Effects of Mulched Drip Irrigation on Soil Physicochemical Properties and Biological Characteristics in Greenhouse Tomato Production: Postprint

Authors: Wang Jingwei, Wang Leiyuan, Li Yuan, Niu Wenquan

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Abstract

To elucidate the soil water and salt transport patterns in crop root zones under mulched drip irrigation conditions and their effects on the 'soil-microorganisms and enzymes-roots' interaction, and to further improve water and fertilizer use efficiency and refine precision irrigation systems, this study used greenhouse tomatoes as the research subject, employed Field TDR 200 for dynamic monitoring of soil water and salt transport in the root zone, examined the effects of conventional drip irrigation and mulched drip irrigation on water and salt transport, root systems, soil microorganisms, and enzyme activities, and analyzed the interactions among root zone soil environmental factors, soil microorganisms and enzymes, and root length density. The results showed that the soil water migration rate under mulched drip irrigation was significantly lower than that under conventional drip irrigation, water distribution was relatively uniform, and the area of soil with water content ≥ irrigation lower limit (22%) within the measurement range was 5 times that of conventional drip irrigation ($P<0.05$); the local salt accumulation rate decreased by 50%, reducing local salt accumulation; soil temperature was significantly increased and soil pH was decreased; the root length density in the surface soil of the root zone was 12.8-28.5 times that of conventional drip irrigation. These changes in environmental factors further enhanced the 'soil-microorganisms and enzymes-roots' interaction, with soil urease activity increasing by 20.83%-30.61% and phosphatase activity increasing by 76.92%-84.61%. Therefore, mulched drip irrigation has greater potential for improving water and soil resource use efficiency than conventional drip irrigation, and related agronomic measures need to be further refined and improved, which can provide support for enhancing water and soil resource use efficiency in facility agriculture in arid regions.

Full Text

Effects of Film-Mulched Drip Irrigation on Soil Physical, Chemical, and Biological Characteristics of Greenhouse Tomato

Jingwei Wang[1],[2], Leiyuan Wang[3], Yuan Li[2],[4], Wenquan Niu[2],[5]*

[1]School of Resources and Environment, Shanxi University of Finance and Economics, Taiyuan 030006, Shanxi, China
[2]Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, Shaanxi, China
[3]School of Public Administration, Shanxi University of Finance and Economics, Taiyuan 030006, Shanxi, China
[4]Northwest Land and Resources Research Center, Shaanxi Normal University, Xi' an 710119, Shaanxi, China
[5]Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, Yangling 712100, Shaanxi, China

Abstract

To investigate the dynamics of soil water and salt transport in crop root zones and their effects on the "soil-microorganisms/enzymes-roots" interactions under film-mulched drip irrigation, and to further enhance water and fertilizer use efficiency while improving precision irrigation systems, this study employed greenhouse tomatoes as the experimental subject. Using Field TDR 200 for dynamic monitoring of water and salt movement in the root zone, we examined the impacts of conventional drip irrigation (CDI) and film-mulched drip irrigation (FDI) on water-salt transport, root development, soil microorganisms, and enzyme activities, while analyzing the interactions among root-zone soil environmental factors, soil microorganisms, enzymes, and root length density. The results demonstrated that FDI significantly reduced soil water migration rates compared with CDI, yielding more uniform water distribution. Within the measurement range, the soil area maintaining moisture content $\geq$ irrigation lower limit (22%) was five times larger under FDI than CDI ($P<0.05$). FDI decreased local salt accumulation rates by 50% and reduced the degree of local salt aggregation. FDI also significantly increased soil temperature while decreasing soil pH. The root length density in the surface soil layer under FDI reached 12.8-28.5 times that of CDI. These environmental modifications further enhanced the "soil-microorganisms/enzymes-roots" interactions, increasing soil urease activity by 20.83%-30.61% and phosphatase activity by 76.92%-84.61%. Therefore, FDI demonstrates greater potential than CDI for improving water and soil resource use efficiency, though related agronomic measures require further refinement and optimization to support enhanced resource utilization efficiency in protected agriculture within arid regions.

Keywords: film mulching; drip irrigation; soil microorganisms; soil enzymes;

root length density

Introduction

Film-mulched drip irrigation technology is becoming increasingly prevalent in arid region agriculture. Drip irrigation delivers water directly to crop root zones as discrete droplets uniformly, timely, and quantitatively [?], resulting in small vertical wetted areas but enlarged lateral infiltration zones [?]. As water enters the soil, it dissolves salts that subsequently migrate with soil moisture toward areas surrounding the drip emitter [?]. Film mulching reduces water evaporation and suppresses upward salt migration [?], creating a root-zone soil environment under film-mulched drip irrigation that differs significantly from conventional irrigation [?]. As a localized irrigation method characterized by low flow rates, high irrigation frequency [?], and moisture conservation through mulching, film-mulched drip irrigation induces frequent wetting-drying cycles in the root zone [?], potentially intensifying spatiotemporal heterogeneity of environmental factors such as soil water, salt, and temperature [?], thereby affecting soil nutrient cycling [?] and influencing crop root growth.

The crop root-zone soil, roots, microorganisms, and enzymes constitute a dynamically changing microenvironment [?]. Soil enzymes serve as crucial drivers of soil nutrient metabolism [?], reflecting environmental quality changes over relatively short periods [?] and representing important indicators for evaluating soil fertility and quality [?]. Research indicates that soil enzymes are closely associated with microorganisms and crop roots [?] while being simultaneously influenced and constrained by root-zone soil water, salt, and thermal conditions [?]. The interactions among these three components constitute the intrinsic soil-driven mechanism for crop water and nutrient absorption [?], ultimately affecting crop growth. However, existing research has primarily focused on water-salt transport, fertilizer distribution, and crop growth responses under film-mulched drip irrigation [?], with less attention devoted to how spatiotemporal heterogeneity of moisture, salt, and temperature in the crop root-zone microdomain affects soil microorganisms, enzyme activities, and root development.

Using conventional drip irrigation as a control, this study investigated the effects of film-mulched drip irrigation on soil environmental factor heterogeneity in the root zone and its subsequent impacts on soil microorganisms, enzyme activities, and root growth. By analyzing the "soil-microorganisms/enzymes-roots" interactions, this research provides insights for improving water and soil resource utilization efficiency and developing precision irrigation systems.

1.1 Experimental Design

The experimental site was located at 108°08 E, 34°16 N, at an altitude of 521 m, with an average annual temperature of 16.3 °C, precipitation of 535.6 mm, sunshine duration of 2,163 h, and frost-free period of 210 days. The test soil was Lou soil from Yangling, Shaanxi, with physical properties shown in .

Table 1 Soil physical properties

Parameter	Description/Value
Soil composition	Sand (2-0.02 mm), Silt (0.02-0.002 mm), Clay (<0.002 mm)
Bulk density	1.35 g · cm^{-3}
pH	[value not provided]
Soil porosity	[value not provided]

The experiment was conducted from October 2014 to May 2015 in a greenhouse facility in Dazhai Township, Yangling District, Shaanxi. The greenhouse measured 108 m east-west and 8 m north-south. The experimental crop was tomato variety "Haidi." The greenhouse was divided into planting plots from east to west, with double ridges established. Each plot covered 3.6 m^2 (6.0 m length, 0.6 m ridge surface width, 0.2 m ridge height, and 0.3 m furrow width). Two treatments were established: conventional ground drip irrigation and film-mulched drip irrigation. For the film-mulched treatment, white light-transmitting high-pressure low-density polyethylene film (Jingjiang Xinfeng Plastic Factory, Jiangsu) with 0.014 mm thickness was applied. Each treatment had three replications, totaling six experimental plots. Each plot contained 34 tomato plants in double rows with 0.30 m plant spacing. The drip tape was positioned between tomato rows with 30 cm emitter spacing, with each emitter located between two plants in adjacent rows. The drip tape was inlaid flat-type (Gansu Dayu Water-saving Group Co., Ltd.) with 16 mm diameter, 0.3 mm wall thickness, operating pressure of 0.1 MPa, and emitter flow rate of 1.2 L · h^{-1}.

Based on our research group' s previous experiments and local farming practices, irrigation at 70% of field capacity could meet tomato growth requirements. Therefore, irrigation upper and lower limits were set at 75% and 70% of field capacity, respectively. To prevent lateral water seepage, plastic film was used to isolate experimental plots.

After tomato transplanting, one emitter per plot was randomly selected as a fixed point, where one 100 cm depth access tube was installed adjacent to the emitter exterior. Two additional access tubes were installed sequentially outward along the direction perpendicular to the drip tape. The three access tubes were linearly distributed perpendicular to the drip tape at 15 cm intervals to monitor soil water and salt transport.

1.2.1 Soil Moisture and Salt

Soil moisture and salt (electrical conductivity) were monitored using Field TDR 200 (Spectrum Technologies, Inc., USA). The probe was inserted into access tubes at 10 cm intervals to a depth of 60 cm. When soil moisture reached the lower limit, water was supplemented to a wetting depth of 40 cm. The irrigation amount was calculated using the formula:

$$M = \frac{s \cdot \rho_b \cdot r \cdot h \cdot (q_1 - q_2)}{\eta}$$

where M is irrigation amount (m^3), s is planned wetting area (m^2), b is soil bulk density ($1.35\ \mathrm{g \cdot m^{-3}}$), r is wetting ratio (0.80), h is wetting layer depth (0.40 m), f is field capacity (31.54%), *q1* and *q2* are irrigation upper limit and measured soil moisture content (%), and is water use coefficient (0.95).

Each experimental plot received water control and irrigation independently based on monitoring conditions. Soil moisture and salt content were monitored on days 1, 3, 6, and 11 after irrigation. Continuous monitoring was conducted for six cycles, with average values calculated.

1.2.2 Soil Temperature and pH

Soil temperature was measured using geothermometers. In each plot, one emitter was randomly selected, and geothermometers were installed at vertical distances of 5, 10, 15, 20, 25, and 30 cm from the emitter. Monitoring occurred on days 1, 3, 6, and 11 after irrigation at 10:00 AM, with average values recorded (°C).

Within the irrigation cycle, on days 1, 3, 6, and 11 after irrigation, soil samples were collected in each plot at vertical distances of 5, 10, 15, 20, 25, and 30 cm from a randomly selected emitter using a small specialized soil auger (2.0 cm inner diameter) at 10 cm intervals to a depth of 60 cm. Soil samples were brought to the laboratory and pH was determined using a pHB-4 pH meter (soil:water ratio 1:5), with average values calculated.

1.2.3 Tomato Root Length Density, Soil Enzymes, and Soil Microorganisms

After completing soil water and salt monitoring, three plants were randomly selected per plot for root sampling, with sampling ranges identical to water-salt monitoring areas. Soil cores (6.0 cm diameter) were collected at 10 cm intervals to a depth of 60 cm. Samples were packaged, labeled, and transported to the laboratory. In a sterile laminar flow hood, root samples were extracted with sterilized tweezers and separated from soil. After cleaning, roots were scanned using a dual-sided scanner (Epson Expression 1600 pro, Model EU-35, Japan) and analyzed using WinRHIZO image analysis system (WinRHIZO Pro2004b, 5.0, Canada) to determine total root length (cm) and calculate root length density.

Fresh soil samples were stored at 4 °C for subsequent enzyme and microbial analyses. Soil urease activity was determined using the phenol-sodium hypochlorite colorimetric method, expressed as mg NH_3-N · g^{-1} · d^{-1} generated per gram of soil after 24 h. Soil phosphatase activity was measured using the disodium phenyl phosphate colorimetric method, expressed as mg phenol · g^{-1} · d^{-1} released per gram of soil after 24 h [?]. Soil suspensions were prepared with sterile water, and fungi, bacteria, and actinomycetes were isolated using Martin' s medium, beef extract peptone medium, and modified Gause' s No. 1 medium, respectively. Cultures were incubated at 37 °C and 25 °C, with colony growth observed and counted. Three plates were used for each microbial type per treatment (three replicates), with average values calculated.

1.3 Data Processing

Data were processed using Excel software, graphed using OriginPro 8.5, and statistically analyzed using SPSS 22.

2.1 Effects of Different Drip Irrigation Methods on Soil Water Movement

The irrigation lower limit in this experiment was 70% of field capacity (soil moisture content 22%). The measurement range for soil moisture content was centered near the emitter (tomato root) covering 0–30 cm horizontally and 0–55 cm vertically from the emitter (1,650 cm^2 area). Within the irrigation cycle, soil water movement rate was evaluated based on the change rate of the proportion of soil area with moisture content $ 20^{2}$).

As shown in [Figure 1: see original paper], under conventional drip irrigation, the proportions of soil area with moisture content $ 20{-1}.Underfilm − mulcheddripirrigation, thecorrespondingproportio
1}$, significantly slower than conventional drip irrigation ($P<0.05$). Under conventional drip irrigation, soil water generally moved from deep layers to the surface and toward tomato roots, resulting in uneven distribution. Within the irrigation cycle, the area maintaining moisture content ≥ irrigation lower limit (22%) was limited to 0–5 cm horizontally and above 20 cm vertically from the root (100 cm^2 area). Film-mulched drip irrigation produced relatively uniform water distribution, with the area maintaining moisture content $ 22^{2}$ area), five times larger than conventional drip irrigation ($P<0.05$).

2.2 Effects of Different Drip Irrigation Methods on Soil Salt Movement

Research indicates that soil electrical conductivity significantly correlates with soluble salt content, and its changing trend can represent salt dynamics [?]. This experiment analyzed soil soluble salt trends by measuring electrical conductivity dynamics ([Figure 2: see original paper]) within the same range as soil moisture monitoring. Results showed that soil salt generally moved with water from deep layers to the surface and toward tomato roots after irrigation. Both irrigation methods caused salt accumulation in the surface layer (soil electrical conductivity $ 4.5ms·cm^{-1}$) within the irrigation cycle. Under conventional drip irrigation, the salt accumulation zone was located 5-30 cm horizontally and 12.5-35 cm vertically from the root. Under film-mulched drip irrigation, the salt accumulation zone was 7.5-30 cm horizontally and 12.5-25 cm vertically from the root. The salt accumulation rates differed between methods: under conventional drip irrigation, the proportion of soil area with electrical conductivity $ 4.5*ms · cm*^{-1}$ on days 1, 3, 6, and 11 after irrigation was 0.88%, 17.68%, 20.39%, and 23.98%, respectively, with an average increase rate of 2.31% · d^{-1}, forming a salt accumulation zone by day 3. Under film-mulched drip irrigation, the corresponding proportions were 3.78%, 4.33%, 16.77%, and 19.4%, with an average increase rate of 1.56% · d^{-1} (significantly lower than conventional drip irrigation, P<0.05), with salt accumulation forming by day 6.

2.3 Effects of Different Drip Irrigation Methods on Soil Temperature and pH

As shown in [Figure 3: see original paper], within the irrigation cycle, the average soil temperature in the region 0-30 cm horizontally and 0-25 cm vertically from the root (750 cm^2 area) was significantly higher under film-mulched drip irrigation than conventional drip irrigation (P<0.05). Under conventional drip irrigation, areas with average temperature $ 18°*Caccountedfor*34.43^{2}$), and $ $20 °C areas accounted for 1.30%. Under film-mulched drip irrigation, areas $ $18 °C accounted for 97.25% of the measurement area (2.82 times that of conventional drip irrigation), and areas $ $20 °C accounted for 50.53% (38.86 times that of conventional drip irrigation).

As shown in [Figure 4: see original paper], within the rectangular area (1,650 cm^2) centered at the emitter (tomato root) extending 0-30 cm horizontally and 0-55 cm vertically, soil pH ranged from 8.1-8.8 under conventional drip irrigation and 7.8-8.4 under film-mulched drip irrigation, with the pH variation range significantly smaller under film-mulched drip irrigation.

2.4 Effects of Different Drip Irrigation Methods on Soil Microorganisms and Enzyme Activities

Under conventional drip irrigation, soil bacteria (60$×10$^{\{8\}-220\times10}${8}$ cfu · g^{-1}) were concentrated in the region 0-10 cm horizontally and 0-35 cm vertically from the root. Under film-mulched drip irrigation, bacterial distribution was relatively uniform, with bacterial content of 40$×10$^{\{8\}-120\times10}${8}$ cfu · g^{-1} in the same region, significantly lower than conventional drip irrigation (P<0.05).

Compared with conventional drip irrigation, film-mulched drip irrigation promoted fungal aggregation ([Figure 5: see original paper]), with soil fungal content of 15$×10$^{\{3\}-45\times10}${3}$ cfu · g^{-1} in the region 0-30 cm horizontally and 0-30 cm vertically from the root. Conventional drip irrigation showed significantly lower fungal content of 5$×10$^{\{3\}-15\times10}${3}$ cfu · g^{-1} (P<0.05) with relatively uniform distribution. Both irrigation methods concentrated actinomycetes in areas above 25 cm vertically from the root ([Figure 5: see original paper]), with conventional drip irrigation showing actinomycete content of 60\$$\times 10^{\{6\}-160\times 10}$\{6\}\$ cfu $\cdot$ g^{-1}, significantly higher than film-mulched drip irrigation at 20\$$\times 10^{\{6\}-140\times 10}$\{6\}\$ cfu $\cdot$ g^{-1} ($P<0.05$).

The distribution patterns of soil urease activity were similar between both methods ([Figure 6: see original paper]), with activity greater in areas above 35 cm vertically from the root, peaking at 15 cm horizontally from the root and decreasing toward both sides. However, film-mulched drip irrigation showed significantly higher urease activity of 29-64 mg NH_3-N $\cdot$ g^{-1} $\cdot$ d^{-1} compared with 24-49 mg NH_3-N $\cdot$ g^{-1} $\cdot$ d^{-1} under conventional drip irrigation ($P<0.05$), representing a 20.83%-30.61% increase. Conventional drip irrigation showed more uniform urease distribution, with the area having urease activity of 19 mg NH_3-N $\cdot$ g^{-1} $\cdot$ d^{-1} below 35 cm vertically from the root accounting for 85.46% of the measurement area, three times larger than film-mulched drip irrigation (28.24%) ($P<0.05$).

As shown in [Figure 6: see original paper], conventional drip irrigation produced relatively dispersed phosphatase activity distribution (13-26 mg phenol $\cdot$ g^{-1} $\cdot$ d^{-1}). Under film-mulched drip irrigation, phosphatase activity gradually decreased from the surface to deeper layers, with activity of 23-48 mg phenol $\cdot$ g^{-1} $\cdot$ d^{-1} in areas above 25 cm vertically from the root, significantly higher than conventional drip irrigation ($P<0.01$), representing a 76.92%-84.61% increase.

2.5 Effects of Different Drip Irrigation Methods on Root Length Density

As shown in [Figure 7: see original paper], tomato roots were primarily distributed in the region 0-25 cm horizontally and above 15 cm vertically from the root. Root length density under conventional drip irrigation ranged from 0.054-0.554 cm $\cdot$ cm^{-3}, significantly lower than film-mulched drip irrigation at 1.54-7.04 cm $\cdot$ cm^{-3}. Root length density generally decreased with increasing horizontal and vertical distance from the root.

2.6 Correlation Analysis

As shown in , under conventional drip irrigation, root length density was significantly positively correlated with soil phosphatase. Soil moisture was significantly positively correlated with temperature, urease, and phosphatase. Soil pH was significantly positively correlated with soil fungi and actinomycetes. Soil urease was significantly positively correlated with phosphatase and actinomycetes. Soil phosphatase was significantly positively correlated with fungi.

As shown in , under film-mulched drip irrigation, root length density was significantly positively correlated with soil moisture, urease, phosphatase, fungi, and actinomycetes, and significantly negatively correlated with soil electrical conductivity. Soil moisture was significantly positively correlated with temperature, urease, phosphatase, bacteria, fungi, and actinomycetes, and significantly negatively correlated with electrical conductivity. Both soil urease and phosphatase were significantly positively correlated with bacteria, fungi, actinomycetes, and soil temperature. Soil urease was significantly positively correlated with phosphatase, and the three microbial groups were significantly positively correlated with each other.

3.1 Film-Mulched Drip Irrigation Significantly Optimizes the Root-Zone Microenvironment

This study found that film-mulched drip irrigation maintained soil moisture content above the irrigation lower limit in the region 0–30 cm horizontally and above 20 cm vertically from the tomato root, significantly outperforming conventional drip irrigation. Qi et al. [?] reported that film-mulched drip irrigation reduces soil water consumption under mulch, consistent with our findings, though they did not investigate water-salt transport rates and patterns with root involvement. Our results revealed that soil moisture in tomato root zones under both irrigation methods moved from deep layers to the surface and toward roots by day 3 after irrigation, but the migration rate under film-mulched drip irrigation was significantly slower than conventional drip irrigation. This lag can be attributed to two factors: first, bare soil evaporation exceeds that under mulched soil [?]; second, although film mulching increases soil temperature, which could accelerate water movement, the film barrier hinders water vapor exchange with the atmosphere, promoting condensation under the film and reducing evaporation [?].

Soil salt migrates with water, and both irrigation methods caused surface salt accumulation, but film-mulched drip irrigation exhibited lower salt accumulation rates than conventional drip irrigation. This occurs because relatively higher surface soil moisture content under mulching inhibits upward migration of deep soil water and salt. Additionally, film-mulched drip irrigation resulted in lower wetting-drying alternation frequency in the vertical profile compared with conventional drip irrigation, further suppressing upward salt migration. Zhou et al. [?] found that film mulching inhibits salt accumulation in the soil surface, consistent with our results, though they did not investigate root involvement. Soil salt migration relates to root physiological activity [?], as roots enrich salts in surrounding soil during water and nutrient absorption [?]. Our measurements revealed that film-mulched drip irrigation promoted greater root growth than conventional drip irrigation. However, the significantly higher shallow soil moisture content under film-mulched drip irrigation reduced water stress compared with conventional drip irrigation, potentially decreasing plant transpiration and slowing water-salt absorption, thereby retarding water-salt migration and resulting in lower vertical salt accumulation rates.

Soil water-salt transport and distribution affect soil pH. Film-mulched drip irrigation significantly reduced soil pH compared with conventional drip irrigation. This occurs because higher evaporation and relative water stress under conventional drip irrigation promote root water absorption, enhancing root surface water-salt exchange and increasing rhizosphere soil pH [?]. Compared with conventional drip irrigation, film-mulched drip irrigation significantly increased root-zone soil temperature and surface root-zone root density (0–25 cm horizontally, 0–5 cm vertically), which could enhance soil colloid exchangeable cation hydrolysis and increase soil pH. However, film-mulched drip irrigation actually decreased pH due to lower water stress in shallow soil, which reduced root surface water-salt exchange [?]. Overall, film-mulched drip irrigation created a relatively moist, warm soil region with less salt aggregation and promoted root growth compared with conventional drip irrigation.

3.2 Film-Mulched Drip Irrigation Enhances "Soil-Microorganisms/Enzymes-Roots" Interactions

Li [?] found that film-mulched drip irrigation had minimal impact on bacterial growth but significantly affected fungi, partially consistent with our results. We further observed that conventional drip irrigation significantly promoted actinomycete growth in the surface root zone (0–35 cm horizontally, 0–25 cm vertically from the root), while film-mulched drip irrigation significantly enhanced fungal growth in the surface root zone (0–30 cm horizontally, 0–30 cm vertically). The different soil water, salt, and thermal conditions created by the two irrigation methods, combined with distinct microbial ecological niches [?], enhanced spatial distribution differences. This benefits microbial community dynamic stability and maximizes soil-microorganism-root interactions for optimal nutrient utilization, promoting root and crop growth [?].

Correlation analysis () indicated that conventional drip irrigation enhanced "soil-microorganisms/enzymes" and "roots-soil enzymes" interactions to some extent, potentially benefiting urease and phosphatase activities. However, measured activities were actually lower under conventional drip irrigation than film-mulched drip irrigation. Zhang [?] reported that film-mulched drip irrigation management significantly increases soil urease activity and promotes nitrogen transformation, consistent with our findings. Soil enzymes originate not only from microorganisms but are also influenced by crop roots and "root-microorganism" interactions [?]. Compared with conventional drip irrigation, film-mulched drip irrigation further strengthened "soil-microorganisms/enzymes-roots"interactions (), benefiting enzyme activity enhancement [?]. This occurs because, in the main root distribution zone, film-mulched drip irrigation produced root length density 12.8–28.5 times that of conventional drip irrigation. Although conventional drip irrigation generally promoted microbial growth, film-mulched drip irrigation significantly enhanced root growth, strengthening "soil-microorganisms/enzymes-roots"interactions and consequently increasing urease and phosphatase activities while promoting root nitrogen and phosphorus absorption [?]. Therefore, film-mulched drip irrigation creates a more suitable soil environment for root growth compared with conventional drip irrigation.

Conclusion

Compared with conventional drip irrigation, film-mulched drip irrigation during the irrigation cycle slowed water migration, reduced salt accumulation, increased soil temperature, and decreased soil pH, thereby optimizing the root-zone microenvironment. Film-mulched drip irrigation significantly increased root density, with surface soil root length density reaching 12.8–28.5 times that of conventional drip irrigation, and enhanced "soil-microorganisms/enzymes-roots" interactions, resulting in increased soil urease and phosphatase activities. However, the specific interaction mechanisms between microbial communities and root growth under film-mulched drip irrigation require further investigation.

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Note: Figure translations are in progress. See original paper for figures.