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Effects of Irrigation, Nitrogen Fertilization, and Aeration on Tomato Yield and Fruit Quality: Insights into Root–Soil–Microbe Interactions Under Greenhouse Conditions

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Abstract

Coordinated irrigation, nitrogen fertilization, and aeration management may improve greenhouse tomato production, but their relationships with root-zone responses remain insufficiently understood. A two-year greenhouse experiment evaluated ten treatment combinations involving two irrigation levels, two nitrogen rates, and three aeration levels, with non-aerated controls included only under full irrigation. Soil conditions, root traits, culturable microbial abundance, yield, and six fruit quality attributes were measured. Path analysis and partial least squares structural equation modeling examined statistical relationships among root-zone indicators and yield. Greater aeration was associated with increased root growth and culturable microbial abundance. Soil pH, oxygen content, and root length were closely associated with microbial abundance. Higher irrigation and nitrogen fertilization generally increased yield but reduced lycopene content, indicating a yield–quality trade-off. The first principal component explained 90.10% and 93.58% of the variation in measured quality attributes in 2021 and 2022, respectively. Lycopene was strongly associated with the comprehensive quality score. A2F1I1 achieved the highest quality score in both years and was a promising combination when prioritizing the measured quality attributes. These findings inform integrated greenhouse management, although the observed statistical associations do not establish biological mechanisms, and broader validation is needed before commercial recommendations.

Keywords: subsurface drip irrigation; root-zone oxygen; rhizosphere; lycopene; principal component analysis; partial least squares structural equation modeling

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1. Introduction

Tomato (*Solanum lycopersicum L.*) is one of the most important vegetable crops worldwide [1–3], extensively cultivated due to its rich nutritional components, such as lycopene and vitamin C, as well as its significant economic value [2,4,5]. With the global population growth and rising living standards, the demand for tomatoes continues to increase [6,7]. Therefore, enhancing both tomato yield and quality is essential for ensuring national food security and promoting sustainable development, positioning tomatoes as a critical crop in global agricultural production. However, challenges such as continuous cropping obstacles and inadequate field management practices are deteriorating the soil environment [8,9], posing a significant threat to both tomato yield and quality. Consequently, improving

the soil environment to boost tomato yield and quality has become a pressing issue in agricultural production.

The irrigation–fertilization–aeration coupled drip irrigation technology is regarded as an effective soil management strategy. It is capable of regulating the irrigation, fertilization, and aeration conditions in the crop root zone, thereby improving the root growth environment [10–13]. Its primary goal is to enhance soil quality and crop productivity through the optimization of the soil environment. Previous studies have largely focused on the effects of irrigation–fertilization integration on greenhouse crop productivity [14–16]. However, the infiltration of irrigation water can displace air from soil pores, leading to periodic water stagnation and reduced soil aeration [17,18]. Furthermore, prolonged fertilization can result in soil acidification, compaction, and secondary salinization—physical and chemical issues that also decrease soil aeration [12,19]. Therefore, incorporating aeration equipment into the irrigation system, in addition to irrigation–fertilization integration, increases the dissolved oxygen content in the irrigation water, addressing the potential soil aeration problems associated with traditional drip irrigation [20,21]. Research has demonstrated that, compared to traditional irrigation–fertilization integration, irrigation–fertilization–aeration coupled drip irrigation technology not only conserves water and fertilizer [22] but also optimizes the crop growth environment by improving soil aeration, thereby enhancing crop water productivity and achieving higher yields and efficiency [23–26]. A study by [27] found that aerated irrigation extended the rapid nitrogen accumulation period and reproductive growth stage of tomatoes, increasing nitrogen absorption and transporting more nitrogen to the fruits. Additionally, the irrigation–fertilization–aeration coupled drip irrigation technology is effective in reducing greenhouse gas emissions [28]. Studies have shown that fertilization and irrigation are the primary factors influencing soil N_2O emissions [29–31], while aerated irrigation alters soil N_2O production and emissions by increasing soil oxygen content [32]. Ref. [29] found that aerated irrigation, when combined with varying irrigation management levels, increased the carbon footprint by an average of 24% and significantly boosted the tomato yield. Moreover, this technology improves the soil structure, modifies the pH of the rhizosphere soil [18,26,33], and increases the content of organic matter, nitrate nitrogen, available phosphorus, and available potassium [34,35], thereby enhancing soil fertility. It also affects the structure of soil microbial communities, stimulates soil enzyme activity and microbial biomass [36,37], and promotes crop growth and physiological activity, thus positively influencing both the soil structure and crop development.

Soil microorganisms are critical indicators of soil health. They play an essential role in soil structure formation, organic matter decomposition, nutrient transformation, and nutrient cycling, as well as in organic matter breakdown and energy flow [38–40], which are critical for crop growth [41]. Research has demonstrated that precise control over the supply of water, nutrients, and oxygen in the soil significantly influences the structure and activity of soil microbial communities [42–44]. Changes in microbial structure are considered a key indicator of soil fertility [45–47]. In a study spanning 11 years, [47] found that a fertilizer with a carbon-to-nitrogen ratio of 33:1 resulted in the highest increase in soil nutrients and microbial activity for greenhouse tomatoes. Furthermore, variations in soil moisture content can influence the availability of soil nutrients [48,49]. The study in [50] demonstrated that different drip irrigation methods, such as surface drip irrigation, subsurface drip irrigation, and alternate drip irrigation, can affect tomato growth and yields by modulating the interaction between roots, soil, and microorganisms. Consequently, the application of water and fertilizer can alter both the composition and activity of soil microbial communities. The authors of [51] showed that aerated irrigation directly influences soil bacterial and fungal communities, enhancing soil organic carbon (SOC), the available phosphorus content, and the tomato yield. In conclusion, numerous studies have explored

and confirmed the effects of individual factors such as water, nutrients, and gases on soil microorganisms. However, research on the combined effects of multiple factors on the soil microenvironment remains relatively limited. Therefore, a comprehensive exploration of the impact of irrigation–fertilization–aeration coupled drip irrigation technology on soil microorganisms is crucial for understanding and optimizing soil ecosystem functions, enhancing crop productivity, and promoting agricultural sustainability.

Previous studies have examined the effects of irrigation, nitrogen fertilization, and aeration on crop growth and soil microbial responses. However, the combined responses of the soil conditions, root morphology, culturable microbial abundance, and greenhouse tomato performance to different combinations of these management practices remain insufficiently understood. In particular, further clarification is needed regarding which soil and root variables are most closely associated with culturable microbial abundance and how these root-zone responses relate to tomato yield. Therefore, this study conducted a two-year greenhouse tomato experiment to (1) evaluate changes in soil environmental conditions, root morphological traits, and the abundance of culturable bacteria, fungi, and actinomycetes under different combinations of irrigation, nitrogen fertilization, and aeration; (2) identify soil and root variables closely associated with culturable microbial abundance using path analysis; and (3) compare tomato growth, yield, and six measured fruit quality attributes among treatments and examine the statistical relationships among the soil conditions, root traits, culturable microbial abundance, and yield using PLS-SEM. These analyses distinguish measured treatment responses from statistical associations and do not, by themselves, establish the biological mechanisms linking soil, roots, microorganisms, and yield. The findings may inform the coordinated management of irrigation, nitrogen fertilization, and aeration in greenhouse tomato production.

2. Materials and Methods

2.1. Planting Information and Experimental Design

The experiment in this study was conducted from March to July in 2021 and 2022 in a solar greenhouse at the Key Laboratory of Agricultural Soil and Water Engineering in Arid Areas, Northwest A&F University. The greenhouse is located in Yangling District, Xianyang City, Shaanxi Province, as shown in Figure 1. Purchased seedlings of tomato (*Solanum lycopersicum* L.) cultivar 'Jinpeng No. 8' were used in both growing seasons. Seedlings were transplanted into the greenhouse plots on 26 March 2021 and 3 April 2022, and the final harvests were completed on 9 July 2021 and 13 July 2022, respectively. At transplanting, seedlings had three or four fully expanded true leaves and one developing leaf. All plots were thoroughly irrigated immediately after transplanting to promote seedling establishment. During the 2021 and 2022 growing seasons, the daily mean greenhouse air temperature ranged from 14.26 to 32.27 °C and from 11.13 to 34.42 °C, respectively. The daily mean relative humidity ranged from 40.97 to 94.27% and from 38.12 to 90.46%, respectively. The daily mean photosynthetically active radiation ranged from 10.90 to 264.14 μmol m^{-2} s^{-1} in 2021 and from 8.46 to 186.01 μmol m^{-2} s^{-1} in 2022. The average dry bulk densities of the soil at depths of 0–40 cm were 1.27, 1.34, 1.42, and 1.37 g/cm^3 at 10 cm intervals, while the field capacity of the 0–60 cm soil layer was 32.1% (volumetric water content). The site has an average annual sunshine duration of 2163.8 h and a frost-free period of 210 days.

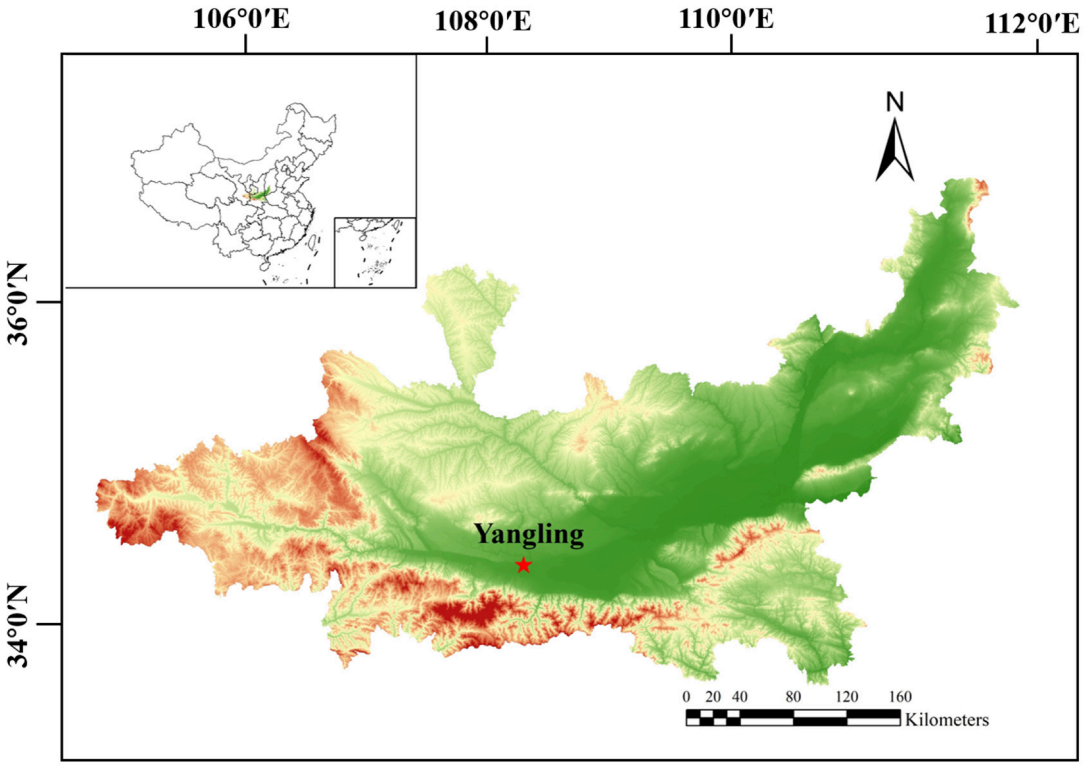


Figure 1. Map of the study area. Reprinted with permission from Ref [52]. Copyright 2025 Sun Yanan.

This experiment employed a completely randomized design with two irrigation levels (I1 and I2, corresponding to crop coefficient k_{cp} values of 0.8 and 1.0, respectively), two nitrogen application levels (F1 and F2, with nitrogen rates of 180 kg/ha and 240 kg/ha), and three aeration levels (A1, A2, and CK, representing single Venturi aeration rates, double Venturi aeration rates, and no aeration control, respectively). These combinations resulted in 10 treatment combinations: CKF1I2, CKF2I2, A1F1I1, A1F2I1, A1F1I2, A1F2I2, A2F1I1, A2F2I1, A2F1I2, and A2F2I2. The non-aerated treatments (CK) were included only under full irrigation (I2) as reference treatments. CKF1I1 and CKF2I1 were intentionally excluded during experimental planning because non-aerated treatments under reduced irrigation (I1) had shown unsatisfactory performance in our previous experiments. Each treatment had three replicate plots, giving a total of 30 plots arranged in a completely randomized design without blocks. Treatments were randomly assigned to the plots before the first growing season to reduce potential positional bias associated with spatial variation within the greenhouse. Irrigation, nitrogen fertilization, and aeration were independently controlled for each plot, which constituted the experimental unit. The same plots and treatment assignments were maintained in 2021 and 2022. Each subplot consisted of a single ridge measuring 4 m in length and 0.8 m in width, with a 40 cm gap between ridges. To prevent seepage and minimize interactions between adjacent subplots, plastic film of 1 m in depth was installed between them. A 16 mm underground drip irrigation pipe was buried centrally at a depth of 15 cm, with a flow rate of 4 L/h and emitters spaced 35 cm apart, positioned 10 cm from the crop stems. Tomato plants were transplanted directly above the emitters, with 11 plants per ridge, spaced 35 cm apart. After seedling establishment, the soil surface was covered with plastic film to reduce evaporation. Plants were topped to retain four fruit trusses per plant, thereby standardizing the number of retained fruit trusses across treatments. Within each growing season, all treatments used the same cultivar and transplanting date and received the same routine crop management practices, except for

the specified irrigation, nitrogen fertilization, and aeration treatments. Phosphorus and potassium application rates were identical across treatments.

The irrigation volume was regulated according to the cumulative pan evaporation (E_{pan}), measured using an evaporation pan (0.20 m in diameter × 0.10 m in depth) positioned 30 cm above the tomato canopy. The pan's height was adjusted as the crop grew to ensure accurate measurements. The evaporation amount in the evaporation pan was measured at 8:00 am daily. After the measurement, the pan was cleaned and refilled with fresh water to 20 mm. The irrigation interval was 3–4 days.

Irrigation water was delivered from a tank via a water pump. In 2021, the total E_{pan} was 213.3 mm, resulting in irrigation quotas of 170.6 mm and 213.3 mm for the I1 and I2 treatments, respectively (Appendix A Table A1). In 2022, E_{pan} increased to 230.8 mm, with corresponding irrigation quotas of 184.6 mm and 230.8 mm for I1 and I2 (Appendix A Table A2). Aeration was implemented using a Mazzei 287 Venturi injector (Mazzei Injector Company, LLC, USA). Pressurized water for irrigation was generated by the pump, and the main pipeline's regulating valve was adjusted to control the flow. For the A1 treatment, the inlet pressure was set at 0.1 MPa and the outlet pressure at 0.02 MPa, while, for A2, the outlet pressure was reduced to 0.01 MPa. The air intake for A1, determined by the exhaust method, accounted for approximately 17% of the irrigation water volume, while that for A2 accounted for 34% [26].

Fertilization management involved the use of biological inoculants (sheepboard balls without *N*, *P*, or *K*), along with 150 kg/ha of phosphorus fertilizer and 240 kg/ha of potassium fertilizer. Nitrogen was applied in two phases: 30% as a basal fertilizer, incorporated into the soil to a depth of 20 cm, and the remaining 70% delivered in four equal applications through the drip irrigation system during the tomato growth period. The basal-to-topdressing ratio followed a schedule of 3:1:2:2:2, with consistent application timings and proportions maintained across both years of the study.

2.2. Measurement Indicators

2.2.1. Soil Sampling

The oxygen (O_2) content in the root-zone soil was determined with a fiber-optic oxygen meter (Firesting-O_2) and an oxygen-sensitive probe (Robust Oxygen Miniprobe). The probe was positioned in the root zone of a plant located centrally within each subplot, inserted at a depth of 0.1 m and 5 cm away from the stem. To reduce atmospheric interference, the insertion holes were packed with moist soil, and the area was covered with plastic film. Data collection began once the probe had stabilized (approximately 1 min). For detailed instructions on the instrument's usage, refer to the literature [10,53]. The soil water-filled pore space (WFPS) was then calculated using the following formula:

$$\mathrm{WFPS} = \theta \frac{r}{1 - r/\rho} \quad (1)$$

where θ is the soil gravimetric water content (%); r is the soil bulk density (g/cm^3); and ρ is the soil particle density (2.65 g/cm^3).

The determination and calculation of the mass fraction of soil nitrate nitrogen (NO_3^--N) was performed with reference to [25]. Root-zone soil samples were collected during each soil moisture measurement using a 2.0 cm diameter soil auger. The pH of the soil was analyzed with a pHB-4 pH meter, employing a soil-to-water ratio of 1:5 (w/v). Soil sampling for microbiological analysis was conducted every 10 days in all 30 experimental plots. On each sampling date, one soil core was collected from the 0–20 cm soil layer near a tomato plant in each plot using a small soil auger, yielding approximately 100 g of soil per plot. Each plot sample was kept separate and analyzed individually; samples were not pooled across plots. The three replicate plots represented each treatment. Samples

were placed in sealed bags and transported to the laboratory in an insulated container on the day of collection. They were stored in a cool, shaded location, and microbiological analyses were completed within three days of sampling. The same plots were sampled repeatedly throughout the growing season, but the sampling location within each plot was changed on each occasion to avoid previously disturbed soil. The abundance of culturable bacteria, fungi, and actinomycetes was determined using the serial dilution plate count method described by Li et al. [54]. For each soil sample, 0.1 mL of the soil suspension was spread onto plates at each of three consecutive dilution levels, with three replicate plates per dilution. Bacteria were cultured on beef extract–peptone agar, fungi on Martin medium, and actinomycetes on modified Gao's No. 1 medium. The replicate plates constituted technical replicates rather than independent experimental replicates [54]. These measurements quantified the culturable microbial abundance and did not characterize the composition, diversity, or functional structure of the entire soil microbial community.

2.2.2. Tomato Root System, Yield, Quality, and Dry Matter Content

At maturity, five plants with similar apparent growth were deliberately selected from each plot for yield assessment; selection was not random. Yield measurements were averaged within each plot to obtain a plot-level value. For fruit quality analysis, five fruits of a similar size and color were selected from each plot and pooled by juicing to produce one composite sample per plot. Soluble solids were assessed with a handheld refractometer, while vitamin C content was measured using the molybdenum blue colorimetric method [55], lycopene levels were determined by UV spectrophotometry [56], and soluble sugar content was analyzed via the anthrone colorimetric method [57]. Organic acid content was measured through acid–base titration [57,58], and the sugar–acid ratio was calculated as the ratio of soluble sugars to organic acid content. For root system analysis, three tomato plants with uniform growth were selected from each subplot, and their aboveground parts were removed. Roots were excavated from a 30 × 30 × 50 cm soil block located between two adjacent plants. The collected roots were analyzed for length, volume, surface area, forks, and tips using the WinRHIZO Pro2004b software (version 5.0; Regent Instrument, Inc., Quebec, QC, Canada). Both root and plant samples were first blanched at 105 °C for 30 min, followed by drying at 75 °C for 24 h, and their dry weights were recorded.

2.3. Statistical Analysis

2.3.1. Path Analysis Method

Path analysis is a tool for examining variable relationships in multivariate statistics. It decomposes correlations into direct (path coefficients) and indirect effects, assessing the direct and indirect influences of independent variables on dependent variables [59–61].

For a system with one dependent variable y and multiple independent variables x_i (i = 1, 2, ..., n), the multiple linear regression equation is expressed as follows:

$$y = a_0 + a_1x_1 + a_2x_2 + \ldots + a_ix_i,\ (i = 1,2\ldots n) \quad (2)$$

where y represents the dependent variable, x_i represents the *ith* independent variable, and a_i represents the partial regression coefficient of x_i on y.

By substituting the actual observed values into Equation (4) and solving the system of equations using the least squares method, the standard matrix equation can be established as follows:

$$\begin{bmatrix} 1 & r_{x_1x_2} & \cdot & r_{x_1x_j} \\ r_{x_2x_1} & 1 & \cdot & r_{x_2x_j} \\ \vdots & \vdots & \vdots & \vdots \\ r_{x_ix_1} & r_{x_ix_2} & \cdot & 1 \end{bmatrix} \times \begin{bmatrix} p_{x_1y} \\ p_{x_2y} \\ \vdots \\ p_{x_ny} \end{bmatrix} = \begin{bmatrix} r_{x_1y} \\ r_{x_2y} \\ \vdots \\ r_{x_ny} \end{bmatrix} \quad (3)$$

where $r_{xi.xj}$ represents the correlation coefficient between variables x_i and x_j, and $P_{xi.y}$ represents the direct path coefficient, indicating the direct influence of variable x_i on y.

$$p_{x_i y} = a_i \times \sigma_{x_i}/\sigma_y, \qquad (i = 1, 2 \ldots n) \tag{4}$$

where σ_{xi} and σ_y represent the standard deviations of x_i and y, respectively, and $r_{xi.xj} \times P_{xi.y}$ represents the indirect path coefficient, indicating the indirect effect of variable x_i on y through variable x_j.

The remaining variables represent the effects of other independent variables and errors on the dependent variable y. The path coefficient P_{ey} is calculated as follows:

$$p_{ey} = \sqrt{1 - (r_{x_1 y} \times P_{x_1 y} + r_{x_2 y} \times P_{x_2 y} + \ldots + r_{x_n y} \times P_{x_n y})} \tag{5}$$

2.3.2. Additional Data Analyses

The experimental data were initially organized and processed in Excel 2016. Statistical analyses were performed using SPSS 26.0, with irrigation (I), nitrogen fertilization (F), and aeration (A) specified as fixed factors. Analyses of variance were conducted separately for 2021 and 2022. No block factor was included because the experiment followed a completely randomized design without blocks. Year was not included in the year-specific models, and observations from the two years were not pooled as independent replicates. Each plot constituted an experimental unit, with three replicate plots per treatment. For repeatedly measured soil variables, observations were averaged over sampling dates within each plot before analysis, so the ANOVA evaluated growing-season mean responses. Individual sampling dates, plants, and fruits were not treated as independent treatment replicates. Normality and homogeneity of variance were assessed before ANOVA. Treatment means were compared using the least significant difference (LSD) method at $p < 0.05$. Analyses of variance were conducted separately for 2021 and 2022. Data from the two years were not pooled as independent replicates, and year was not included as a factor in the year-specific analyses. No combined-year treatment effect was estimated. Pearson correlation analysis was performed in Origin Pro 2021 to explore the relationships between root system indicators and soil environmental factors. Principal component analysis (PCA) was used for a comprehensive analysis of tomato quality, with the specific methodology referenced in the paper [62]. To model the interactions among soil factors, rhizosphere microorganisms, root systems, and yield, partial least squares structural equation modeling (PLS-SEM) was applied using the SmartPLS 4.0 software (University of South Alabama). Figures were created using Origin Pro 2021.

3. Results

3.1. Variations in Soil Environmental Factors

The soil pH, O_2, WFPS, and NO_3^--N content throughout the entire growth period of greenhouse tomatoes were monitored. The results from the two-year experiment (2021–2022) indicated that the pH range in the 0–20 cm soil layer was 7.72–8.09 in 2021 and 7.81–8.21 in 2022. The average soil pH in 2021 was 7.92, and, in 2022, it was 7.98, representing a significant increase of 3% (2021) and 4.2% (2022) compared to the initial soil pH values ($p < 0.05$ *) (Figure 2a). Fertilization and aeration treatments had a significant effect on the changes in soil pH (Table 1). The soil pH increased significantly with higher fertilization levels. In 2021, the soil pH in the F2 treatment was 0.04 higher (0.55%) compared to the F1 treatment, and, in 2022, it increased by 0.07 (0.9%) ($p < 0.05$ *). Furthermore, increasing the aeration level significantly increased the soil pH (Table 1). In both 2021 and 2022, that of the A2 treatment was significantly higher than those of the A1, CK treatments—by 0.64%, 2.18%

and 1.26%, 2.19%, respectively ($p < 0.05$ *). In addition, there was a significant interaction effect between aeration and fertilization on the soil pH ($p < 0.05$ *) (Table 1).

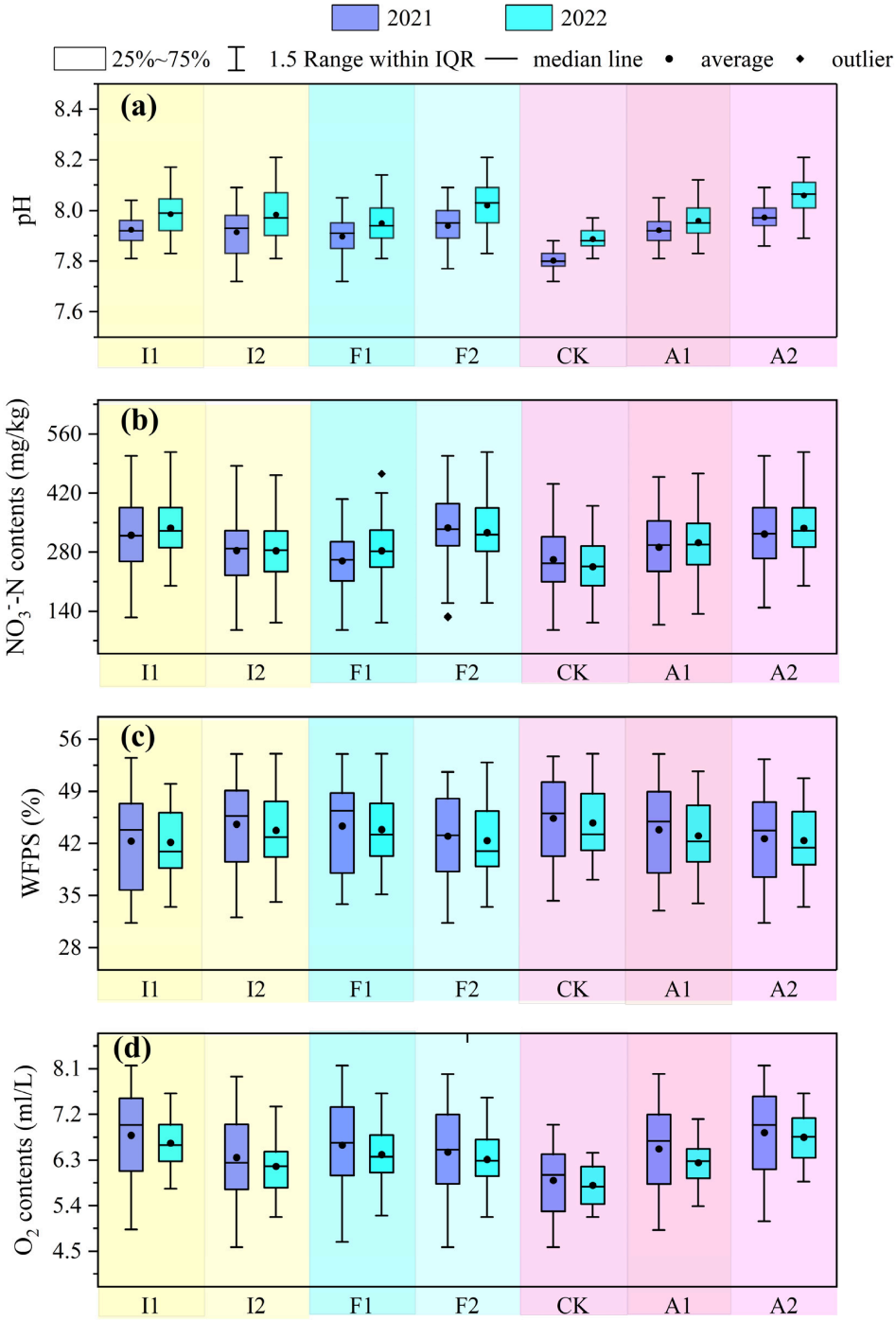


Figure 2. Effects of irrigation–fertilization–aeration models on soil environmental factors in a two-year (2021–2022) greenhouse tomato experiment. (**a**–**d**) represent the changes in soil pH, NO_3^--N content, soil water-filled porosity (WFPS), and oxygen (O_2) content under different irrigation, fertilization, and aeration factors in the 2021 and 2022 experiments, respectively. I, F, and A represent the effects of irrigation, fertilization, and aeration on each index, respectively. I1: 80% ET_c; I2: 100% ET_c; F1 = 180 kg/ha; F2 = 240 kg/ha; CK: unaerated subsurface drip irrigation; A1: one-multiplier aerated subsurface drip irrigation; A2: two-multiplier aerated subsurface drip irrigation, respectively. *Note: Purple box represents the results of the 2021 experiments and blue box represents the results of the 2022 experiments, respectively.*

Table 1. Analysis of variance results for the effects of irrigation, fertilization, aeration, and their interactions on soil environmental factors in the tomato root zone during 2021 and 2022.

Factor \ Indicator	2021				2022			
	pH	WFPS	NO_3^--N	O_2	pH	WFPS	NO_3^--N	O_2
I	NS	**	**	**	NS	**	**	**
F	**	**	**	**	**	**	**	**
A	**	**	**	**	**	**	**	**
I × F	NS	NS	NS	NS	NS	NS	NS	NS
I × A	NS	**	NS	*	NS	**	NS	*
A × F	*	NS	*	NS	*	NS	*	NS
I × F × A	NS	NS	NS	*	NS	NS	NS	NS

*Note: I, F, and A represent the effects of irrigation, fertilization, and aeration on each index, respectively; × stands for the interaction effect; I × F and I × A are the interaction effects of irrigation and fertilization and of irrigation and aeration on each index, respectively; F × A is the interaction effect of fertilization and aeration on each index; I × F × A is the interaction effect of irrigation, fertilization, and aeration on each index. * and ** are the marked levels of 0.05 and 0.01, respectively.*

Fertilization, aeration, and irrigation treatments significantly influenced the soil NO_3^--N content (Table 1). Specifically, the soil NO_3^--N content increased significantly with higher fertilization levels. The 2021 and 2022 experiments demonstrated that the soil NO_3^--N content in the F2 treatment increased significantly, by 30.28% and 15.09%, respectively, compared to the F1 treatment ($p < 0.05$ *) (Figure 2b). Additionally, the soil NO_3^--N content significantly increased with higher aeration levels. In the 2021 experiment, the A2 treatment resulted in significant increases of 10.83% and 23.03% compared to the A1 and CK treatments, respectively. In 2022, the increases were 11.38% and 37.5%, respectively ($p < 0.05$ *) (Figure 2b). However, increasing irrigation levels significantly reduced the soil NO_3^--N content. The I2 treatment resulted in a decrease of 11.43% (2021) and 16.01% (2022) compared to the I1 treatment ($p < 0.05$ *).

The two-year experiment revealed that the WFPS in the tomato root zone soil exhibited a fluctuating decreasing trend. The WFPS range in 2021 and 2022 was 31.35–54.02% and 33.49–54.06%, respectively, with no significant differences between the years (Figure 2c). However, significant differences in WFPS were observed between treatments in the 0–20 cm soil layer of the tomato root zone. As the fertilization levels increased, the WFPS significantly decreased ($p < 0.05$ *) (Figure 2c). In both the 2021 and 2022 experiments, the WFPS in the F1 treatment was 3.17% and 3.56% higher than that in the F2 treatment, respectively. However, the soil WFPS significantly increased with increasing irrigation levels. In this study, the I2 treatment resulted in a significant increase of 5.39% (2021) and 3.86% (2022) compared to the I1 treatment. Furthermore, aeration irrigation significantly reduced the soil WFPS, and the WFPS decreased significantly with increasing aeration levels. In the 2021 experiment, the A2 treatment reduced the soil WFPS by 2.76% and 6.07% compared to the A1 and CK treatments, respectively. In 2022, the A2 treatment reduced the soil WFPS by 1.52% and 5.29% compared to the A1 and CK treatments ($p < 0.05$ *) (Figure 2c) (Table 1).

The results of the two-year greenhouse tomato experiment indicated a consistent trend in the variation in soil O_2 content in the tomato root zone. In 2021, the soil O_2 content fluctuated within the range of 4.58 mL/L to 8.16 mL/L, while, in 2022, it fluctuated between 5.18 mL/L and 7.61 mL/L (Figure 2d). Although interannual variations had no significant effect on the soil O_2 content, the fertilization, aeration, and irrigation treatments notably influenced its variation (Table 1). As the fertilization levels increased, the soil O_2 content decreased. In 2021, the O_2 content in the F2 treatment was 2% lower than that in the F1 treatment, and, in 2022, it decreased by 1.5% (Figure 2d). Additionally, aeration–irrigation had a particularly significant effect on the variation in soil O_2 content. In the 2021 experiment, the average O_2 content in the A2 treatment was significantly higher, by 4.93% and 16.02%,

than that in the A1 and CK treatments, respectively. In 2022, this increase was 8.07% and 16.42%, respectively. However, increasing the irrigation level led to a reduction in soil O_2 content. In both the 2021 and 2022 experiments, the average O_2 content in the I1 treatment was 6.92% and 7.47% higher than that in the I2 treatment, respectively ($p < 0.05$ *) (Figure 2d). Furthermore, there was a significant interaction effect between irrigation and aeration on soil O_2 content (Table 1).

Additionally, path analysis was employed to examine the impacts of irrigation, fertilization, and aeration on soil environmental factors. The results revealed that aeration was the major factor affecting changes in soil pH, O_2, and NO_3^--N levels, with direct path coefficients of 0.830 ***, 0.513 ***, and 0.795 ***, respectively. Moreover, the response of soil NO_3^--N content to fertilization was also highly significant, with a path coefficient of 0.671 ***. Irrigation was the main factor influencing the soil WFPS, with a direct path coefficient of 0.510 ***. The impacts of irrigation, fertilization, and aeration on the root-zone soil pH were all positive, while both fertilization and aeration treatments had a significant negative effect on the WFPS. Irrigation significantly negatively affected the changes in NO_3^--N and O_2 content (Table 2).

Table 2. Path analysis of irrigation, fertilization, and aeration effects on soil environmental factors.

Factor \ Indicator	pH	WFPS	NO_3^--N	O_2
Irrigation	0.237 ***	0.510 ***	−0.323 ***	−0.307 ***
Fertilization	0.342 ***	−0.498 ***	0.671 ***	−0.151 ***
Aeration	0.830 ***	−0.473 ***	0.513 ***	0.795 ***
R^2	0.733	0.888	0.926	0.908

*Note: Irrigation, fertilization, and aeration were the factors in the experiment design; there was only a direct path coefficient and no indirect path coefficient, respectively. *** is the marked levels of 0.001, respectively.*

3.2. Tomato Root System and Rhizosphere Microorganisms

A comprehensive evaluation of the tomato root system was conducted through a two-year greenhouse experiment. The results showed that irrigation, fertilization, and aeration treatments had significant effects on the root length, root volume, root surface area, root forks, and root tips of tomatoes. However, interannual variations had no significant effect on the growth changes of the root system. Aerated irrigation significantly affected the growth of the tomato root system (Table 3). With an increase in aeration levels, the tomato root length, root volume, root surface area, root forks, and root tips increased significantly ($p < 0.05$ *) (Table 3). In this study, the root length of tomatoes in the A2 treatment was 1.25 times and 1.96 times longer than in the A1 and CK treatments in 2021 and 1.24 times and 1.86 times longer in 2022 ($p < 0.05$ *). The root surface area in the A2 treatment was 1.12 times and 1.17 times that of the A1 and CK treatments in 2021 and 1.13 times and 1.18 times in 2022. The number of root tips was 1.03 times and 1.46 times higher than in the A1 and CK treatments in 2021 and 1.05 times and 1.47 times higher in 2022. Furthermore, in 2021, the root volume and number of root forks in the A2 treatment were 22.3% and 48.1% higher than in the CK treatment, respectively. These increases were 12.4% and 47.7% in 2022.

Table 3. Effects of different irrigation, fertilization, and aeration treatments on tomato root system, consisting of root length, root volume, root surface aera, root forks, and root tips, during 2021 and 2022 experiments on tomato in greenhouse.

Treatment	2021—Root System					2022—Root System				
	Length	Volume	Area	Forks	Tips	Length	Volume	Area	Forks	Tips
CKF1I2	615.32 i	12.21 h	443.96 f	3956 j	2166 i	689.31 j	13.76 g	463.33 g	4021 i	2278 g
CKF2I2	733.79 h	13.49 f	498.37 d	5218 h	3273 f	777.67 i	14.82 d	516.27 e	5406 g	3311 e
A1F1I1	944.65 g	12.46 g	440.51 f	4968 i	2988 h	972.36 h	14.03 f	461.66 g	4987 h	3025 f
A1F2I1	1086.36 e	13.90 e	498.16 d	5277 g	4104 c	1111.42 f	15.21 c	514.74 e	5379 g	4206 c
A1F1I2	1011.37 f	13.38 f	486.26 e	5672 f	3275 f	1073.74 g	14.16 f	496.71 f	5611 f	3298 e
A1F2I2	1187.65 d	15.85 b	540.16 c	7111 b	5078 a	1251.66 d	15.92 b	558.96 c	7236 b	5066 a
A2F1I1	1095.84 e	14.02 d	492.13 de	5826 e	3204 g	1142.72 e	14.39 e	530.06 d	5964 e	3302 e
A2F2I1	1336.75 b	15.62 c	547.86 bc	7031 c	4060 d	1377.63 b	16.04 b	574.22 b	7162 c	4206 c
A2F1I2	1298.56 c	15.92 b	550.21 b	6325 d	3895 e	1341.62 c	16.02 b	569.68 b	6555 d	4021 d
A2F2I2	1557.38 a	17.29 a	620.08 a	7986 a	4738 b	1598.76 a	17.77 a	633.20 a	8166 a	4855 b
Significance										
I	**	**	**	**	**	**	**	**	**	**
F	**	**	**	**	**	**	**	**	**	**
A	**	**	**	**	**	**	**	**	**	**
I × F	**	**	NS	**	**	**	**	**	**	**
I × A	**	**	**	**	**	**	**	**	**	**
F × A	**	**	NS	**	**	**	**	**	**	**
I × F × A	NS	**	*	**	**	NS	*	NS	**	**

*Note: Different letters in the same column indicate significant differences at *p* < 0.05 level based on the least significant difference (LSD) test. I, F, and A represent the effects of irrigation, fertilization, and aeration on each index, respectively; × stands for the interaction effect; I × F and I × A are the interaction effects of irrigation and fertilization and of irrigation and aeration on each index, respectively; F × A is the interaction effect of fertilization and aeration on each index; I × F × A is the interaction effect of irrigation, fertilization, and aeration on each index. * and ** are the marked levels of 0.05 and 0.01, respectively.*

Higher fertilization levels also stimulated tomato root system growth. As fertilization increased, significant improvements were observed in the root length, surface area, tips, volume, and number of root forks ($p < 0.05$ *) (Table 3). Specifically, in the F2 treatment, the root length, root surface area, and number of root tips were 1.19, 1.12, and 1.37 times those of the F1 treatment in 2021 and 1.17, 1.11, and 1.36 times those of the F1 treatment in 2022. Additionally, the root volume and number of root forks in the F2 treatment increased by 12%, 22% and 10.2%, 22.9% compared to the F1 treatment in the 2021 and 2022 experiments, respectively. However, when the irrigation level was raised to full irrigation, the tomato root length decreased—a phenomenon observed in both the 2021 and 2022 experiments. In the 2021 experiment, the root length in the I2 treatment was 4% shorter than that in the I1 treatment and 3% shorter in 2022. However, with an increase in irrigation levels, the root surface area, number of root tips, root volume, and number of root forks all increased. In the I2 treatment, the root surface area and number of root tips were 1.06 and 1.04 times those of the I1 treatment in 2021 and 1.04 and 1.03 times in 2022. Additionally, with the increase in irrigation levels, the root volume and number of root forks of tomatoes increased by 4.9% and 4.7% in 2021 and by 3.3% and 5% in 2022, respectively. Furthermore, with the exception of the root length and root surface area of tomatoes, the interactions of irrigation × fertilization, irrigation × aeration, fertilization × aeration, and irrigation × fertilization × aeration significantly influenced all root system parameters. This result was evident in both the 2021 and 2022 experiments (Table 3).

The rhizospheric microbial community of tomatoes was monitored throughout the growing season, including the quantities of bacteria, fungi, and actinomycetes, in the 2021 and 2022 experiments. The quantities of bacteria, fungi, and actinomycetes in the tomato rhizosphere soil showed a fluctuating upward trend with the growth of the tomato plants. The total number of bacteria per gram of dry soil in each treatment fluctuated between 0.91×10^8 and 17.22×10^8 (2021) and 0.99×10^8 and 20.11×10^8 (2022) (Figure 3a,d).

The average number of bacteria per gram of dry soil throughout the growing season was 9.77×10^8 (2021) and 10.16×10^8 (2022). The number of fungi in each gram of dry soil in the ten treatments fluctuated between 2×10^4 and 18.03×10^4 (2021) and 3.41×10^4 and 19.35×10^4 (2022), with annual average totals of 9.16×10^4 (2021) and 9.98×10^4 (2022) (Figure 3b,e). The total number of actinomycetes per gram of dry soil fluctuated between 1.18×10^6 and 12.00×10^6 (2021) and 1.76×10^6 and 12.99×10^6 (2022), with annual average totals of 5.76×10^6 (2021) and 6.65×10^6 (2022) (Figure 3c,f). Aeration–irrigation significantly increased the number of bacteria, fungi, and actinomycetes in the tomato rhizosphere soil. In the 2021 experiment, the total number of bacteria per gram of dry soil in the A2 treatment was significantly higher than in the CK treatment, by 91.28% and by 30.55%, compared to the A1 treatment ($p < 0.05$ *) (Table 4). A similar increase was observed in the 2022 experiment, with the A2 treatment showing increases of 30.65% and 118.75% compared to the A1 and CK treatments, respectively ($p < 0.05$ *) (Table 4). Furthermore, the total number of fungi per gram of dry soil in the A2 treatment increased by 33.11% and 99.31% compared to the A1 and CK treatments in 2021 and by 38.86% and 92.11% in 2022. The total number of actinomycetes increased significantly, by 43.6% and 116.46%, compared to the A1 and CK treatments in 2021 and by 28.34% and 104.46% in 2022 ($p < 0.05$ *) (Table 4). However, increasing the fertilization and irrigation levels significantly reduced the number of soil microbes in the rhizosphere. In the 2021 experiment, the numbers of bacteria, fungi, and actinomycetes in the F2 treatment were significantly reduced, by 9.88%, 19.61%, and 18.43%, respectively, compared to the F1 treatment (Table 4). In 2022, these reductions were 10%, 9.07%, and 14.22%, respectively ($p < 0.05$ *). The quantities of bacteria, fungi, and actinomycetes in the I2 treatment were reduced by 3.44%, 2.98%, and 1.07%, respectively, compared to the I1 treatment in 2021 and by 5.52%, 4.46%, and 3.91% in 2022 ($p < 0.05$ *) (Table 4).

Table 4. Soil microbial content, including bacteria, fungi, and actinomycetes per gram of dry soil, in the tomato root zone under different irrigation, fertilization, and aeration factors in 2021 and 2022.

Treatment		2021			2022		
		Bacteria ($\times 10^8$/g)	**Fungi ($\times 10^4$/g)**	**Actinomycetes ($\times 10^6$/g)**	**Bacteria ($\times 10^8$/g)**	**Fungi ($\times 10^4$/g)**	**Actinomycetes ($\times 10^6$/g)**
I	I1	10.22 b	9.58 c	5.97 c	10.82 a	10.50 a	7.00 a
	I2	9.87 c	9.29 d	5.91 c	10.22 b	10.03 b	6.73 b
F	F1	10.53 b	10.43 b	6.53 b	11.01 a	10.70 a	7.36 a
	F2	9.49 d	8.38 d	5.33 d	9.91 c	9.73 c	6.32 c
A	A1	9.45 d	8.82 d	5.36 d	10.04 c	9.29 c	6.58 c
	A2	12.34 b	11.74 b	7.69 b	13.12 a	12.90 a	8.45 a
	CK	6.45 e	5.89 f	3.55 f	6.00 f	6.72 e	4.13 e
Mean		9.77	9.16	5.76	10.16	9.98	6.65

*Note: Different letters in the same column indicate significant differences at *p* < 0.05 level based on the least significant difference (LSD) test. I represents I1 and I2 irrigation treatments; F represents F1 and F2 fertilization; A represents A1, A2, and CK aeration treatments, respectively.*

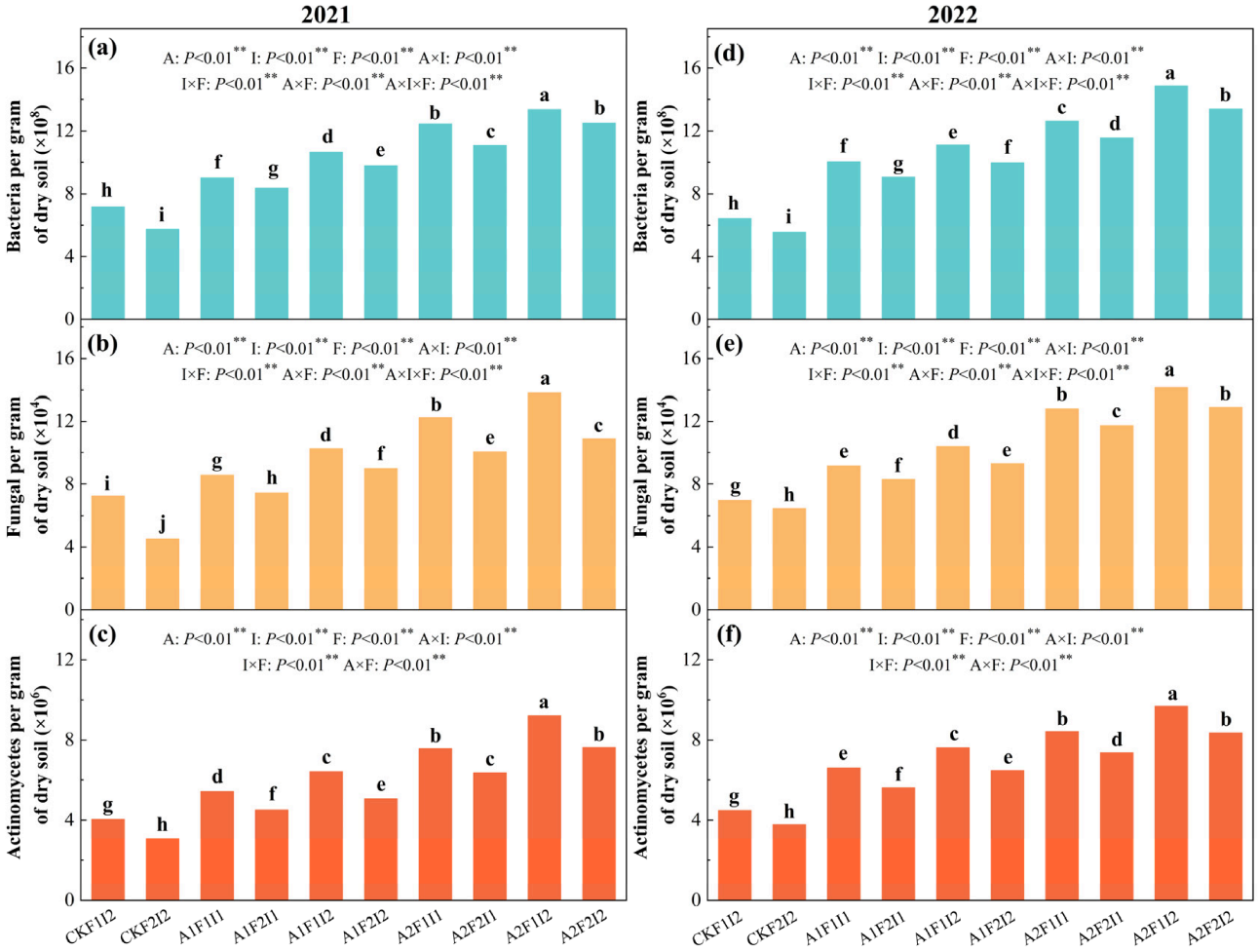


Figure 3. Content of different microorganisms in greenhouse tomato root zone soil under different treatments in 2021 and 2022 experiments. (**a**,**d**) represent soil bacterial content in the root zone of greenhouse tomato under different treatments in the 2021 and 2022 experiments; (**b**,**e**) represent soil fungal content; (**c**,**f**) represent soil actinomycetes content, respectively. Different letters in the same column indicate significant differences at $*p* < 0.05$ level based on the least significant difference (LSD) test. A × F and A × I are the interaction effects of aeration and fertilization and of aeration and irrigation on each index, respectively; F × I is the interaction effect of fertilization and irrigation on each index; A × F × I is the interaction effect of aeration, fertilization, and irrigation on each index. ** represents significance level of 0.01.

3.3. Statistical Relationships Among Soil Conditions, Root Traits, and Culturable Microbial Abundance

The path analysis explained 90%, 90–91%, and 88–89% of the variations in bacteria, fungi, and actinomycetes in the rhizospheric soil in the 2021 and 2022 experiments ($p < 0.001$ ***) (Figures 4 and 5). This indicates that the factors considered in the experiment effectively explained the variations in bacteria, fungi, and actinomycetes in the tomato rhizospheric soil. These results indicate that the variables included in the models accounted for a substantial proportion of the observed variation in culturable microbial abundance.

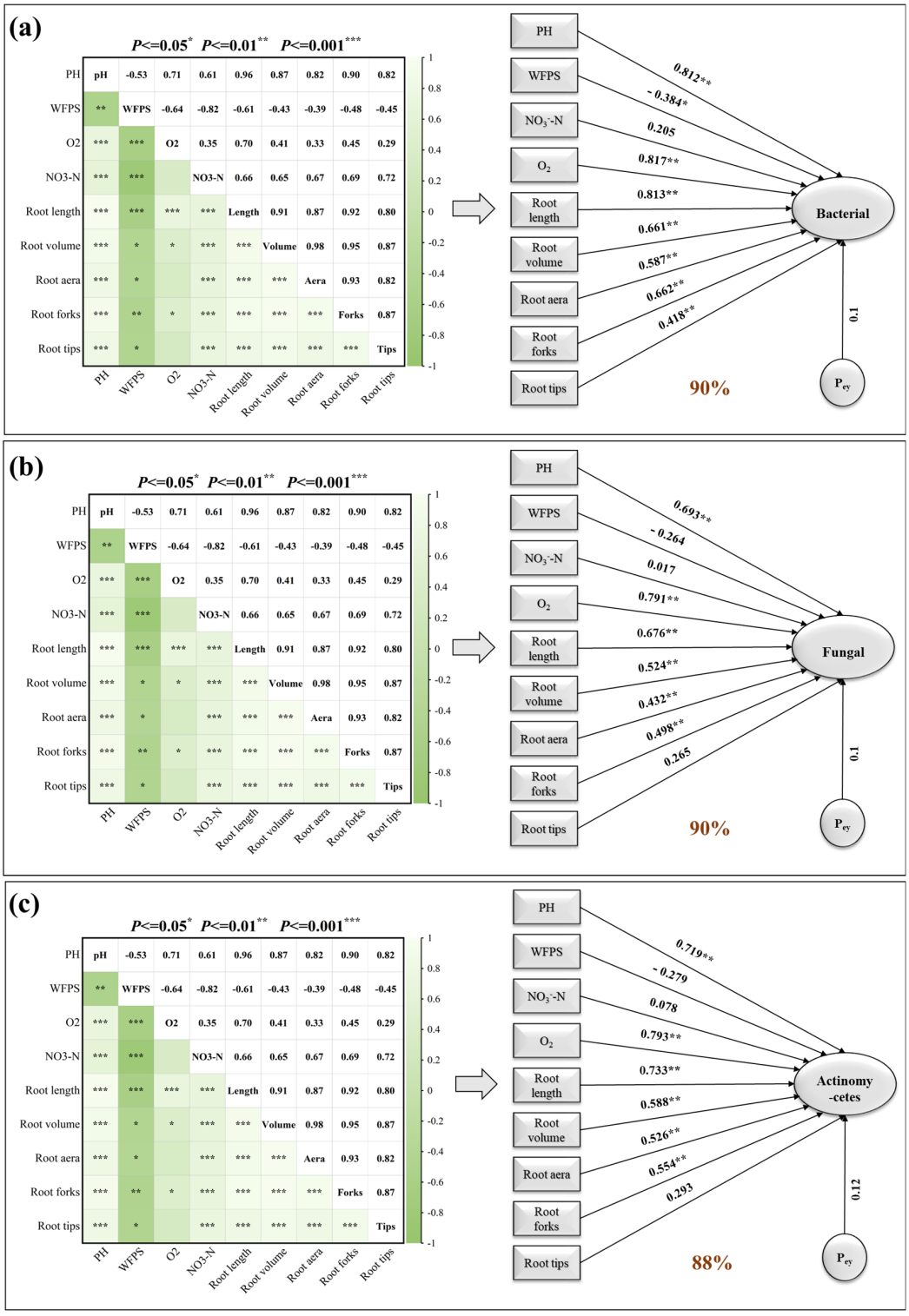


Figure 4. The correlation coefficients between soil pH, soil water-filled pore space (WFPS), soil nitrate N content (NO_3^--N), soil oxygen content (O_2), root length, root volume, root area, root forks, and root tips and their quantified total effects on soil bacteria (**a**), soil fungi (**b**), and soil actinomycetes (**c**) in greenhouse tomato root zone soil in 2021, respectively. *Notes: The black values represent the path coefficient. *, **, and *** represent statistical significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. P_{ey} represents the correlation coefficient of the remaining variables and bacteria, fungi, and actinomycetes. The red values represent the extent to which the bacteria, fungi, and actinomycetes can be explained by the pH, WFPS, NO_3^--N, O_2, root length, root volume, root area, root forks, and root tips.*

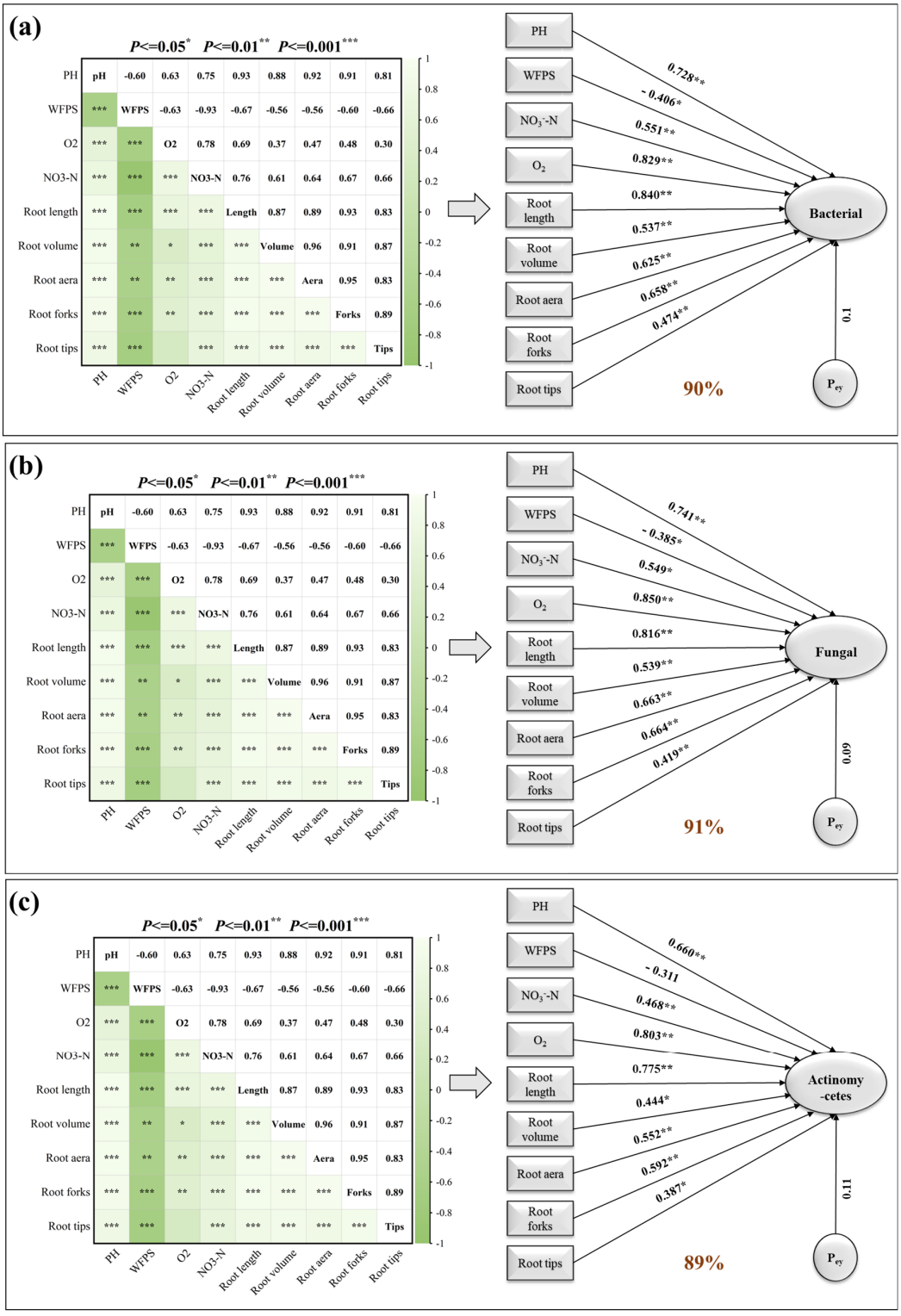


Figure 5. The correlation coefficients between soil pH, soil water-filled pore space (WFPS), soil nitrate N content (NO_3^--N), soil oxygen content (O_2), root length, root volume, root area, root forks, and root tips and their quantified total effects on soil bacteria (**a**), soil fungi (**b**), and soil actinomycetes (**c**) in greenhouse tomato root zone soil in 2022, respectively. *Notes: The black values represent the path coefficient. *, **, and *** represent statistical significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. P_{ey} represents the correlation coefficient of the remaining variables and bacteria, fungi, and actinomycetes. The red values represent the extent to which the bacteria, fungi, and actinomycetes can be explained by the pH, WFPS, NO_3^--N, O_2, root length, root volume, root area, root forks, and root tips.*

The correlation analysis in the 2021 and 2022 experiments showed significant interactive relationships between the soil environmental factors and root system indicators. Notably, a significant negative correlation was observed between the soil WFPS and root system indicators. In contrast, the tomato root length showed a highly significant positive correlation ($p < 0.001$ ***) with the soil pH, NO_3^--N content, and O_2 content. Additionally, the soil pH was strongly positively correlated ($p < 0.001$ ***) with the root length, volume, surface area, forks, and tips of tomato plants (Figures 4 and 5). The path analysis results for tomato rhizospheric soil bacteria indicated that the root length, soil pH, and soil O_2 content had the greatest total effects on the bacterial population (Table 5). The total effects were 0.813–0.84, 0.73–0.8132, and 0.817–0.83 in 2021 and 2022, respectively ($p < 0.01$ **) (Table 5). These results indicate that the tomato root length, soil O_2 content, and pH are closely associated with the abundance of culturable rhizosphere bacteria. The path analysis results for rhizospheric soil fungi indicated that the soil pH, O_2 content, and root length had the greatest total effects on fungal community abundance, with the total effects ranging from 0.693 to 0.741, 0.791 to 0.85, and 0.676 to 0.816 in the 2021 and 2022 trials ($p < 0.01$ **) (Table 6). Thus, the soil pH, O_2 content, and root length showed strong associations with the abundance of culturable rhizosphere fungi. The path analysis results for rhizospheric actinomycetes in the 2021 and 2022 experiments showed that the soil pH, O_2 content, and root length had the greatest total effects on the abundance of rhizospheric actinomycetes, with total effects ranging from 0.66 to 0.719, 0.793 to 0.803, and 0.733 to 0.775 ($p < 0.01$ **) (Table 7). Therefore, the soil pH, O_2 content, and root length are closely associated with the abundance of culturable rhizosphere actinomycetes. In summary, the soil pH, O_2 content, and root length showed strong statistical associations with the culturable microbial abundance in the tomato root zone. In the 2021 experiment, there were highly significant positive correlations between the soil pH and the O_2 content and root length, with correlation coefficients of 0.71 and 0.96 (Figures 4 and 5). A highly significant positive correlation was also found between O_2 content and the root length, with a correlation coefficient of 0.7. Similar results were observed in the 2022 experiment, with correlation coefficients of 0.63, 0.93, and 0.69 ($p < 0.001$ ***) (Figures 4 and 5). Additionally, the soil WFPS exhibited a negative effect on the abundance of bacteria, fungi, and actinomycetes in the rhizospheric soil of tomatoes (Figures 4 and 5). In the 2021 and 2022 experiments, the effect values of the WFPS on bacteria, fungi, and actinomycetes were −0.384, −0.264, −0.279, and −0.406, −0.385, −0.311, respectively. Moreover, the WFPS exhibited a highly significant negative correlation with key factors affecting bacteria, fungi, and actinomycetes, such as the soil pH, O_2 content, and plant root length. The correlation coefficients were −0.53, −0.64, −0.61 (2021) and −0.6, −0.63, −0.67 (2022) ($p < 0.001$ ***) (Figures 4 and 5).

Table 5. Quantification of the effects of soil pH, soil water-filled pore space (WFPS), NO_3^--N content, oxygen (O_2) content, root length, root volume, root area, root forks, and root tips on soil bacteria in the root zone of tomato in the 2021 and 2022 experiments based on the path analysis method.

Effect Factor	2021										2022									
	r	Path Coefficient									r	Path Coefficient								
		pH	WFPS	NO_3^--N	O2	Root Length	Root Volume	Root Area	Root Forks	Root Tips		pH	WFPS	NO_3^--N	O2	Root Length	Root Volume	Root Area	Root Forks	Root Tips
PH	0.812 **	**0.563 ** **	0.313	−0.584	0.17	−0.224	0.363	0.156	0.344	−0.29	0.728 **	**−0.148**	−0.126	−0.393	0.506	0.968	−0.318	0.185	−0.22	0.275
WFPS	−0.384 *	−0.3	**−0.589 ** **	0.792	−0.154	0.143	−0.181	−0.075	−0.181	0.161	−0.406 *	0.089	**0.21 ***	0.491	−0.507	−0.701	0.202	−0.112	0.147	−0.225
NO_3^--N	0.205	0.342	0.485	**−0.962 ** **	0.084	−0.155	0.275	0.128	0.264	−0.255	0.551 **	−0.11	−0.196	**−0.527 ** **	0.62	0.794	−0.22	0.128	−0.163	0.225
O2	0.817 **	0.398	0.375	−0.335	**0.241 ***	−0.164	0.171	0.063	0.17	−0.103	0.829 **	−0.094	−0.133	−0.409	**0.798 ** **	0.722	−0.134	0.095	−0.117	0.102
Root length	0.813 **	0.539	0.36	−0.636	0.168	**−0.234**	0.381	0.166	0.351	−0.284	0.840 **	−0.137	−0.141	−0.401	0.552	**1.044**	−0.313	0.179	−0.225	0.282
Root volume	0.661 **	0.487	0.254	−0.629	0.098	−0.212	**0.42 ***	0.187	0.362	−0.307	0.537 **	−0.13	−0.117	−0.321	0.297	0.904	**−0.361 ** **	0.193	−0.222	0.295
Root area	0.587 **	0.459	0.231	−0.643	0.08	−0.204	0.41	**0.191**	0.353	−0.29	0.625 **	−0.136	−0.117	−0.335	0.377	0.93	−0.346	**0.201**	−0.231	0.283
Root forks	0.662 **	0.508	0.28	−0.666	0.108	−0.216	0.399	0.177	**0.381 ** **	−0.31	0.658 **	−0.134	−0.127	−0.354	0.384	0.968	−0.329	0.191	**−0.243**	0.302
Root tips	0.418 **	0.461	0.268	−0.693	0.07	−0.188	0.364	0.157	0.333	**−0.354 ** **	0.474 **	−0.119	−0.139	−0.348	0.239	0.862	−0.312	0.167	−0.216	**0.341 ** **

*Note: The correlation coefficient is denoted by "r". The path coefficient in bold print indicates the direct path coefficient, and the normal print indicates indirect path coefficients. *, and ** represent statistical significance at $p < 0.05$, and $p < 0.01$, respectively.*

Table 6. Quantification of the effects of soil pH, soil water-filled pore space (WFPS), NO_3^--N content, oxygen (O_2) content, root length, root volume, root area, root forks, and root tips on soil fungi in the root zone of tomato in the 2021 and 2022 experiments based on the path analysis method.

Effect Factor	2021										2022									
	r	Path Coefficient									r	Path Coefficient								
		pH	WFPS	NO_3^--N	O2	Root Length	Root Volume	Root Area	Root Forks	Root Tips		pH	WFPS	NO_3^--N	O2	Root Length	Root Volume	Root Area	Root Forks	Root Tips
PH	0.693 **	**0.8 ** **	0.314	−0.624	0.151	−0.365	1.013	−0.229	0.039	−0.406	0.741 **	**−0.137**	−0.127	−0.337	0.526	0.646	−0.447	0.611	−0.097	0.104
WFPS	−0.264	−0.426	**−0.59 ** **	0.846	−0.136	0.233	−0.506	0.11	−0.02	0.226	−0.385 *	0.082	**0.212 ***	0.421	−0.526	−0.468	0.283	−0.369	0.065	−0.085
NO_3^--N	0.017	0.486	0.486	**−1.028 ** **	0.074	−0.252	0.766	−0.188	0.03	−0.357	0.549 **	−0.102	−0.198	**−0.452 ** **	0.644	0.53	−0.309	0.422	−0.072	0.085
O2	0.791 **	0.566	0.376	−0.358	**0.214 ***	−0.266	0.478	−0.093	0.019	−0.145	0.850 **	−0.087	−0.135	−0.351	**0.829 ** **	0.482	−0.189	0.313	−0.051	0.039
Root length	0.676 **	0.766	0.36	−0.68	0.15	**−0.381**	1.063	−0.245	0.04	−0.398	0.816 **	−0.127	−0.142	−0.344	0.574	**0.697 ** **	−0.439	0.591	−0.099	0.107
Root volume	0.524 **	0.692	0.255	−0.672	0.087	−0.346	**1.171 ** **	−0.275	0.041	−0.43	0.539 **	−0.121	−0.119	−0.276	0.308	0.604	**−0.507 ** **	0.635	−0.098	0.112

Table 6. *Cont.*

Effect Factor	2021										2022									
	r	Path Coefficient									r	Path Coefficient								
		pH	WFPS	NO_3^--N	O2	Root Length	Root Volume	Root Area	Root Forks	Root Tips		pH	WFPS	NO_3^--N	O2	Root Length	Root Volume	Root Area	Root Forks	Root Tips
Root area	0.432**	0.652	0.231	−0.687	0.071	−0.332	1.144	**−0.281**	0.04	−0.407	0.663**	−0.126	−0.118	−0.287	0.391	0.621	−0.486	**0.663****	−0.102	0.107
Root forks	0.498 **	0.722	0.281	−0.711	0.096	−0.351	1.114	−0.26	**0.043 ****	−0.434	0.664 **	−0.124	−0.128	−0.304	0.399	0.646	−0.462	0.631	**−0.107**	0.114
Root tips	0.265	0.654	0.268	−0.74	0.062	−0.306	1.014	−0.23	0.038	**−0.496 ****	0.419 **	−0.11	−0.14	−0.299	0.248	0.576	−0.439	0.55	−0.095	**0.129**

*Note: The correlation coefficient is denoted by "r". The path coefficient in bold print indicates the direct path coefficient, and the normal print indicates indirect path coefficients. *, and ** represent statistical significance at $p < 0.05$, and $p < 0.01$, respectively.*

Table 7. Quantification of the effects of soil pH, soil water-filled pore space (WFPS), NO_3^--N content, oxygen (O_2) content, root length, root volume, root area, root forks, and root tips on soil actinomycetes in the root zone of tomato in the 2021 and 2022 experiments based on the path analysis method.

Effect Factor	2021										2022									
	r	Path Coefficient									r	Path Coefficient								
		pH	WFPS	NO_3^--N	O2	Root Length	Root Volume	Root Area	Root Forks	Root Tips		pH	WFPS	NO_3^--N	O2	Root Length	Root Volume	Root Area	Root Forks	Root Tips
PH	0.719 **	**0.327**	0.222	−0.564	0.296	−0.089	0.442	0.324	0.075	−0.314	0.660 **	**−0.18**	−0.186	−0.388	0.514	1.027	−0.52	0.272	−0.149	0.27
WFPS	−0.279	−0.174	**−0.418 ****	0.765	−0.267	0.057	−0.221	−0.156	−0.04	0.175	−0.311	0.108	**0.311 ****	0.485	−0.515	−0.743	0.33	−0.164	0.099	−0.221
NO_3^--N	0.078	0.198	0.344	**−0.929 ****	0.146	−0.061	0.334	0.265	0.057	−0.276	0.468 **	−0.134	−0.29	**−0.52 ****	0.63	0.843	−0.36	0.188	−0.11	0.221
O2	0.793 **	0.231	0.266	−0.323	**0.419 ****	−0.065	0.208	0.131	0.037	−0.112	0.803 **	−0.114	−0.197	−0.404	**0.811 ****	0.767	−0.219	0.139	−0.079	0.1
Root length	0.733 **	0.313	0.255	−0.614	0.293	**−0.093**	0.464	0.346	0.076	−0.308	0.775 **	−0.167	−0.209	−0.396	0.561	**1.108 ****	−0.511	0.263	−0.152	0.277
Root volume	0.588 **	0.283	0.181	−0.608	0.171	−0.084	**0.511 ***	0.388	0.079	−0.333	0.444 *	−0.159	−0.174	−0.317	0.302	0.96	**−0.59 ****	0.283	−0.15	0.29
Root area	0.526 **	0.267	0.164	−0.621	0.139	−0.081	0.499	**0.397**	0.077	−0.315	0.552 **	−0.166	−0.173	−0.331	0.383	0.987	−0.565	**0.295**	−0.156	0.278
Root forks	0.554 **	0.295	0.199	−0.643	0.187	−0.086	0.486	0.368	**0.083**	−0.336	0.592 **	−0.163	−0.188	−0.349	0.39	1.027	−0.538	0.281	**−0.164**	0.297
Root tips	0.293	0.267	0.19	−0.669	0.122	−0.075	0.443	0.326	0.073	**−0.384 ****	0.387 *	−0.145	−0.206	−0.344	0.242	0.915	−0.51	0.245	−0.145	**0.335 ****

*Note: The correlation coefficient is denoted by "r". The path coefficient in bold print indicates the direct path coefficient, and the normal print indicates indirect path coefficients. *, and ** represent statistical significance at $p < 0.05$, and $p < 0.01$, respectively.*

3.4. Tomato Yield, Quality, and Dry Matter Weight

Following the measurement and analysis of tomato plants at harvest in the two-year greenhouse experiment with 10 treatments, the results showed that aeration, irrigation, and fertilization treatments had significant effects on the dry matter content of tomato plants. With the increase in the aeration level, the dry matter content of tomato plants significantly increased. The total dry matter content in the A2 treatment was significantly higher than that in the A1 and CK treatments, by 9.84% and 17.55% in 2021 and 8.13% and 17.84% in 2022 (Figure 6). The irrigation and fertilization levels also had a significant positive effect on the total dry matter content of the plants (Table 8). In the 2021 experiment, that of the I2 treatment significantly increased, by 6.82%, compared to I1, and that of the F2 treatment significantly increased, by 10.52%, compared to F1. In the 2022 experiment, those of the I2 and F2 treatments were significantly higher than those of I1 and F1, by 9.45% and 9.17%, respectively ($p < 0.05$ **) (Figure 6). Correspondingly, the dry stem, dry leaf, and dry root values in the A2 treatment were 14.08%, 5.96%, and 4.44% higher than those in the A1 treatment and 26.7%, 9.76%, and 6.75% higher than in the CK treatment in 2021 (Table 8). The increases observed in 2022 were 6.26%, 10.08%, 9.08% and 18.84%, 17.42%, and 12.65% compared to A1 and CK, respectively (Table 8). Furthermore, in both 2021 and 2022, the dry stem, dry leaf, and dry root values in the I2 treatment were 6.45%, 7.67%, and 3.29% higher than in the I1 treatment and 10.51%, 8.82%, and 5.23%, respectively. The dry stem, dry leaf, and dry root values in the F2 treatment were 9.64%, 8.97%, and 33.21% higher than those in the F1 treatment in 2021 and 9.05%, 7.88%, and 21.86% higher in 2022. In addition, the interaction between irrigation and aeration significantly affected the total dry weight of tomato plants, while the interaction between irrigation, fertilization, and aeration had no significant effect on the dry matter of tomato plants (Table 8).

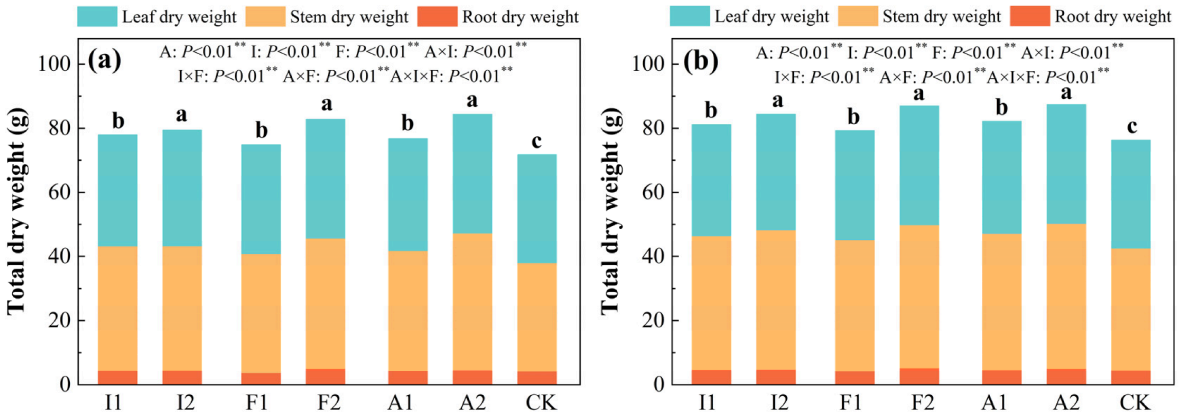


Figure 6. Root dry weight, stem dry weight, leaf dry weight, and total dry weight of tomato plants under different irrigation, fertilization, and aeration factors in 2021 and 2022 experiments. (**a**) represents 2021 experiment and (**b**) represents 2022 experiment; I, F, and A represent the effects of irrigation, fertilization, and aeration on each index, respectively. I1: 80% ET_c; I2: 100% ET_c; F1 = 180 kg/ha; F2 = 240 kg/ha, respectively. CK: unaerated subsurface drip irrigation; A1: one-multiplier aerated subsurface drip irrigation; A2: two-multiplier aerated subsurface drip irrigation. Different letters in the same column indicate significant differences at *p* < 0.05 level based on the least significant difference (LSD) test. A × F and A × I are the interaction effects of aeration and fertilization and of aeration and irrigation on each index, respectively; F × I is the interaction effect of fertilization and irrigation on each index; A × F × I is the interaction effect of aeration, fertilization, and irrigation on each index. ** represents significance level of 0.01.

Table 8. Effects of different irrigation, fertilization, and aeration treatments on tomato yield, lycopene, and dry matter weight, consisting of root, stem, and leaf, during the 2021 and 2022 experiments on tomato in the greenhouse.

Treatment	2021						2022					
	Tomato Dry Matter Weight (g)				Yield ($t\ hm^{-2}$)	Lycopene ($ug\ g^{-1}$)	Tomato Dry Matter Weight (g)				Yield ($t\ hm^{-2}$)	Lycopene ($ug\ g^{-1}$)
	Root	Stem	Leaf	Total			Root	Stem	Leaf	Total		
CKF1I2	3.63 f	31.85 g	31.90 g	67.38 g	47.23 d	35.78 i	3.99 f	36.15 i	34.11 g	74.25 h	49.79 i	33.87 i
CKF2I2	4.85 c	35.69 f	35.60 d	76.14 e	48.93 c	31.44 j	4.93 cd	40.06 g	37.92 e	82.91 f	51.90 h	29.56 j
A1F1I1	3.69 ef	34.91 f	32.58 f	71.18 f	45.14 e	54.05 d	4.02 f	38.96 h	35.29 f	78.27 g	53.22 g	56.32 d
A1F2I1	4.88 c	37.96 e	35.16 d	78.00 d	46.76 d	50.10 f	5.07 bc	43.05 d	38.65 de	86.77 d	55.63 f	52.19 f
A1F1I2	3.80 e	37.21 e	34.22 e	75.23 e	52.23 b	47.85 g	4.16 f	42.11 e	38.77 de	85.04 e	60.36 e	48.72 g
A1F2I2	4.98 bc	39.94 d	37.87 b	82.79 c	54.79 a	41.17 h	5.17 b	46.35 b	40.95 c	92.47 b	63.42 c	43.11 h
A2F1I1	3.78 e	39.71 d	34.17 e	77.66 d	48.41 c	61.20 a	4.43 e	41.08 f	39.01 d	84.52 e	59.77 e	68.77 a
A2F2I1	5.09 b	42.98 b	36.77 c	84.84 b	49.13 c	55.48 c	5.25 b	43.94 c	41.64 c	90.83 c	61.96 d	63.92 b
A2F1I2	3.94 d	41.73 c	37.25 c	82.92 c	52.93 b	56.10 b	4.78 d	46.35 b	42.76 b	93.89 b	68.05 b	59.16 c
A2F2I2	5.30 a	46.72 a	39.98 a	92.00 a	54.67 a	51.30 e	5.64 a	49.77 a	45.74 a	101.15 a	72.57 a	55.28 e
Significance												
I	**	**	**	**	**	**	**	**	**	**	**	**
F	**	**	**	**	**	**	**	**	**	**	**	**
A	**	**	**	**	**	**	**	**	**	**	**	**
I × F	NS	NS	*	**	*	**	NS	NS	NS	**	**	NS
I × A	NS	NS	**	*	**	**	*	**	*	**	**	**
F × A	*	*	NS	*	*	**	NS	**	NS	**	**	**
I × F × A	NS	*	NS	**	**	**	NS	NS	NS	**	*	**

*Note: Different letters in the same column indicate significant differences at *p* < 0.05 level based on the least significant difference (LSD) test. I, F, and A represent the effects of irrigation, fertilization, and aeration on each index, respectively; × stands for the interaction effect; I × F and I × A are the interaction effects of irrigation and fertilization and of irrigation and aeration on each index, respectively; F × A is the interaction effect of fertilization and aeration on each index; I × F × A is the interaction effect of irrigation, fertilization, and aeration on each index. * and ** are the marked levels of 0.05 and 0.01, respectively.*

During the harvest period of tomatoes, the yield and quality were measured and analyzed. The results showed that aeration–irrigation significantly increased the tomato yield. The yield of tomatoes in the A2 treatment was 3.13% and 6.67% higher than that in the A1 and CK treatments in 2021, with the increase reaching 12.78% and 28.99% in 2022 ($p < 0.05$ **) (Figure 7a,b). In addition, increasing the irrigation and fertilization levels also significantly improved the tomato yield. In 2021, the yield of tomatoes in the I2 and F2 treatments was 9.37% and 3.39% higher than in the I1 and F1 treatments, with the increase being 5.85% and 4.91% in 2022 ($p < 0.05$ **). Among these, the interactions between irrigation and fertilization, irrigation and aeration, and fertilization and aeration significantly affected the tomato yield, but the interaction between irrigation, fertilization, and aeration had no significant effect on yield (Table 8).

Principal component analysis (PCA) was used to analyze six quality indicators of tomato in 2021 and 2022. The results showed that the first principal component explained 90.1% (2021) and 93.58% (2022) of the total variance in the six quality indicators, both exceeding the 85% threshold (Table 9). Therefore, the first principal component contained the most significant information about the six tomato quality traits. The first principal component score and comprehensive quality score (CQS) were calculated for each treatment (Table 10). The relationships between the six measured quality attributes and CQS were then examined (Table 11). Lycopene showed a strong positive relationship with the CQS in both years, with R^2 values of 0.98 in 2021 and 0.97 in 2022. However, SSC showed a slightly higher R^2 of 0.98 in 2022. Thus, lycopene was one of the indicators that was most strongly associated with the CQS under the present experimental conditions. Because the CQS was derived from the same six attributes, these relationships describe associations within the evaluated dataset rather than the independent validation of lycopene as an indicator of overall tomato quality. An analysis of the lycopene content in the fruits from the two-year experiment showed that, with the increase in the aeration level, the lycopene content significantly increased. In the 2021 experiment, that of the A2 treatment was significantly

higher, by 16% and 66.68%, than those of the A1 and CK treatments, respectively. In 2022, the value of A2 was 23.36% and 94.81% higher than those of the A1 and CK treatments, respectively. However, when the irrigation level was increased to full irrigation, the lycopene content decreased. The I2 treatment showed a reduction of 11.05% (2021) and 14.48% (2022) in lycopene content compared to the I1 treatment. In addition, increasing the fertilization level also significantly reduced the lycopene content. In 2021, the F2 treatment showed a 10% reduction in lycopene content compared to the F1 treatment, while, in 2022, the reduction was 8.54% ($p < 0.05$ **) (Figure 7c,d). Furthermore, the interaction between irrigation, fertilization, and aeration had a significant effect on the lycopene content in the fruits (Table 8).

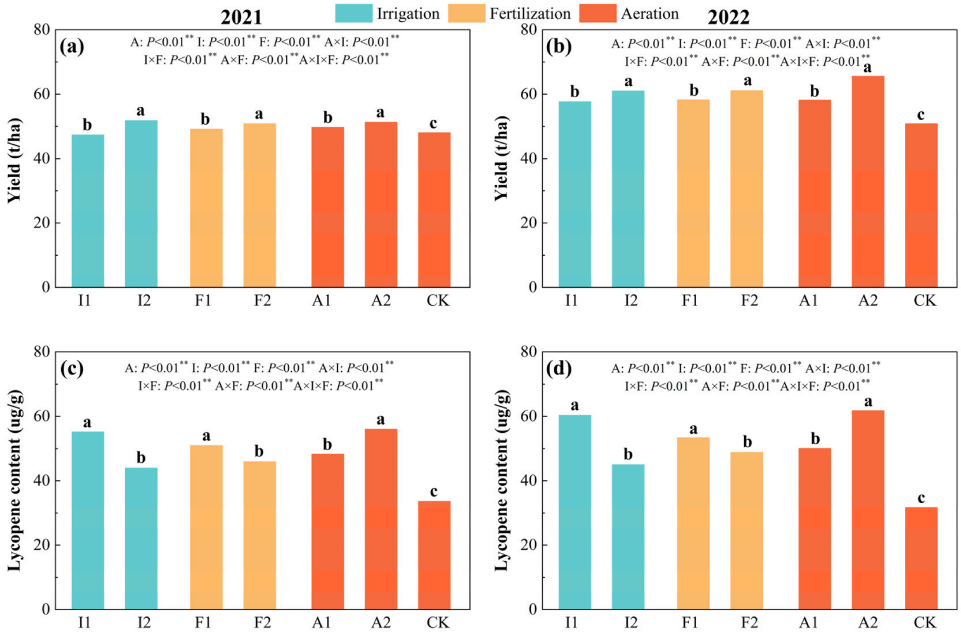


Figure 7. Yield and lycopene content of tomato under different irrigation, fertilization, and aeration factors in 2021 and 2022 experiments. (**a**,**c**) represent 2021 experiment and (**b**,**d**) represent 2022 experiment; I, F, and A represent the effects of irrigation, fertilization, and aeration on each index, respectively. I1: 80% ET_c; I2: 100% ET_c; F1 = 180 kg/ha; F2 = 240 kg/ha, respectively. CK: unaerated subsurface drip irrigation; A1: one-multiplier aerated subsurface drip irrigation; A2: two-multiplier aerated subsurface drip irrigation. Different letters in the same column indicate significant differences at *p* < 0.05 level based on the least significant difference (LSD) test. A × F and A × I are the interaction effects of aeration and fertilization and of aeration and irrigation on each index, respectively; F × I is the interaction effect of fertilization and irrigation on each index; A × F × I is the interaction effect of aeration, fertilization, and irrigation on each index. ** represents significance level of 0.01.

Table 9. Eigenvalues and percentages of tomato quality principal components in 2021 and 2022.

Principal Component	2021			2022		
	Eigenvalue	Percentage	Cumulative Percentage (%)	Eigenvalue	Percentage	Cumulative Percentage (%)
1	5.41	90.10	90.10	5.62	93.58	93.58
2	0.51	8.52	98.62	0.28	4.65	98.23
3	0.06	0.93	99.54	0.06	0.91	99.14
4	0.01	0.20	99.75	0.04	0.61	99.75
5	0.01	0.16	99.91	0.01	0.20	99.95
6	0.01	0.10	100.00	0.00	0.05	100.00

Table 10. Scores of the comprehensive tomato quality evaluated by principal component analysis under different irrigation, fertilization, and aeration treatments in 2021 and 2022.

Treatment	2021		2022	
	f_1	CQS	f_1	CQS
CKI2F1	−5.63	−5.07	−5.98	−5.88
CKI2F2	−10.14	−9.13	−9.36	−9.21
A1I1F1	2.67	2.40	2.23	2.19
A1I1F2	0.18	0.16	−0.64	−0.63
A1I2F1	−0.25	−0.22	−1.97	−1.93
A1I2F2	−4.47	−4.03	−5.02	−4.94
A2I1F1	7.95	7.17	8.27	8.14
A2I1F2	4.52	4.07	5.53	5.44
A2I2F1	4.01	3.61	4.71	4.63
A2I2F2	1.16	1.05	2.22	2.19

Note: f_1 represents the first principal component, and CQS represents the comprehensive quality score.

Table 11. Eigenvalue regression relationships between various tomato quality indicators and the comprehensive quality score (CQS) in 2021 and 2022.

Quality Indicator	2021		2022	
	Regression Equation	R^2	Regression Equation	R2
Lycopene	y = 1.938CQS + 48.447	0.98	y = 2.236CQS + 51.09	0.97
VC	y = 0.126CQS + 4.219	0.93	y = 0.123CQS + 4.317	0.95
SSC	y = 0.001CQS + 0.046	0.96	y = 0.002CQS + 0.054	0.98
OA	y = −0.0001CQS + 0.006	0.72	y = −0.0001CQS + 0.007	0.81
TSS	y = 0.150CQS + 6.337	0.88	y = 0.151CQS + 6.449	0.93
SAR	y = 0.291CQS + 7.304	0.93	y = 0.459CQS + 8.704	0.97

A structural equation model was established to describe the relationships between soil environmental factors, root system indicators, rhizosphere soil microorganisms, and tomato yield (Figure 8). The measurement model loadings were all greater than 0.7, with the minimum value being 0.742 (O_2) and the maximum value being 0.991 (fungi), which indicates the good internal consistency and construct reliability of the measurement model. Within the specified PLS-SEM model, root traits and culturable microbial abundance showed significant direct statistical associations with tomato yield, with standardized path coefficients of 0.704 and 0.435, respectively (Figure 8). Soil conditions were significantly associated with root traits and culturable microbial abundance, with standardized path coefficients of 0.819 and 0.609, respectively. These estimates describe relationships conditional on the specified model and do not establish biological causation. The modeled pathways suggest potential links among soil conditions, root traits, culturable microbial abundance, and yield that require further experimental verification.

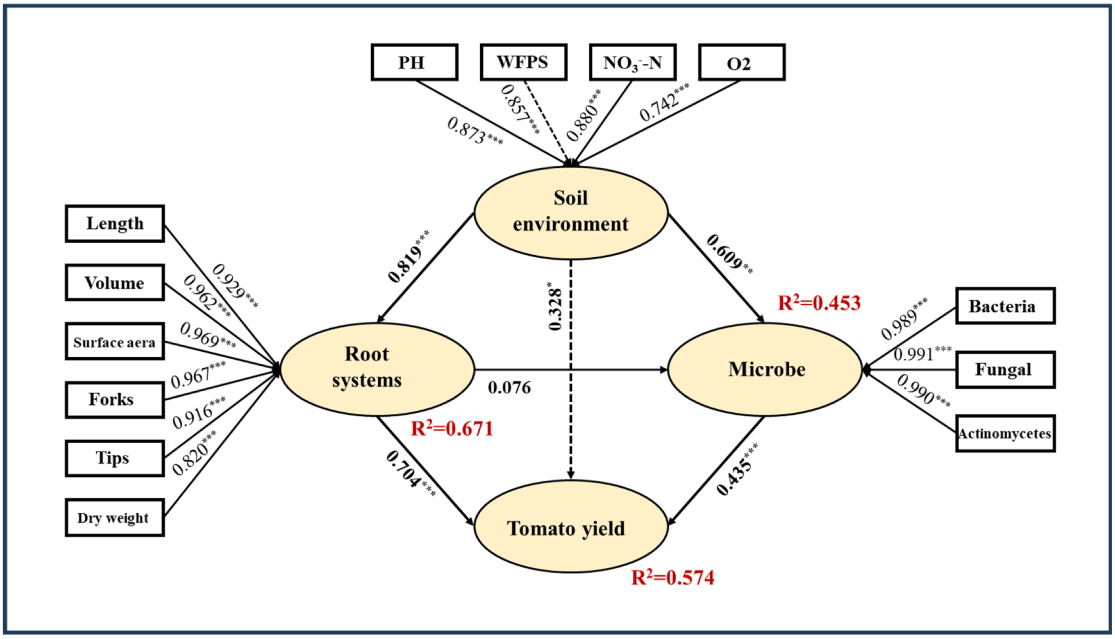


Figure 8. Structural equation model of the effect of irrigation–fertilization–aeration coupling. One-way arrows represent the direct influence of one variant on another. The numbers adjacent to the path arrows indicate the relationship's effect size in terms of the standardized coefficient. *Note: Black solid lines indicate positive correlations, while black dashed lines indicate negative correlations; *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$. R^2 is the proportion of variance explained by the model.*

4. Discussion

4.1. Effects of the Irrigation–Fertilization–Aeration Coupling Model on the Root System of Tomato

Soil environmental factors (such as soil pH, WFPS, NO_3^--N, and O_2 content) are key determinants of crop growth in soil, influenced by field management practices (irrigation volume, fertilization rates, irrigation methods, etc.) [25]. In this study, the soil pH was significantly influenced by fertilization and aerated irrigation, with aerated irrigation being the key factor driving changes in soil pH (Table 2). This result is consistent with the findings of other studies [12,63]. Additionally, the use of nitrogen fertilizer is a key factor contributing to soil acidification in agricultural fields. Studies show that applying 105 kg ha^{-1} of nitrogen fertilizer annually can lower the soil pH by 0.27 units over 10 years [64,65]. In this study, the pH value of the F2 treatment increased by 0.05 compared to the F1 treatment (Figure 2a), which may have been related to the irrigation method used (aerated irrigation). The experimental results revealed that aerated irrigation significantly increased the soil pH, with the A2 treatment showing a 2.18% higher pH compared to the CK treatment (Figure 2a). Additionally, the interaction between aeration and fertilization had a notable effect on the soil pH (Table 1). In this study, compared to the CK treatment, aerated irrigation injected air into the soil, significantly increasing the O_2 content in the soil and correspondingly reducing the soil WFPS (Figure 2c). Moreover, during the drip irrigation process in the irrigation–fertilization–aeration coupling model, water and air are delivered to the crop root zone, which not only improves soil aeration but also provides favorable conditions for nitrification in the soil [11]. The application of nitrogen fertilizer provides abundant substrates for nitrifying bacteria, promoting nitrification and thus driving the conversion of $NH4^+$-N to NO_3^--N [11,66–68]. This mechanism also explains why aeration and fertilization significantly increased the NO_3^--N content in the tomato root-zone soil [69]. Aerated irrigation promotes the activity of microorganisms such as Nitrosospira species associated with nitrification and Pseudomonas species and Bacillus species related to phosphorus and potassium metabolism, while inhibiting the activity of microorganisms like

Rhodospirillum species associated with denitrification [70,71]. This regulation of microbial activity influences changes in soil pH. Research indicates that the soil environment under the irrigation–fertilization–aeration coupled drip irrigation model is more favorable for the life activities of soil microorganisms. This may be because the irrigation–fertilization–aeration coupled model indirectly promotes an increase in soil pH by improving soil chemical properties and the activity of rhizosphere microorganisms.

Healthy root systems are crucial for efficient water and nutrient absorption, supporting crop growth. This study found that irrigation, fertilization, and aeration significantly influenced the growth of greenhouse tomato roots. With increasing aeration levels, there was a notable increase in root length, volume, surface area, forks, and tips (Table 3). The authors of [72] also reported similar findings, observing that, compared to no aeration, 1.5 times the ventilation volume increased the tomato root length, root surface area, root tips, and root system activity by 7.9%, 6.3%, 14.5%, and 7.0%, respectively. Oxygen deficiency in the root-zone soil inhibits crop root system growth, causing a transition from normal aerobic respiration to anaerobic respiration [26]. Research indicates that a compacted soil structure reduces the photosynthetic efficiency of plants, whereas aerated irrigation improves soil aeration, supplying adequate oxygen to plant roots, which is more favorable for root growth [10,73]. Additionally, the root system is the main route through which crops absorb water and nutrients, so irrigation and fertilization are the primary factors driving rhizosphere development. Irrigation provides sufficient water for the root system and creates favorable moisture conditions for the activity of rhizosphere soil microorganisms, promoting their metabolic activity. Adequate water supply stimulates root expansion, enhancing the effective absorption of water and nutrients and creating a healthy environment for crop growth [73–76]. However, excessive irrigation can result in soil saturation, placing the roots in an oxygen-deprived state, which affects normal root respiration and growth [52,77,78]. This finding is consistent with the results of this study, where increasing the irrigation level to full irrigation led to a reduction in tomato root length (Table 3). Furthermore, the appropriate application of nitrogen fertilizer can stimulate the branching and development of root hairs, enhancing the root system's ability to absorb water and nutrients [79]. However, the interaction between irrigation, fertilization, and aeration (Table 3) suggests that individual management practices are insufficient to fully maximize root growth. Therefore, appropriately regulating irrigation management practices can improve the root growth environment, enhance the efficiency of water and nutrient absorption, and thus improve plant health and yields.

4.2. Effects of the Irrigation–Fertilization–Aeration Coupling Model on Root–Soil–Microbe Interactions

The irrigation–fertilization–aeration coupled drip irrigation technology can significantly alter the number of rhizosphere microorganisms, promote root growth, and enhance crop growth [80]. However, current research on the irrigation–fertilization–aeration coupling model of drip irrigation technology does not comprehensively explore the key factors influencing root–soil–microbe interactions. In this study, the tomato root length, rhizosphere soil pH, and O_2 content showed strong statistical associations with the abundance of culturable bacteria, fungi, and actinomycetes (Figures 4 and 5; Tables 5–7). These associations do not establish direct causal effects or demonstrate the maintenance of a root–soil–microbe interaction network. The roots are a vital habitat for microorganisms, and the rhizosphere microbial community enhances nutrient mineralization and water supply through its interactions with the roots [81]. At the same time, the root system is the primary organ for water and nutrient absorption in plants, and its growth and development are influenced by various factors, including water, nutrients, the soil structure, and gas exchange. Root growth is not

only affected by direct environmental factors but is also closely related to microbial activity in the soil [82,83]. Proper irrigation levels can maintain soil moisture, which promotes root expansion and branching, increases the root hair density, and effectively enhances the absorption capacity for water and nutrients. Soil microorganisms play a crucial role in the root–soil–microbe interaction. Microbial communities provide nutrient support to plants through activities such as organic matter decomposition, nutrient mineralization, and nitrogen fixation [40,84]. They also enhance plant resistance and nutrient absorption capacity through symbiotic relationships with the roots. The organic acids and other metabolites secreted by the roots stimulate microbial growth. In return, microorganisms enhance the nutrient absorption efficiency of roots by promoting nutrient mineralization and conversion [85,86]. Aerated irrigation alleviates soil hypoxia by increasing the oxygen concentration in the soil, improving root respiration and nutrient absorption. Additionally, oxygen supply helps to maintain the activity of aerobic microorganisms in the soil, promoting nutrient mineralization and transformation and improving soil fertility. Studies have shown that aerated irrigation shifts the microbial community in the soil towards aerobic microorganisms [51], such as rhizobia and decomposing bacteria, which play an active role in the decomposition of organic matter and nitrogen transformation [87–90]. Under aerated irrigation conditions, the oxygen concentration in the soil is significantly increased, inhibiting the activity of anaerobic microorganisms, thereby reducing the release of harmful gases (such as ammonia and hydrogen sulfide) and improving the rhizosphere environment.

Irrigation, fertilization, and aeration have a significant effect on tomato roots, the soil environment, and microbial communities. Appropriate irrigation, fertilization, and aeration management measures can optimize soil moisture, nutrients, and gas supply, promoting healthy root growth and enhancing microbial metabolism and functionality. In this study, the irrigation–fertilization coupling drip irrigation model combined with aerated irrigation significantly enhanced the soil's moisture retention, nutrient supply, and oxygen concentration, thereby optimizing root growth and microbial activity. Appropriate irrigation and fertilization levels can improve the effectiveness of water and nutrients in the soil, while aerated irrigation helps to address the oxygen deficiency in waterlogged soils [40,42], further promoting root health and microbial activity [91,92]. Since the soil pH and O_2 content have the greatest influence on root growth, and the key factor affecting the soil pH and O_2 content is the aeration level, aeration has a much more significant effect on rhizosphere soil bacteria, fungi, and actinomycetes compared to fertilization and irrigation. Aerated irrigation provides sufficient oxygen, improving the soil gas exchange conditions, alleviating oxygen deficiency caused by excessive moisture, and promoting normal root respiration. Under optimal oxygen supply, the roots are able to more efficiently absorb water and nutrients, and the soil microorganisms benefit from a better growth environment, particularly enhancing the proliferation of aerobic microorganisms [93]. As a result, aerated irrigation improves the soil oxygen levels and, by enhancing microbial activity, further stabilizes the function of the root–soil–microbe system. Together, these observations suggest that coordinated irrigation, nitrogen fertilization, and aeration management may influence interrelated soil, root, and microbial responses. However, the present analyses do not demonstrate a positive feedback loop among these components. The biological processes discussed above provide possible explanations for the observed associations, rather than mechanisms demonstrated by this experiment. Although irrigation, nitrogen fertilization, and aeration were experimentally manipulated, the soil conditions, root traits, and culturable microbial abundance were measured as responses to these treatments. Their covariation may therefore partly reflect shared treatment responses. Path analysis and PLS-SEM describe statistical relationships within the specified models but cannot, by themselves, establish the direction of biological causation or confirm feedback processes. Moreover, root respiration, ATP production,

nutrient uptake rates, root exudation, and microbial functional activity were not directly measured. Evidence from previous studies supports the plausibility of these processes, but their operation and relative contributions under the present experimental conditions require further experimental verification. The microbial measurements in this study represent only the fractions of bacteria, fungi, and actinomycetes that could be cultured under the selected conditions. They do not characterize the composition, diversity, or functional structure of the entire soil microbial community. Consequently, increases in culturable microbial abundance should not be interpreted as direct evidence of enhanced microbial functionality or improved soil health.

4.3. Effects of the Irrigation–Fertilization–Aeration Coupling Model on Tomato Dry Matter, Yield, and Quality

In the management of agricultural production, the rational adjustment of irrigation, fertilization, and aeration plays a crucial role in influencing the growth, yield, and quality of greenhouse crops [25,70]. Moreover, the accumulation of dry matter in crops serves as a critical indicator for assessing their healthy growth and production potential [26]. Aerated irrigation is a key factor in enhancing the total dry matter content in tomatoes [27]. Under conditions of sufficient oxygen supply, tomatoes can synthesize dry matter more effectively. In this study, the irrigation amount, fertilization level, and aeration level all had a significant positive effect on the total dry matter of tomatoes. Among these factors, aerated irrigation showed the most significant effect. Compared to the CK treatment, the total dry matter of tomato plants increased by 7.71% to 17.55% and 9.71% to 17.84% in 2021 and 2022, respectively (Figure 6). The research conducted in [94] also yielded similar findings, indicating that nitrogen fertilization and aerated irrigation enhanced the dry matter accumulation and NUE of cucumbers [95]. Oxygen deficiency in the root zone can lead to the accumulation of abscisic acid, ethanol, and ethylene [23,96] and may also reduce the photosynthetic rate, leading to stomatal closure [97]. Aerated irrigation alleviates this condition, promoting the healthy growth of tomato roots and microbial activity [98,99], ultimately improving the tomato yield and quality. This result is also supported by the study [100]. The application of nitrogen fertilizer is an important factor in increasing tomato yields, with higher nitrogen application significantly boosting tomato yields. In this study, the tomato yield under the F2 treatment was significantly higher than that of F1, increasing by 3.39% (Figures 6b and 7a). Additionally, the impact of the irrigation–fertilization–aeration coupling drip irrigation model on root–soil–microbe interactions inevitably affects the tomato yield [50]. In this study, the irrigation management measures of the irrigation–fertilization–aeration coupling model significantly increased the tomato yield by influencing the soil pH and $NO3^{-}$-N content; promoting root length, root volume, and root surface area growth; and accelerating the absorption of soil moisture and nutrients (Figure 8). Furthermore, numerous studies have shown that a rational combination of irrigation levels, fertilization levels, and aeration levels can enhance the efficiency of water and nutrient absorption by tomato roots, thereby promoting tomato growth and uniform fruit enlargement, ultimately increasing yields [101,102].

Lycopene, one of the main carotenoids in tomatoes, has significant antioxidant properties and offers numerous health benefits. Therefore, lycopene content is widely regarded as an important indicator for evaluating tomato quality and nutritional value [70,80,103]. In the present study, lycopene was one of the indicators that was most strongly associated with the comprehensive quality score derived from six measured fruit quality attributes (Table 11). This finding is restricted to the evaluated attributes and experimental conditions. PCA summarizes the covariance among measured variables; it does not establish any single attribute as a universal proxy for fruit quality. Moreover, the association between lycopene

and the CQS does not constitute independent validation because lycopene itself was included in the construction of the score. Commercially relevant traits, including firmness, external color, flavor and volatile composition, marketability, and postharvest performance, were not assessed. Responses in these traits may differ from those of the measured attributes and may depend on the production and storage conditions. Therefore, the present results should not be extrapolated to reflect overall commercial quality or shelf life. Through the regulation of irrigation, fertilization, and aeration levels, along with the optimization of the root–soil–microbe system, the synthesis and accumulation of lycopene in tomatoes can be significantly influenced. Appropriate irrigation amounts and proper fertilization provide the essential conditions for plant growth, while the regulation of the aeration level improves the soil oxygen content in the tomato root zone, addressing issues of over-irrigation or soil hypoxia [104]. The synergistic effect of these three factors ensures healthy root systems, promotes nutrient absorption by tomato roots, and provides sufficient nutrients and energy for lycopene synthesis. From a practical perspective, root-zone aeration should be considered as a component of integrated greenhouse management alongside irrigation scheduling, nutrient supply, drainage, and climate management. Its additional benefit is expected to depend on the extent to which oxygen availability constrains root-zone processes. Aeration may be more useful where irrigation and soil conditions restrict oxygen supply, whereas its benefit may be smaller in well-aerated root zones. It should therefore complement appropriate water and nutrient management rather than compensate for excessive irrigation or an unsuitable nutrient supply. The present experiment did not compare aeration with alternative agronomic interventions, so their relative effectiveness and economic value cannot be ranked. Furthermore, only 'Jinpeng No. 8' was evaluated. Differences among cultivars and rootstocks in terms of root characteristics and tolerance to oxygen limitation may affect their responses to aeration. Extrapolation to other tomato cultivars, rootstocks, vegetable species, or production systems should therefore be considered cautiously and requires further validation.

5. Conclusions

This study investigates greenhouse tomatoes under a two-year irrigation–fertilization–aeration coupling drip irrigation model, analyzing the soil environment, root system, rhizosphere microbiota, yield, and quality. The irrigation–fertilization–aeration coupling drip irrigation model significantly affects soil environmental factors and root growth, with a significant interaction between soil environmental factors and root indicators. The factors considered in this study effectively explain the changes in the rhizosphere soil microbiota of tomatoes, including bacteria, fungi, and actinomycetes. The soil pH, oxygen content, and root length were closely associated with the culturable microbial abundance. The specified models also identified statistical relationships among the soil conditions, root traits, culturable microbial abundance, and tomato yield. These associations do not establish causal pathways or demonstrate a root–soil–microbe feedback network. Among the six fruit quality attributes evaluated, lycopene was one of the indicators that was most strongly associated with the PCA-derived comprehensive quality score under the present experimental conditions. Among the treatments evaluated, A2F1I1 achieved the highest comprehensive quality score in both years and may be considered a promising combination when greater emphasis is placed on the measured fruit quality attributes. However, higher irrigation and nitrogen fertilization generally increased the yield while reducing the lycopene content, indicating a yield–quality trade-off. The preferred treatment therefore depends on the production objectives, and the present results do not establish a universally or economically optimal strategy. Validation across multiple sites and cultivars and a broader range of treatment

levels and an economic evaluation are needed before general commercial recommendations can be made.

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Appendix A

Table A1. Tomato irrigation quota for the whole reproductive period in 2021.

Irrigation Time	Days After Transplanting (d)	E_{pan} (mm)	Irrigation Quota (mm)	
			0.8 ET_c	1.0 ET_c
2021/4/15	20	9.43	7.50	9.43
2021/4/19	24	9.29	7.43	9.29
2021/4/22	27	2.29	1.86	2.29
2021/4/28	33	5.00	4.00	5.00
2021/5/1	36	11.43	9.14	11.43
2021/5/5	40	9.43	7.50	9.43
2021/5/10	36	18.50	14.79	18.50
2021/5/14	49	13.00	10.43	13.00
2021/5/19	54	10.93	8.71	10.93
2021/5/24	59	10.64	8.50	10.64
2021/5/29	64	14.71	11.79	14.71
2021/6/2	68	13.21	10.57	13.21
2021/6/6	72	12.29	9.86	12.29
2021/6/11	77	13.71	10.93	13.71
2021/6/16	82	10.00	8.00	10.00
2021/6/22	88	14.57	11.71	14.57
2021/6/28	94	12.43	9.93	12.43
2021/6/29	95	1.71	1.36	1.71
2021/7/4	100	11.50	9.21	11.50
2021/7/8	104	9.21	7.36	9.21
Total	/	213.28	170.58	213.28

Note: 0.8 ET_c represents irrigation quota of I1, respectively; 1.0 ET_c represents irrigation quota of I2; E_{pan} represents cumulative pan evaporation (mm).

Table A2. Tomato irrigation quota for the whole reproductive period in 2022.

Irrigation time	Days After Transplanting (d)	E_{pan} (mm)	Irrigation Quota (mm)	
			0.8 ET_c	1.0 ET_c
2022/4/24	21	13.5	10.8	13.5
2022/4/28	25	9.7	7.76	9.7
2022/5/1	28	5.7	4.56	5.7
2022/5/6	33	16.4	13.12	16.4

Table A2. *Cont.*

Irrigation time	Days After Transplanting (d)	E_{pan} (mm)	Irrigation Quota (mm)	
			0.8 ET_c	1.0 ET_c
2022/5/11	38	12.9	10.32	12.9
2022/5/17	44	10.2	8.16	10.2
2022/5/20	47	8.9	7.12	8.9
2022/5/24	51	12.6	10.08	12.6
2022/5/28	55	9.9	7.92	9.9
2022/6/1	59	10.5	8.4	10.5
2022/6/6	64	11.4	9.12	11.4
2022/6/10	68	13.3	10.64	13.3
2022/6/11	69	1.8	1.44	1.8
2022/6/15	73	12.3	9.84	12.3
2022/6/19	77	18.5	14.8	18.5
2022/6/21	80	7.7	6.16	7.7
2022/6/25	84	8.8	7.04	8.8
2022/6/29	88	8.4	6.72	8.4
2022/7/3	92	11.5	9.2	11.5
2022/7/6	95	8.4	6.72	8.4
2022/7/10	99	18.4	14.72	18.4
Total	/	230.8	184.64	230.8

Note: 0.8 ET_c represents irrigation quota of I1, respectively; 1.0 ET_c represents irrigation quota of I2; E_{pan} represents cumulative pan evaporation (mm).

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