment. In summary, T2 treatment proved to be the most beneficial for the root growth of grape seedlings.

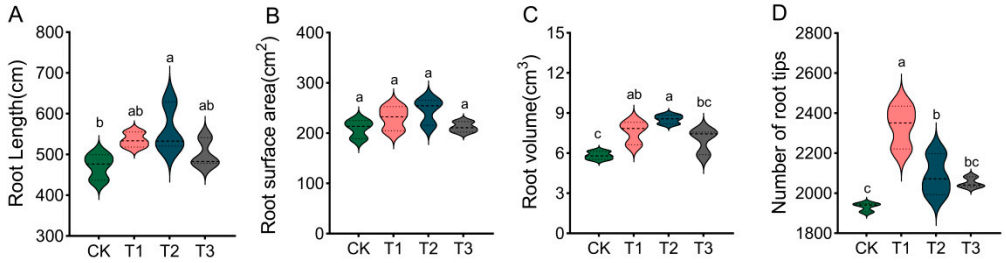


Figure 3. Impact of aerated irrigation duration on root morphological indices of grape seedlings, aeration durations are 0 min (CK), 10 min (T1), 20 min (T2), and 30 min (T3) per day. (**A**) Root length; (**B**) Root surface area; (**C**) Root volume; (**D**) Number of root tips. Note: Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

3.2. Effects of Aerated Irrigation Duration on Microbial Diversity of the Rhizosphere Soil of Grape Seedlings

High-throughput sequencing yielded 3,632,356 valid sequences for fungi and 3,534,942 for bacteria. Each sample generated a minimum of 68,705 valid sequences, averaging 100,898 for bacteria and 98,193 for fungi. Following noise reduction with DADA2, 96,576 ASVs were identified for bacteria and 9164 for fungi. The sequencing depth index coverage for both bacterial and fungal samples exceeded 99.6%, indicating comprehensive representation of microbial composition. This suggests that the depth of sequencing essentially covered all species present, ensuring reliable sequencing results.

Alpha diversity indices can accurately reflect microbial richness and diversity. In this experiment, Chao1 and Shannon indices were used to assess the differences in the richness and diversity of microbial composition in the rhizosphere soil of grape seedlings. As shown in Table 2, the Shannon and Chao1 indices for rhizosphere soil bacteria under all treatments exhibited an increasing and then decreasing trend with longer aeration durations, with T2 treatment showing a significantly higher Shannon index compared to CK and T3 treatments, but no significant difference in the Chao1 index among treatments. For fungi, the Shannon index ranked T2 > T1 > CK > T3, with T2 treatment being 14.9%, 5.9%, and 19.2% higher than the CK, T1, and T3 treatments, respectively. Although T3 treatment did not significantly affect the Chao1 index of the fungal community compared to CK treatment, T2 treatment showed a 13.3% increase over CK treatment, which was significant. This suggests that the optimal aerated irrigation duration of 20 min resulted in the highest diversity and abundance of both bacterial and fungal communities in the rhizosphere soil of grape seedlings.

Table 2. Microbial richness and diversity indices in the rhizosphere soil of grape seedlings, aeration durations are 0 min (CK), 10 min (T1), 20 min (T2), and 30 min (T3) per day.

Treatment	Shannon		Chao1	
	Bacteria	Fungi	Bacteria	Fungi
CK	10.50 ± 0.12 b	4.20 ± 0.20 bc	2760.45 ± 15.47 a	276.06 ± 8.12 b
T1	12.31 ± 0.24 ab	4.56 ± 0.03 ab	3110.28 ± 53.54 a	298.59 ± 9.82 ab
T2	14.14 ± 0.91 a	4.83 ± 0.08 a	3006.08 ± 196.43 a	312.83 ± 10.54 a
T3	10.59 ± 0.58 b	4.05 ± 0.09 c	2874.71 ± 476.98 a	279.78 ± 9.38 b

Note: Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

3.3. Effects of Aerated Irrigation Duration on the Rhizosphere Soil Microbial Community of Grape Seedlings

3.3.1. Impact on the Rhizosphere Soil Bacterial Community of Grape Seedlings

To assess the influence of different aerated irrigation durations on the structure of the soil bacterial community in the rhizosphere soil of grape seedlings, the species composition of each group was analyzed and compared. As presented in Figure 4A, the top

five dominant bacterial phyla by relative abundance across treatments were Proteobacteria, Acidobacteriota, Gemmatimonadota, Bacteroidota, and Actinobacteriota, collectively accounting for 77.5% of the total. The relative abundance of Proteobacteria exhibited a gradual increase with longer aeration durations, peaking under T3 treatment, where it was 16.2%, 16.1%, and 11.3% higher than under CK, T1, and T2 treatments, respectively. In contrast, Acidobacteriota and Gemmatimonadota reached the highest relative abundances under T2 treatment, showing increases ranging from 4.5% to 48.0% and 21.7% to 91%, respectively, compared to the other treatments (CK, T1, and T3 treatments). Conversely, Bacteroidota and Actinobacteriota were more abundant under CK than under any of the aerated irrigation treatments. The dominant bacterial genera identified across the different aeration durations included *unidentified_Chloroplast*, *Sphingomonas*, *MND1*, *Clade Ia*, and *Planktomarina*. Notably, the relative abundance of *Sphingomonas* was significantly higher in T1 treatment, exceeding CK, T2, and T3 treatment by 8.6%, 26.2%, and 91.4%, respectively. The relative abundance of *MND1* increased and then decreased across treatments, peaking in T2 treatment and reaching its lowest in T3 treatment.

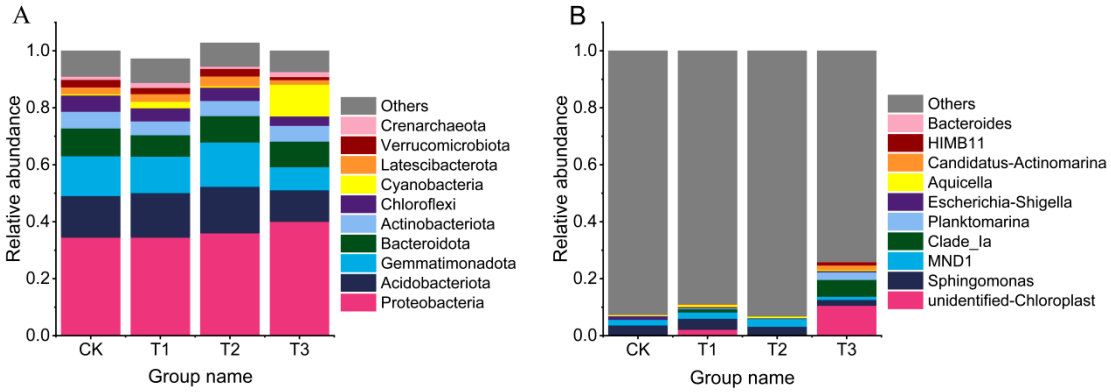


Figure 4. Community structure of bacterial phylum (**A**) and genus (**B**) in the rhizosphere soil of grape seedlings under different aerated irrigation durations.

3.3.2. Impact on the Rhizosphere Soil Fungal Community of Grape Seedlings

Fungal communities exhibited a simpler composition compared to bacterial communities (Figure 5). In terms of relative abundance, the top four dominant fungal phyla across all aeration duration treatments were Ascomycota, Chytridiomycota, Mortierellomycota, and Basidiomycota, collectively accounting for 92.7% of the total (Figure 5A). The dominant fungal genera identified under each treatment included *Pseudeurotium*, *Botryotrichum*, *Coniochaeta*, *Enterocarpus*, and *Rhizophlyctis*, which together comprised 65.3% of the total abundance (Figure 5B). The relative abundances of *Pseudeurotium*, *Coniochaeta*, and *Rhizophlyctis* were higher under T1 treatment compared to other treatments. In contrast, *Enterocarpus* displayed the highest relative abundance in T2 treatment, being 1.54, 0.55, and 1.22 times higher than in CK, T1, and T3 treatments, respectively.

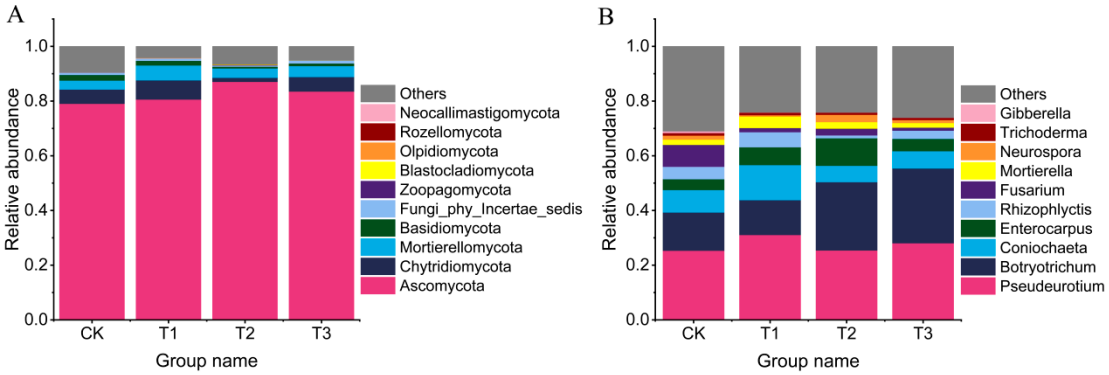


Figure 5. Community structure of fungal phylum (**A**) and genus (**B**) in the rhizosphere soil of grape seedlings under different aerated irrigation durations.

3.4. Effects of Aerated Irrigation Duration on Aerobic Microorganisms in the Rhizosphere Soil of Grape Seedlings

The impact of different aerated irrigation durations on the aerobic bacterial genera in the rhizosphere soil of grape seedlings is illustrated in Figure 6A. The relative abundance of *Flavobacterium* differed significantly among treatments, peaking under T2 treatment, which was 0.56 and 3.20 times significantly higher than under CK and T3 treatments, respectively, although no significant difference was noted when compared to T1 treatment. The relative abundance of *Lysobacter* followed the rankings of T2 > CK > T1 > T3. In contrast, the relative abundance of *Sphingomonas* was significantly higher under T1 treatment, being 1.04-fold greater than that under T3 treatment. Similarly, the relative abundance of *Gemmatimonas* increased and then decreased with increasing durations of aerated irrigation, reaching its highest level under T1 treatment, where it was 18.1% to 35.2% higher than in the other treatments. The relative abundance of *Ellin6067* was the highest under T2 treatment, being 27.9%, 43.1%, and 62.6% higher than under CK, T1, and T3 treatments, respectively.

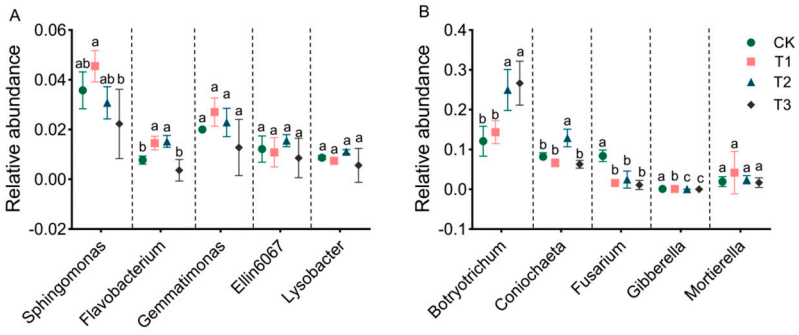


Figure 6. Effects of different aerated irrigation durations on aerobic microorganisms in the rhizosphere soil of grape seedlings, aeration durations are 0 min (CK), 10 min (T1), 20 min (T2), and 30 min (T3) per day. Note: (**A**). Aerobic bacteria of the genus. (**B**). Aerobic fungi of the genus. Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

The aerated irrigation duration also significantly influenced the relative abundance of aerobic fungal species in the rhizosphere soil (Figure 6B). Compared to CK, the aerated irrigation treatments effectively increased the relative abundance of *Botryotrichum*, which was the highest under T3 treatment, being 1.2 and 0.85 times significantly greater than under CK and T1 treatments, respectively. The relative abundance of *Coniochaeta* peaked under T2 treatment, being 0.57, 0.94, and 1.05 times significantly higher than under CK, T1, and T3 treatments, respectively. Conversely, the relative abundances of *Fusarium* and *Gibberella* significantly decreased with longer aerated irrigation durations, with the highest values recorded under CK treatment. In addition, no significant effect was observed on the relative abundance of *Mortierella* across the different aerated irrigation durations.

3.5. Correlation Analysis of Grape Seedling Growth with the Genus of Aerobic Microorganisms in the Rhizosphere Soil

The results of Pearson's correlation analysis revealed significant relationships between the growth of both the root system and the above-ground parts of grape seedlings and the genera of aerobic microorganisms (Figure 7). Specifically, root activity exhibited a significant positive correlation with the relative abundances of *Coniochaeta*, *Lysobacter*, and *Ellin6067*. The SPAD value also showed a significant positive correlation with the relative abundance of *Coniochaeta*. Furthermore, the relative abundance of *Botryotrichum* was significantly positively correlated with plant stem thickness. Conversely, a significant negative correlation was observed between the relative abundance of *Gibberella* and below-ground biomass.

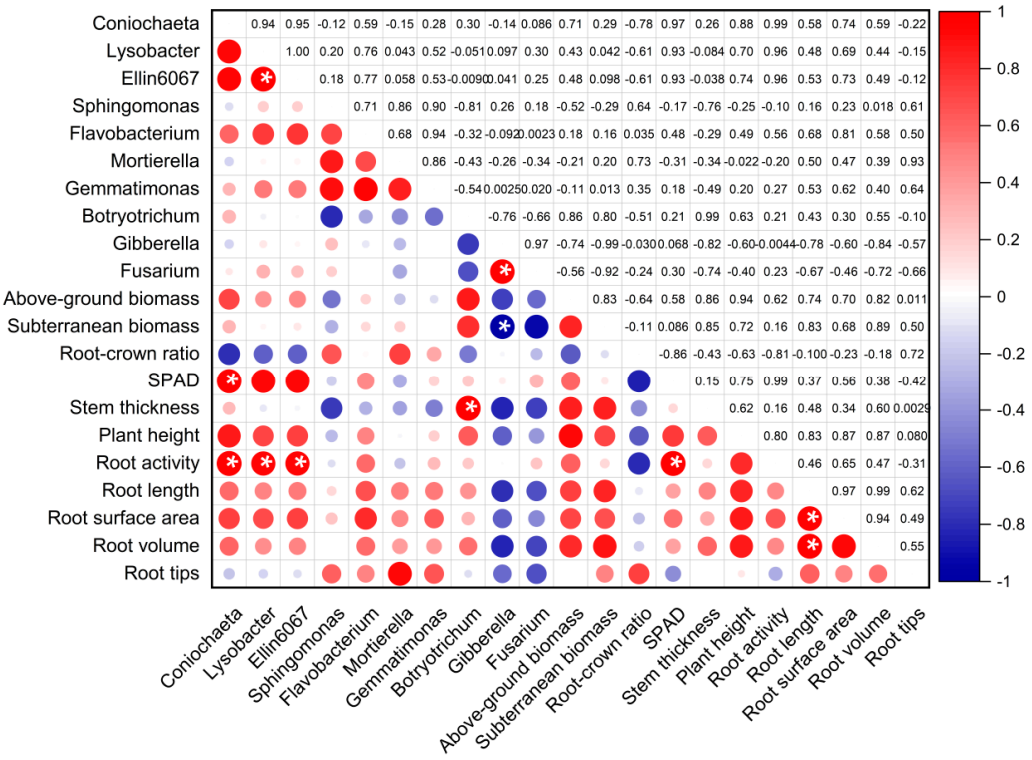


Figure 7. Correlation analysis between grape seedling growth indices and dominant microbial genera in the rhizosphere soil. Note: Red and blue colors indicate positive and negative correlations, respectively, and * indicates significant correlation ($p < 0.05$).

4. Discussion

4.1. Effects of Aerated Irrigation Duration on the Growth of Grape Seedlings

Aerated irrigation offers advantages over traditional irrigation methods by supplying optimal water and nutrients for crop growth while enhancing the soil microenvironment through improved aeration and the regulation of water, fertilizer, air, and heat ratios [33]. Previous studies, such as those by Qian et al. [34], demonstrated that aerated treatments can effectively promote plant growth, increasing above-ground dry matter and yield in crops like cucumber and melon. Similarly, Li et al. [18] reported significant increases in tomato plant height and stem thickness under aerated conditions. Our findings align with these results, showing that aerated irrigation significantly promoted grape seedling height, with the most pronounced effect observed at a duration of 20 min. While a positive effect on stem thickness was noted, it did not reach statistical significance (Figure 2). This discrepancy with previous studies may stem from variations in crop varieties, soil conditions, and climate. Li et al. [18] indicated that increasing the rhizosphere soil oxygen level positively influences crop canopy growth. Seridou et al. [14] concluded that inadequate soil aeration during irrigation is detrimental to above-ground plant growth. Our findings confirm that

aerated irrigation treatments enhanced both above-ground and below-ground biomass, with the highest values recorded under T2 treatment (Table 1), aligning with the results of previous studies. Chlorophyll content is closely linked to a plant's photosynthetic capacity and directly affects plant biomass and yield, serving as a crucial indicator of nutritional growth [35]. Prior research has shown that aerated treatments significantly boost chlorophyll content in plant leaves [36]. The results of this study showed that T2 treatment effectively increased plant leaf SPAD values, and at 15 d after aerated irrigation, leaf SPAD values were significantly lower under T1 and T3 treatments compared to CK treatment. This suggests that a 20 min aerated irrigation duration could improve the rhizosphere soil aeration of grape seedlings, effectively promote crop growth, strengthen biomass accumulation, and positively affect overall crop health.

4.2. Effects of Aerated Irrigation Duration on Root Morphology of Grape Seedlings

The root systems of crops play a crucial role in exchanging materials, energy, and information with the external environment. The morphological characteristics and functionality of roots are affected by the soil's physical and chemical properties, as well as fertilizer application, all of which directly impact the growth and development of above-ground organs, the morphological composition of the plants, and, ultimately, the crop yield [37]. Aerated irrigation increases root length and effectively promotes root growth, thereby facilitating water and nutrient uptake by plant roots [21]. In this study, aerated irrigation significantly boosted the root system growth of grape seedlings. The total root length and root volume were notably higher with a 20 min irrigation aerated duration compared to other durations, while the number of root tips peaked at 10 min of aerated irrigation. The morphological indices of the root system showed a trend of initially increasing and then decreasing with longer aeration durations. This pattern suggests that, while aerated irrigation improves rhizosphere aeration and promotes root growth, excessive aeration could lead to elevated soil oxygen levels that may cause oxygen damage to root cells of grape seedlings, negatively affecting root growth [38]. In this experiment, the observed effects of different aerated irrigation durations on the growth of grape seedlings were consistent with the changes in root morphology, with the most favorable outcomes occurring at the T2 treatment duration. Nonetheless, when aeration was extended to T3 treatment, slight oxygen injury was noted, which may have suppressed plant growth. Overall, the growth of grape seedlings under aerated irrigation conditions remained superior to that observed under the un-aerated CK condition.

4.3. Effects of Aerated Irrigation Duration on the Diversity and Structure of the Rhizosphere Soil Microbial Community in Grape Seedlings

Microorganisms represent the most diverse and abundant biota on Earth, with soil microorganisms forming essential components of soil ecosystems. Their diversity reflects terrestrial biodiversity and can effectively regulate the biogeochemical cycling of nutrients, which is vital for the functioning of terrestrial ecosystems [39]. Rhizosphere soil microorganisms are an important bioindicator for assessing plant health and productivity [40]. Previous studies have shown that various agricultural practices can have a profound impact on microbial communities [41], and rhizosphere soil aeration significantly affects the abundance and diversity of soil microbial communities in the rhizosphere soil of crops [42,43]. And climatic conditions, soil type, aeration intensity, field management, and other environmental conditions can influence plant physiology and soil microbial activity, thereby affecting the structural composition of the rhizosphere microbial community [44]. The results of this study showed that the diversity and richness of bacterial species in the rhizosphere soil of grape seedlings were higher than those of fungi. Aerated irrigation treatments (T1, T2, and T3) promoted the richness and diversity of microbial communities compared to the non-aerated CK treatment, indicating that aerated irrigation could enhance rhizosphere microbial abundance [45]. Notably, the highest microbial diversity was recorded with the 20 min aerated irrigation duration. However, extending the duration

of aerated irrigation to 30 min (T3) resulted in a decrease in bacterial and fungal diversity. This decline can be attributed to the fact that, while aerated irrigation relieved the soil from low-oxygen stress, thereby initially enhancing microbial diversity, prolonged aeration increased gas flow within the soil significantly. This heightened air flow can disturb microbial communities, ultimately leading to a reduction in both the number of microorganisms and their diversity [9].

The oxygen content in soil significantly affects the soil microbial community structure [42]. In recent years, various agricultural management practices, such as straw return [46], soil aeration [47], application of organic fertilizers [48], and the use of biochar [49], have been employed to enhance soil aeration, thereby affecting the composition of soil microbial communities. The dominant bacterial phyla in this study were Proteobacteria and Gemmatimonadota, while the dominant bacterial genera were *MND1* and *Clade_Ia*, which also included *Sphingomonas*, a genus known for promoting plant growth and strengthening plant resistance. Previous studies have demonstrated that variations in soil oxygen content can directly impact microbial biomass and community structure [26]. Our findings indicate that aerated irrigation treatments significantly increased the relative abundance of *Sphingomonas* in the rhizosphere of grape seedlings, particularly with a 10 min aeration duration. *Sphingomonas* are aerobic Gram-negative bacteria [50]; thus, the enhanced oxygen concentration resulting from aerated irrigation contributed to a substantial increase in their relative abundance. Moreover, the relative abundances of other dominant bacterial genera were also affected by different durations of aerated irrigation. The dominant fungal genera observed included *Pseudeurotium*, *Botryotrichum*, *Coniochaeta*, *Enterocarpus*, and *Rhizophlyctis*. Specifically, the relative abundances of *Pseudohyphae*, *Coniochaeta*, and *Rhizophlyctis* were significantly higher under the 10 min aeration condition, while *Botryotrichum* peaked at 20 min of aeration (Figure 5). This suggests that aerated irrigation improved the habitat conditions for these fungi, leading to increased abundance. However, prolonged aeration durations can disturb the growth of microorganisms due to frequent airflow, making their relative abundance decrease to some extent [9].

4.4. Effects of Aerated Irrigation Duration on Aerobic Microbial Genera in the Rhizosphere Soil of Grape Seedlings

Rhizosphere soil microbial communities are important regulators of plant growth, development, and stress tolerance [51], also serving as an ecological barrier to limit pathogen invasion [52]. Microorganisms directly and indirectly influence soil nutrient cycling and organic matter decomposition through their interactions with plant roots, thus effectively regulating crop growth and development [53]. For example, plant growth-promoting bacteria can promote nutrient uptake, stress tolerance, plant growth and development, and yield through symbiosis with plants (secretion of organic acids, enzymes, plant hormones, antioxidants, and cytokinins) [54]. In addition to this, plant growth-promoting bacteria fix atmospheric nitrogen and effectively improve soil organic carbon content, soil pH, and soil porosity [55], thus improving soil fertility as well as soil health. The ability of plants to absorb nutrients from the soil is closely related to root morphological indicators such as root length, root surface area, and root activity [1]. Suitable soil aeration conditions significantly impact both microbial communities and the metabolic activities of plant roots [42]. In this study, we observed a close relationship between the growth of both above-ground and root structures of grape seedlings and the presence of aerobic microorganisms. The results showed that aerated irrigation treatments could effectively increase the relative abundances of aerobic microorganisms, particularly *Coniochaeta*, *Lysobacter*, and *Ellin6067*, with the most pronounced effects seen in T2 treatment (Figure 6). Notably, a significant positive correlation was found between the relative abundances of *Coniochaeta*, *Lysobacter*, and *Ellin6067* and the root activity (Figure 7), which contributed positively to plant growth. There is mutually beneficial coexistence between plant rhizosphere soil microorganisms and their hosts or pathogenicity to their hosts as determinants of crop health and productivity [40]. Beneficial rhizosphere soil microorganisms can inhibit or directly kill pathogens in a variety

of ways, leading to a reduction in soil-borne diseases [56]. *Coniochaeta* is recognized as a beneficial fungus with biocontrol properties that is capable of degrading hemicellulose in the soil and producing natural enzymes and bioactive compounds [57]. The genus *Lysobacter* is known to mitigate plant diseases; for instance, Ji Guanghai et al. [58] showed that *Lysobacter* can effectively inhibit a variety of pathogenic bacteria, including those causing rice leaf blight. Additionally, *Ellin6067*, an ammonia-oxidizing bacterium [59], plays a vital role in the nitrogen cycle, helping to maintain nitrogen balance and create favorable soil conditions for root growth, thus promoting overall plant health. By comparison, the relative abundances of the aerobic fungal genera *Gibberella* and *Fusarium* both decreased as the duration of aerated irrigation increased (Figure 6B). Significant negative correlations were observed between the relative abundances of *Gibberella* and *Fusarium* and the dry weight of the plant's underground portions, indicating adverse effects on grape growth (Figure 7). In the process of agricultural production, *Gibberella* and *Fusarium* are known to be destructive phytopathogenic fungi that cause plant diseases. For example, *Gibberella* is responsible for wheat blast and potato tuber dry rot [60], while *Fusarium* can cause round spot root rot in grapes. These fungi can inhibit root growth and reduce nutrient uptake efficiency, thus adversely affecting the growth of grapes [61]. Overall, aerated irrigation could effectively increase the relative abundance of beneficial microorganisms such as *Coniochaeta*, *Lysobacter*, and *Ellin6067* in the rhizosphere soil while reducing pathogenic fungi like *Gibberella* and *Fusarium*. The most favorable effects on grape seedling growth were achieved with a 20 min aeration duration (T2).

5. Conclusions

(1) An aerated irrigation duration of 20 min significantly increased plant height, above-ground and below-ground biomass, total root length, and root volume in greenhouse grapes compared to other treatments. Additionally, a duration of 10 min notably increased the number of root tips.

(2) The Shannon index and Chao1 index of the rhizosphere soil fungal community were significantly enhanced after aeration, with the most pronounced effects observed at a 20 min aeration duration. The Shannon index of the bacterial community was also significantly higher at this duration; however, no significant differences were found in the Chao1 index across treatments, indicating that 20 min of aeration could effectively promote the diversity and richness of microbial communities in the rhizosphere soil.

(3) An aeration duration of 10 min significantly increased the relative abundance of *Sphingomonas*. The highest relative abundances of beneficial genera, including *Flavobacterium*, *Ellin6067*, and *Coniochaeta*, were observed at an aeration duration of 20 min. Conversely, the phytopathogenic fungi *Fusarium* and *Gibberella* were significantly more abundant under the non-aerated condition compared to all aerated treatments.

(4) Under aerated irrigation conditions, the relative abundances of *Coniochaeta*, *Lysobacter* and *Ellin6067* showed significant positive correlations with the root activity of grape seedlings. In contrast, a significant negative correlation was found between the relative abundance of *Gibberella* and below-ground biomass.

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References

1. Xiao, Z.Y.; Lei, H.J.; Lian, Y.J.; Zhang, Z.H.; Pan, H.W.; Yin, C.; Dong, Y.C. Impact of Aerated Drip Irrigation and Nitrogen Application on Soil Properties, Soil Bacterial Communities and Agronomic Traits of Cucumber in a Greenhouse System. *Plants* **2023**, *12*, 3834. [CrossRef]
2. Ma, Y.; Liu, Z.H.; Xi, B.D.; He, X.S.; Li, Q.L.; Qi, Y.J.; Jin, M.Y.; Guo, Y. Characteristics of Groundwater Pollution in a Vegetable Cultivation Area of Typical Facility Agriculture in a Developed City. *Ecol. Indic.* **2019**, *105*, 709–716. [CrossRef]
3. Pineda, I.T.; Lee, Y.D.; Kim, Y.S.; Lee, S.M.; Park, K.S. Review of Inventory Data in Life Cycle Assessment Applied in Production of Fresh Tomato in Greenhouse. *J. Clean. Prod.* **2021**, *282*, 124395. [CrossRef]
4. Wang, S.P.; Li, B. Overview of Facility Grape Development in China. *Deciduous Fruits* **2019**, *51*, 1–5.
5. Luo, Z.K.; Zhang, S.; Zhao, Z.G.; Minasny, B.; Chang, J.F.; Huang, J.Y.; Li, B.H.; Shi, Z.; Wang, M.M.; Wu, Y.S.; et al. Soil-smart cropping for climate-smart production. *Geoderma* **2024**, *451*, 117061. [CrossRef]
6. Lei, H.J.; Hu, S.G.; Pan, H.W.; Zang, M.; Liu, X. Research Progress on Soil Aeration and Oxygen Irrigation. *Acta Pedol. Sin.* **2017**, *54*, 297–308. [CrossRef]
7. Ma, J.W.; Rukh, G.; Ruan, Z.Q.; Xie, X.C.; Ye, Z.Q.; Liu, D. Effects of Hypoxia Stress on Growth, Root Respiration, and Metabolism of Phyllostachys praecox. *Life* **2022**, *12*, 808. [CrossRef]
8. Lei, H.J.; Lian, Y.L.; Du, J.; Pan, H.W.; Li, X.H.; Li, D.X.; Jin, C.C.; Xiao, Z.Y.; Hou, Y.R. Dynamic Optimization of Greenhouse Tomato Irrigation Schedule Based on Water, Fertilizer and Air Coupled Production Function. *Agronomy* **2023**, *13*, 776. [CrossRef]
9. Li, Y.; Niu, W.Q.; Zhang, M.Z.; Xue, L.; Wang, J.W. The Effect of Aerated Irrigation on Soil Enzyme Activities and Microbial Quantity of Greenhouse Muskmelon. *Trans. Chin. Soc. Agric. Mach.* **2015**, *46*, 121–129.
10. Sun, Y.N.; Duan, L.B.; Zhong, H.Y.; Cai, H.J.; Xu, J.T.; Li, Z.J. Effects of Irrigation-Fertilization-Aeration Coupling on Yield and Quality of Greenhouse Tomatoes. *Agric. Water Manag.* **2024**, *299*, 108893. [CrossRef]
11. Xiao, R.; Sun, K.P.; Lei, H.J.; Zhang, T.Y.; Chen, J. Study on the Growth, Physiological Characteristics, Nutrient Absorption, and Yield Relationship of Greenhouse Peppers under Aerated Irrigation. *J. North China Univ. Water Resour. Electr. Power* **2023**, *44*, 78–86.
12. 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.* **2021**, *280*, 124509. [CrossRef]
13. Yu, Z.Z.; Wang, H.X.; Zou, H.F.; Sun, H.T.; Wang, H.Y. Changes in Respiration Rates and Relationships with Soil Water and Oxygen under Aerated Irrigation in Red Soils. *Chin. J. Trop. Crops* **2022**, *43*, 110–118. [CrossRef]
14. Seridou, P.; Kalogerakis, N. Disinfection applications of ozone micro- and nanobubbles. *Environ. Sci. Nano* **2021**, *8*, 3493–3510. [CrossRef]
15. Zhou, Y.P.; Li, Y.K.; Liu, X.J.; Wang, K.Y.; Muhammad, T. Synergistic improvement in spring maize yield and quality with micro/nanobubbles water oxygation. *Sci. Rep.* **2019**, *9*, 1–10. [CrossRef]
16. Gao, L.L.; Li, J.; Huang, H.Y.; Xiang, B.; Li, S.F. The Effect of Aerated Irrigation under Drip Irrigation on Root Zone Habitat Factors and Yield of Winter Potato in Yunnan. *Agric. Res. Arid. Areas* **2022**, *40*, 108–115. [CrossRef]
17. Palencia, P.; Martinez, F.; Padua, D.; Oliveira, J.A. Effects of Oxyfertigation on Strawberry Plant Growth and Fruit Quality in a Soilless Growing System. *Acta Hortic.* **2019**, *1256*, 512–519. [CrossRef]
18. Li, Y.; Niu, W.Q.; Xu, J.; Wang, J.W.; Zhang, M.Z.; Lv, W. Root Morphology of Greenhouse Produced Muskmelon under Sub-surface Drip Irrigation with Supplemental Soil Aeration. *Sci. Hortic.* **2016**, *201*, 287–294. [CrossRef]
19. Rao, X.J.; Fu, Y.B.; Huang, J.; Feng, Y.Z.; Wang, Z.G. Effect of Oxygen Irrigation on Cotton Nutritional Characteristics and Soil Fertility. *Acta Pedol. Sin.* **2018**, *55*, 797–803.
20. Lu, Z.H.; Cai, H.J.; Wang, J.; Li, Z.J. Effects of Rhizosphere Aeration at Different Growth Stages on Growth and Yield of Greenhouse Tomatoes. *Sci. Agric. Sin.* **2012**, *45*, 1330–1337.
21. Bhattarai, S.P.; Su, N.H.; Midmore, D.J.; Sparks, D.L. Oxygation Unlocks Yield Potentials of Crops in Oxygen-limited Soil Environments. *Adv. Agron.* **2005**, *88*, 313–377. [CrossRef]
22. Shigyo, N.; Umeki, K.; Hirao, T. Seasonal Dynamics of Soil Fungal and Bacterial Communities in Cool-temperate Montane Forests. *Front. Microbiol.* **2019**, *10*, 1944. [CrossRef]
23. Zhang, M.Q.; Wang, X.Q.; Guan, H.B.; Yu, J.; Zhang, Y. The Effects of Salt Stress on the Growth of Balloonflower Seedlings and the Number of Rhizosphere Microorganisms. *West China J. Pharm. Sci.* **2024**, *39*, 89–93.
24. Velmurugan, A.; Swarnam, T.P.; Jaisankar, I.; Swain, S.; Subramani, T. Vegetation–Soil–Microbial Diversity Influences Ecosystem Multifunctionality across Different Tropical Coastal Ecosystem Types. *Trop. Ecol.* **2021**, *63*, 1–13. [CrossRef]
25. Zeglin, L.H.; Dahm, C.N.; Barrett, J.E.; Gooseff, M.N.; Fitpatrick, S.K.; Takacs-Vesbach, C.D. Bacterial Community Structure along Moisture Gradients in the Parafluvial Sediments of Two Ephemeral Desert Streams. *Microb. Ecol.* **2011**, *61*, 543–556. [CrossRef]
26. Biggs-Weber, E.; Aigle, A.; Prosser, J.I.; Gubry-Rangin, C. Oxygen Preference of Deeply-rooted Mesophilic Thaumarchaeota in Forest Soil. *Soil Biol. Biochem.* **2020**, *148*, 107848. [CrossRef]
27. Chen, H.; Shang, Z.H.; Cai, H.J.; Zhu, Y. Irrigation Combined with Aeration Promoted Soil Respiration through Increasing Soil Microbes, Enzymes, and Crop Growth in Tomato Fields. *Catalysts* **2019**, *9*, 945. [CrossRef]

28. Chen, Z.; Maltz, M.R.; Cao, J.X.; Yu, H.; Shang, H.; Aronson, E. Elevated O_3 Alters Soil Bacterial and Fungal Communities and the Dynamics of Carbon and Nitrogen. *Sci. Total Environ.* **2019**, *677*, 272–280. [CrossRef]
29. Coats, V.C.; Rumpho, M.E. The Rhizosphere Microbiota of Plant Invaders: An Overview of Recent Advances in the Microbiomics of Invasive Plants. *Front. Microbiol.* **2014**, *5*, 368. [CrossRef]
30. Xie, H.X.; Cai, H.J.; Zhang, Z.H. Comprehensive Benefit Evaluation of Aerated Irrigation for Greenhouse Muskmelon. *Trans. Chin. Soc. Agric. Mach.* **2010**, *41*, 79–83.
31. Richter, A.K.; Frossard, E.; Brunner, I. Polyphenols in the woody roots of Norway spruce and European beech reduce TTC. *Tree Physiol.* **2007**, *27*, 155–160. [CrossRef]
32. Anand, S.; Kundan, D.; Marcus, G.; Harchao, C.; Freschet, G.T.; York, L.M. RhizoVision Explorer: Open-source Software for Root Image Analysis and Measurement Standardization. *AoB PLANTS* **2021**, *13*, plab056. [CrossRef]
33. Wang, H.Y.; Wang, C.; Wang, F.; Wang, H.X.; Ma, G.Q.; Yu, Z.Z. Effects of Aerated Irrigation Technology on Soil and Crop Growth. *Res. Agric. Mech.* **2024**, *46*, 17–24.
34. Zhang, Q.; Du, Y.D.; Cui, B.J.; Sun, J.; Wang, J.; Wu, M.L.; Niu, W.Q. Aerated Irrigation Offsets the Negative Effects of Nitrogen Reduction on Crop Growth and Water-nitrogen Utilization. *J. Clean. Prod.* **2021**, *313*, 127945. [CrossRef]
35. Al-Gaadi, K.A.; Tola, E.; Madugundu, R.; Zeyeda, A.M.; Alameen, A.A.; Edrris, M.K.; Edress, H.F.; Mahjoop, O. Response of Leaf Photosynthesis, Chlorophyll Content and Yield of Hydroponic Tomatoes to Different Water Salinity Levels. *PLoS ONE* **2024**, *19*, 0293098. [CrossRef]
36. Li, Y.; Niu, W.Q.; Lv, W.; Gu, J.; Zou, X.Y.; Wang, J.W.; Liu, L.; Zhang, M.Z.; Xu, J. Aerated Irrigation Improving Photosynthesis Characteristics and Dry Matter Accumulation of Greenhouse Tomato. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 125–132.
37. Huang, J.; Hu, T.S.; Yasir, M.; Gao, Y.; Chen, C.; Zhu, R.; Wang, X.; Yuan, H.W.; Yang, J.W. Root Growth Dynamics and Yield Responses of Rice (*Oryza sativa* L.) under Drought-Flood Abrupt Alternating Conditions. *Environ. Exp. Bot.* **2019**, *157*, 11–25. [CrossRef]
38. Li, J.; Pan, Y.C.; Jiao, X.Y.; Hu, W.Y.; Liu, Y. Effects of Aerated Irrigation on Soil Reducibility and Rice Growth after Wheat Straw Incorporation. *Trans. Chin. Soc. Agric. Mach.* **2021**, *52*, 250–259.
39. Wu, B.H.; Luo, H.Y.; Wang, X.T.; Liu, H.K.; Peng, H.; Sheng, M.P.; Xu, F.; Xu, H. Effects of Environmental Factors on Soil Bacterial Community Structure and Diversity in Different Contaminated Districts of Southwest China Mine Tailings. *Sci. Total Environ.* **2022**, *802*, 149899. [CrossRef]
40. Darriaut, R.; Antonielli, L.; Martins, G.; Ballestra, P.; Vivin, P.; Marguerit, E.; Mitter, B.; Masneuf-Pomarede, I.; Compant, S.; Ollat, N. Soil composition and rootstock genotype drive the root associated microbial communities in young grapevines. *Front. Microbiol.* **2022**, *13*, 1031064. [CrossRef]
41. Finkel, O.M.; Castrillo, G.; Paredes, S.H.; Gonzalez, I.S.; Dangl, J.L. Understanding and exploiting plant beneficial microbes. *Curr. Opin. Plant Biol.* **2017**, *38*, 155–163. [CrossRef]
42. Qian, Z.Z.; Zhuang, S.Y.; Gao, J.S.; Tang, L.Z.; Harindintwali, J.D.; Wang, F. Aeration Increases Soil Bacterial Diversity and Nutrient Transformation under Mulching-induced Hypoxic Conditions. *Sci. Total Environ.* **2022**, *817*, 152659. [CrossRef]
43. 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]
44. Bamba, M.; Akyol, T.K.; Azuma, Y.; Quilbe, J.; Andersen, S.U.; Sato, S. Synergistic effects of plant genotype and soil microbiome on growth in Lotus japonicus. *FEMS Microbiol. Ecol.* **2024**, *100*, 56. [CrossRef]
45. Zhu, J.J.; Niu, W.Q.; Zhang, Z.H.; Siddique, K.; 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]
46. Liu, D.T.; Song, C.C.; Xin, Z.H.; Fang, C.; Liu, Z.H.; Xu, Y.P. Agricultural Management Strategies for Balancing Yield Increase, Carbon Sequestration, and Emission Reduction after Straw Return for Three Major Grain Crops in China: A Meta-analysis. *J. Environ. Manag.* **2023**, *340*, 117965. [CrossRef]
47. Zhu, J.J.; Xu, N.; Siddique, K.H.M.; Zhang, Z.H.; Niu, W.Q. Aerated Drip Irrigation Improves Water and Nitrogen Uptake Efficiencies of Tomato Roots with Associated Changes in the Antioxidant System. *Sci. Hortic.* **2022**, *306*, 111471. [CrossRef]
48. Liu, J.A.; Shu, A.P.; Song, W.F.; Shi, W.C.; Li, M.C.; Zhang, W.X.; Li, Z.Z.; Liu, G.R.; Yuan, F.S.; Zhang, S.X.; et al. Long-term Organic Fertilizer Substitution Increases Rice Yield by Improving Soil Properties and Regulating Soil Bacteria. *Geoderma* **2021**, *404*, 115287. [CrossRef]
49. Zhang, Y.F.; Wang, J.M.; Feng, Y. The Effects of Biochar Addition on Soil Physicochemical Properties: A Review. *Catena* **2021**, *202*, 105284. [CrossRef]
50. Liu, H.; Wei, L.L.; Zhu, L.F.; Wei, H.; Bai, Y.X.; Liu, X.L.; Li, S.B. Advances in the Study of *Sphingomonas*. *Microbiol. Bull.* **2023**, *50*, 2738–2752.
51. Salas-González, I.; Reyt, G.; Flis, P.; Custódio, V.; Gopaulchan, D.; Bakhoum, N.; Dew, T.P.; Suresh, K.; Franke, R.B.; Dangl, J.L.; et al. Coordination between microbiota and root endodermis supports plant mineral nutrient homeostasis. *Science* **2020**, *371*, 6265. [CrossRef] [PubMed]
52. Hacquard, S.; Spaepen, S.; Garrido-Oter, R.; Schulze-Lefert, P. Interplay Between Innate Immunity and the Plant Microbiota. *Annu. Rev. Phytopathol.* **2017**, *55*, 565–589. [CrossRef] [PubMed]

53. Wang, R.Q.; Xiao, Y.P.; Lv, F.J.; Hu, L.Y.; Wei, L.G.; Yuan, Z.Q.; Lin, H.X. Bacterial Community Structure and Functional Potential of Rhizosphere Soils as Influenced by Nitrogen Addition and Bacterial Wilt Disease under Continuous Sesame Cropping. *Appl. Soil Ecol.* **2018**, *125*, 117–127. [CrossRef]
54. Gupta, P.; Kumar, V.; Usmani, Z.; Rani, R.; Chandra, A.; Gupta, V.K. A comparative evaluation towards the potential of Klebsiella sp. and Enterobacter sp. in plant growth promotion, oxidative stress tolerance and chromium uptake in *Helianthus annuus* (L.). *J. Hazard. Mater.* **2019**, *377*, 391–398. [CrossRef] [PubMed]
55. Fasusi, O.A.; Cruz, C.; Babalola, O.O. Agricultural Sustainability: Microbial Biofertilizers in Rhizosphere Management. *Agriculture* **2021**, *11*, 163. [CrossRef]
56. Ratnadass, A.; Fernandes, P.; Avelino, J.; Habib, R. Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: A review. *Agron. Sustain. Dev.* **2011**, *32*, 273–303. [CrossRef]
57. Gao, H.X.; Li, Y.; Zhu, Z.X. Two New Asian Records of *Coniochaeta* from China. *Mycosystema* **2022**, *20*, 96–108.
58. Ji, G.H. Research Progress on *Lysobacter* and Its Role in Plant Disease Control. *J. Yunnan Agric. Univ.* **2011**, *26*, 124–130.
59. Li, X.; Lu, Y.Z.; Chen, Y.; Zhu, G.C.; Zeng, R.J. Constraining Nitrification by Intermittent Aeration to Achieve Methane-driven Ammonia Recovery of the Mainstream Anaerobic Effluent. *J. Environ. Manag.* **2021**, *295*, 113103. [CrossRef]
60. Cui, Y.F.; Huang, Y.; Jiang, L.H. Advances in the Study of *Gibberella* spp. in Agricultural Production. *Chin. Agric. Sci. Bull.* **2007**, *7*, 441–446. [CrossRef]
61. Zhang, H.H.; Xi, J.S.; Lv, Q.; Wang, J.W.; Yu, K.; Zhao, F.Y. Effect of Aerated Irrigation on the Growth and Rhizosphere Soil Fungal Community Structure of Greenhouse Grape Seedlings. *Sustainability* **2022**, *14*, 12719. [CrossRef]

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