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Effects of Irrigation Strategy and Plastic Film Mulching on Soil N_2O Emissions and Fruit Yields of Greenhouse Tomato

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Abstract: Agriculture is a major source of global greenhouse gas emissions. Approximately 1/3 of vegetables in China are produced in greenhouses. However, the effects of different irrigation strategies and plastic film (PF) mulching combinations on N_2O emissions and tomato fruit yields in greenhouses are unclear. The aims of this study were to explore the effects of micro-sprinkler irrigation under plastic film (MSPF), drip irrigation under plastic film (DIPF) and micro-sprinkler irrigation (MSI) on the soil nutrients, enzyme activity, *nirS*-type denitrifying bacterial community, N_2O emissions and fruit yields of tomato. The results showed that MSPF could improve the uniformity of soil water distribution and surface (0–40 cm) soil water content. Film mulching could increase soil temperature at depths of 5–25 cm. Both MSPF and DIPF increased microbial nitrogen, promoted the activity of rhizosphere soil urease and leucine aminopeptidase, changed the community of denitrifying bacteria, accelerated the turnover of soil nutrients and improved yield and water use efficiency. PF mulching had a greater impact on the *nirS*-type denitrifying bacterial community when compared to irrigation strategy. We conclude that MSPF can be used to configure commercially available installation and operation. The comprehensive benefit of MSPF treatment is that it is more profitable than that of DIPF.

Keywords: irrigation strategy; plastic film mulching; denitrifying bacteria community; N_2O emissions; yield

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1. Introduction

Tomatoes are widely loved by vegetable farmers and consumers due to their high fruit yield, nutrition and good taste [1,2]. In Northern China, most tomatoes are planted in greenhouses. It is well known that soil water is one of the key factors regulating tomato growth in facility agriculture [3]. According to statistics, water consumption from irrigation accounts for more than 60% of the total water consumption in the Loess Plateau of China [4,5]. The irrigation water for facility agriculture in this area mainly comes from groundwater, further aggravating the water resource crisis [6–8].

It is estimated that farmland accounts for approximately 13.8% of global greenhouse gas emissions worldwide [9]. Greenhouse gas emissions, such as CO_2, CH_4, and N_2O, are affected by environmental factors [10]; additionally, an estimated 66% of global N_2O emissions are attributed to crop production, and N_2O emissions are expected to double by 2050 [11,12]. Irrigation also affects N_2O emissions by regulating soil biochemical reactions, such as soil enzyme activity, soil respiration, nitrification, denitrification and mineralization [13]. Previous research has shown that the global warming potential of N_2O is approximately 265 times that of CO_2 on a centennial scale [14]. Therefore, under the condition of a shortage of water resources and increased N_2O emissions, it is of great significance to obtain a feasible irrigation strategy in facility agriculture. Different irrigation strategies cause different soil water contents and distributions and affect the soil N turnover rate, microbial biomass and soil enzyme activity, all of which change the N_2O emissions and plant production [15,16]. A suitable irrigation strategy can not only reduce the waste of water resources and N_2O emissions but also achieve higher fruit yields. The results from a field experiment showed that drip irrigation is a water-saving technology, and it is applied mainly in fields and greenhouse crops [17]. It was found that the soil N_2O emissions under drip irrigation and sprinkler irrigation were 54.31% and 53.30% lower than those under furrow irrigation [18,19].

Micro-sprinkler irrigation is a new water-saving irrigation technology that has been developed in recent years. Compared with drip irrigation, the manufacturing cost is greatly reduced because it has no labyrinth channel emitters [20,21]. Plastic film can also change the soil microenvironment and increase the soil water content, temperature and fruit yield [22,23]. Micro-sprinkler irrigation and plastic film covering were combined to form micro-sprinkler irrigation under plastic film (MSPF). To date, MSPF has achieved good applicable effects in greenhouses [20,21]. Compared with drip irrigation, the velocity of a single hole in MSPF is approximately 15 times that of drip irrigation, meaning MSPF has a stronger sediment-carrying capacity and better anti-clogging performance [24,25]. The flow velocity of micro-sprinkler emitters is approximately 40 times that of drip irrigation, and the irrigation duration is shorter [26,27]. Micro-sprinkler irrigation reduces the transport of soil water to deep soil and limits the lateral development of roots, and the soil nutrient cycle is also changed due to the increase in the soil dry–wet cycle [28,29].

Due to the great difference in wetted soil area caused by different irrigation strategies, we hypothesize that the difference in soil moisture distribution can change the soil temperature, enzyme activity and soil biochemical reaction and affect the soil N_2O emissions and fruit yield. Furthermore, existing studies have not explored the mutual relation between irrigation strategy and *nirS*-type denitrifying bacteria abundances, N_2O emissions and fruit yield. The objective of this study was to determine the response of enzyme activity, the nitrogen cycle, N_2O emissions and fruit yields of tomato on sandy loam soils of the semiarid area of Northwest China under MSPF, DIPF and MSI treatments.

2. Materials and Methods

2.1. General Description of Field Site and Materials

The experiment was conducted in the greenhouse at Xi'an Modern Agricultural Science and Technology Extension Center (108°52′ E, 34°03′ N, altitude 435 m). The study site is located on the southern edge of the Loess Plateau. The mean annual temperature is approximately 13.3 °C, and the mean annual rainfall is 613.75 mm. The average bulk density of the 0–1.0 m soil layer is 1.53 g/cm^3, and the field capacity is 25.40% (mass water content). The soil is sandy loam, and detailed soil information is shown in Table 1.

Table 1. Physical and chemical properties of the soil at the study site.

Texture	Clay	Silt	Gravel	
Effective diameter (mm)	<0.002	0.002–0.02	>0.02	
Content (%)	6.47	29.63	63.9	
Nutrient	Total organic matter	Total phosphorus	Total potassium	Total nitrogen
Content (g/kg)	5.53	0.38	14.33	0.36

The experiment was performed from March 2019 to January 2020 using the tomato cultivar Jingfan 401 (Jing-Yan-Yi-Nong Seed Sci-tech Co., Ltd., Beijing, China). Seventeen tomato seedlings per plot were planted in double rows, with a row spacing of 50 cm, a plant spacing of 40 cm, and row lengths of 3.4 m for each plot. The spacing of each plot was 4 m, and the waterproof membrane, styrene–butadiene–styrene block copolymer, was embedded in the middle to prevent the exchange of water between plots. Guard rows were set up at both ends of the experimental field. Micro-sprinkler pipes (φ16 micro-sprinkler pipe, Hebei Plentirain Irrigation Equipment Technology Co. Ltd., Shijiazhuang, Hebei, China), 28 mm in diameter with an emitter spacing of 0.30 m, were laid spaced 0.50 m apart along the ridges. Drip irrigation pipes (φ16 subsurface drip irrigation pipe, Qinchuan Water-saving irrigation equipment engineering Co. Ltd., Yangling, Xianyang, China), with an emitter spacing of 0.30 m, were laid spaced 0.50 m apart along the ridges. All agronomic management measures taken during the growth period, such as fertilization and chemical spraying, were the same for all treatments.

During the spring experiment, 20-day-old seedlings were transplanted into beds on 27 March 2019, irrigation began on 4 April 2019, and irrigation stopped on 15 July 2019. All the fruit was harvested on 25 July 2019. During the autumn experiment, seedlings were transplanted on 23 August 2019, irrigation began on 30 August 2019, and irrigation stopped on 17 January 2020. All the fruit was harvested on 30 January 2020.

2.2. Experimental Design

Three irrigation strategies were adopted in the experiment: micro-sprinkler irrigation under plastic film (MSPF), drip irrigation under plastic film (DIPF) and micro-sprinkler irrigation (no plastic film, MSI). The treatments were randomized within each block, and each of them was repeated 3 times.

Evaporation was recorded by a φ20 cm evaporation pan. The evaporation amount was measured at 8:00 a.m. every 5 d. The irrigation quota (W) was calculated according to Equation (1), and the temperature, irrigation times and amounts are recorded in Figure 1:

$$W = A \times E_{pan} \times k_{cp} \tag{1}$$

where E_{pan} represents the evaporation within the interval of two irrigation events based on the cumulative evaporation from the evaporation pan (mm); A represents the planned irrigation area (m^2); and k_{cp} represents the crop-pan coefficient. In this study, the crop-pan coefficient of k_{cp} is 1.0.

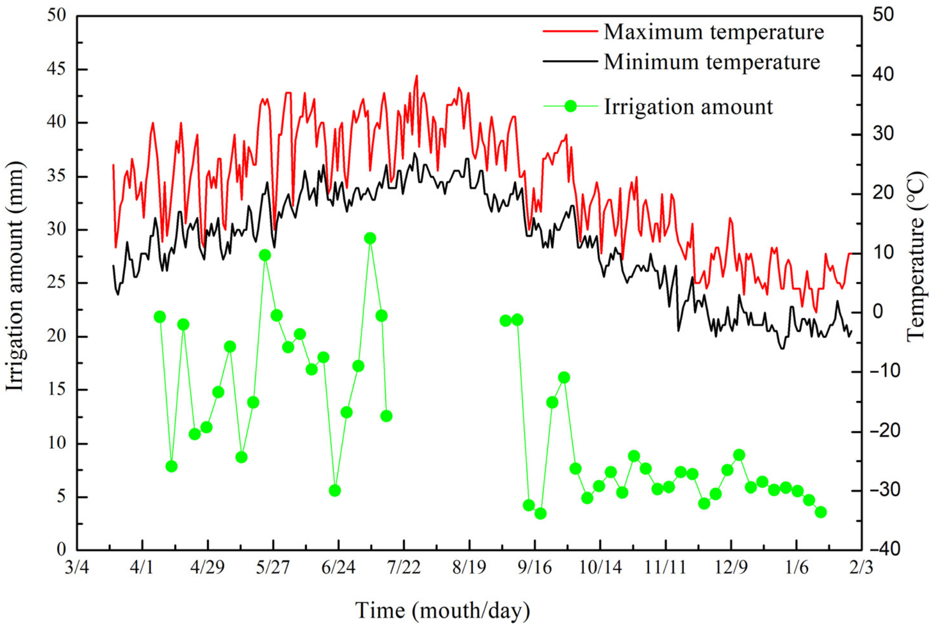

Figure 1. Irrigation date, amount and greenhouse temperature during the growing season.

2.3. Test Items and Methods

2.3.1. Soil Physicochemical Properties and Soil Microorganisms

The soil shaking method was used to collect the rhizosphere soil, the whole 10–20 cm root system was dug from the soil, and a soft bristle brush was used to brush and collect the soil that was closely associated with the roots. The obtained soil samples were sifted through a 2 mm steel sieve. The community of *nirS*-type denitrifying bacteria in rhizosphere soil was determined at 72 d after transplant, and the total nitrogen (TN), soil microbial biomass nitrogen (MBN) and soil urease (UR), and leucine aminopeptidase (LAP) activity in rhizosphere soil were determined at 36, 72 and 110 days after transplant during spring and autumn.

Soil Moisture and Temperature

A TDR soil moisture sensor (Trime-Pico-Iph, Imko, Inc., Ettlingen, Germany) was used to measure the soil water content in the 0–80 cm soil layers. Three monitoring points were selected in each plot. Soil moisture was monitored at 66 d, 76 d, 86 d, 96 d and 106 d after planting in both the spring and the autumn seasons. Geothermal meters (5, 15 and 25 cm) (Beijing Weixin Yiao Science and Technology Development Co., Ltd., Beijing, China) were used to measure the soil temperature at soil layer depths of 5, 15 and 25 cm. The measurement time was the next day after irrigation.

Soil TN and MBN

TN was extracted by the semimicro Kjeldahl method [30]. The soil microbial nitrogen was extracted by the chloroform fumigation-K_2SO_4 method. Determination of the MBN in extracted filtrate was performed by a total organic nitrogen analyzer (multiN/C3100, Analytik Jena AG, Jena, Germany) [31].

Soil Enzyme Activity

UR activity was measured by the phenol-sodium hypochlorite colorimetric method [32]. LAP activity was measured by enzyme-linked immunosorbent assay (RT-6100, Shanghai Precision Instruments Co., Ltd., Shanghai, China) [33].

Soil *nirS*-Type Denitrifying Bacteria Community

1. DNA extraction and PCR amplification; 2. Illumina MiSeq sequencing; 3. sequencing data processing. The experimental procedures were previously described in detail [34].

2.3.2. N_2O Emission

N_2O emissions were evaluated using static chamber methodology with air analysis by gas chromatography. Samples were collected by static dark box method. The box was made of 6 mm thick polyvinyl chloride (PVC) material (20 cm × 20 cm × 20 cm) and a base box (20 cm × 20 cm× 10 cm). The outer surface of the box was wrapped with sponge and tin foil, and the top was equipped with a small fan for stirring air. Before this field trial, the base box was inserted into soils in the center of each plot. The N_2O emission rate from rhizosphere soil was measured at 11:00 a.m. 20, 36, 40, 56, 72, 85, 100 and 110 d after transplantation. The soil N_2O emissions were determined using Equation (2) as follows:

$$F = 1000 \times \rho \frac{V}{A} \frac{P}{P_o} \frac{T_o}{T} \frac{dC_t}{d_t} \tag{2}$$

where F (μg m^{-2} h^{-1}) is the emission rate of N_2O; ρ (mg m^{-3}) is the density of N_2O under standard conditions; A (m^2) is the base area; V (m^3) is the chamber volume; P_o is the atmospheric pressure under standard conditions; P is the atmospheric pressure located inside the chamber; $T_0$and T are the absolute temperatures under standard conditions and in the chamber, respectively; and $\frac{dC_t}{d_t}$ (h^{-1}) is the variation in the N_2O concentration over time.

2.3.3. Yield and Water Use Efficiency

During the mature period, fruit yield was measured by an electronic scale. The water consumption (ET_a) was calculated by Equation (3):

$$ET_a = I \pm 1000 \times H \times (\theta_{t1} - \theta_{t2}) \tag{3}$$

where ET_a (mm) is the water consumption; I (mm) is the irrigation quota during the growth period; H (m) is the depth, $H = 0.8$ m; and θ_{t1} and θ_{t2} are the 80 cm average soil water contents at times t1 and t2, respectively (cm^3/cm^3). Crop *WUE* was calculated by Equation (4):

$$WUE = 1000 * Y/ET_a \quad (4)$$

where *WUE* (kg/m^3) is the crop water use efficiency, and Y (kg/hm^2) is the crop grain yield.

2.4. Data Analysis

Statistical analysis was performed using SPSS 22.0 (IBM Crop., Armonk, New York, NY, USA) and plotted by OriginPro 2019 (Origin Lab Corporation, Northampton, MA, USA). The mean differences between treatments were assessed by analysis of variance (ANOVA). The differences were compared using Duncan's test with a significance level of $p < 0.05$.

3. Results

3.1. Effects of Irrigation Strategy and Plastic Film Mulching on Soil Water and Temperature in the Tomato Root Zone

As shown in Figure 2, MSPF increased the soil water content in the 0–40 cm soil layer during both spring and autumn. The MSI treatment had the lowest water content in the deeper soil layer (40–80 cm). Compared with MSPF, the average soil water content in the 0–40 cm soil layer under the DIPF treatment decreased by 4.80% and 2.38% during spring and autumn, respectively. Compared with MSI, the average soil water content of the 0–40 cm soil layer under the MSPF treatment increased by 8.08% and 4.87% during spring and autumn, respectively, and the 0–80 cm soil water increased by 8.99% and 7.19%, respectively. The results showed that the MSPF treatment could effectively enhance the soil water content at 0–40 cm and improve the uniformity of soil water in the 0–80 cm soil layer.

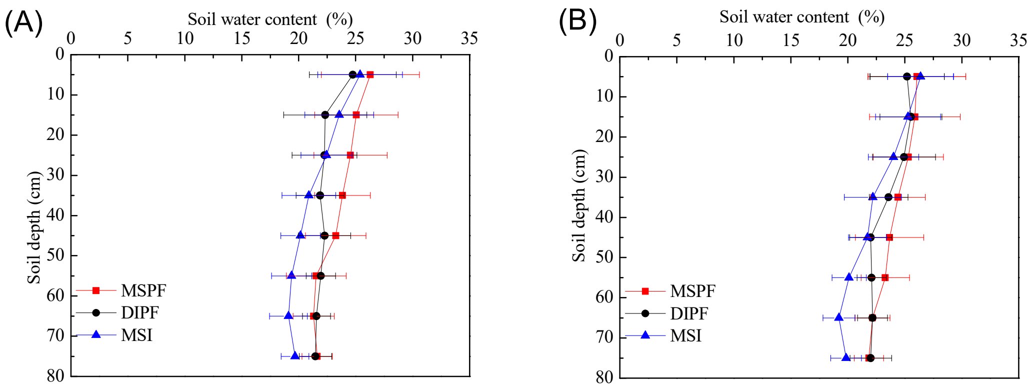

Figure 2. Average soil water content under different irrigation strategies during spring (**A**) and autumn (**B**).

Figure 3 shows that the variation tendency of the soil temperature was similar to that of the greenhouse temperature (Figure 1). During the spring growing season, compared with DIPF, the 5, 15 and 25 cm layer soil temperatures under the MSPF treatment increased by 2.32%, 3.21% and 1.63%, respectively. During the autumn growing season, these values increased by 1.36%, 2.93% and 0.68%, respectively. During the two growing seasons, compared with the DIPF treatment, the average soil temperature in the 5–25 cm soil layer under the MSPF treatment increased by 2.39% and 1.66%, respectively. During spring, compared with MSI, the 5, 15 and 25 cm layer soil temperatures under the MSPF treatment increased by 6.17%, 5.45% and 15.93%, respectively. During the autumn, the temperatures increased by 0.30%, 4.32% and 1.02%, respectively. During the two growing seasons, the average soil temperatures in the 5–25 cm soil layer under the MSPF treatment increased by 5.85% and 1.68%, respectively.

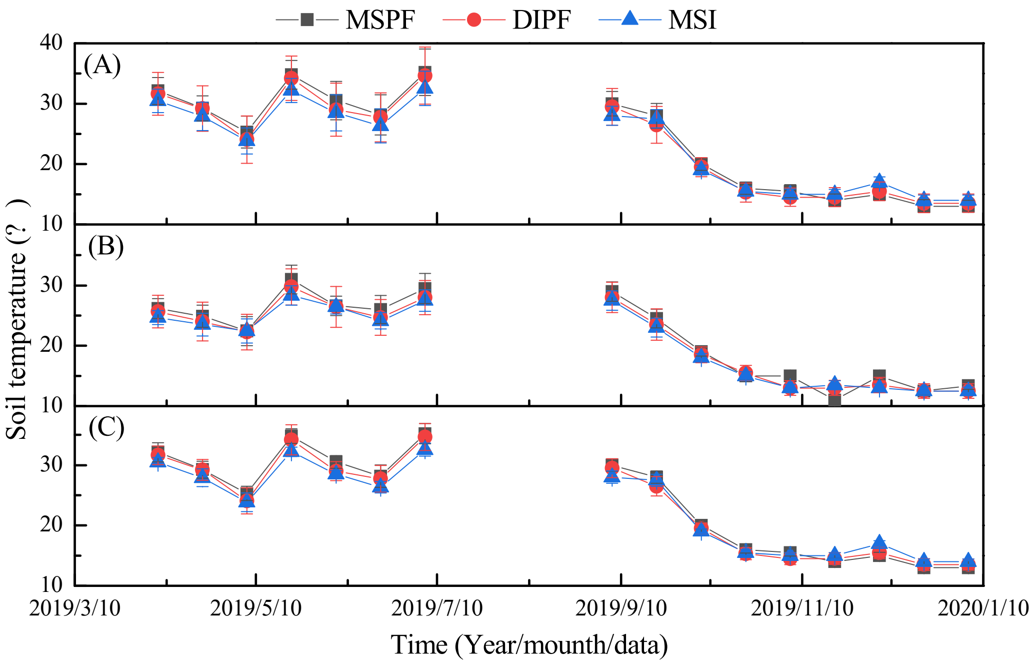

Figure 3. Soil temperature at 5 cm (**A**), 15 cm (**B**) and 25 cm (**C**) depths under different irrigation strategies.

3.2. Effects of Irrigation Strategy and Plastic Film Mulching on Soil Total Nitrogen (TN) and Microbial Biomass Nitrogen (MBN)

The effects of different treatments on TN and MBN are shown in Figure 4. The results showed that TN decreased with the age of the plants and that MBN increased with the age of the plants. The MSI treatment had the maximum TN at 72 and 110 d after the transplant of tomato, and the MSPF treatment had the minimum observed TN. The average TN during spring and autumn decreased by 2.42% and 3.16%, respectively, under the MSPF treatment compared with the DIPF treatment. In addition, they decreased by 12.50% and 10.50%, respectively, under the MSPF treatment compared with the MSI treatment. The results of this experiment showed that the MSPF treatment significantly enhanced MBN, especially at 72 and 110 d after tomato transplantation.

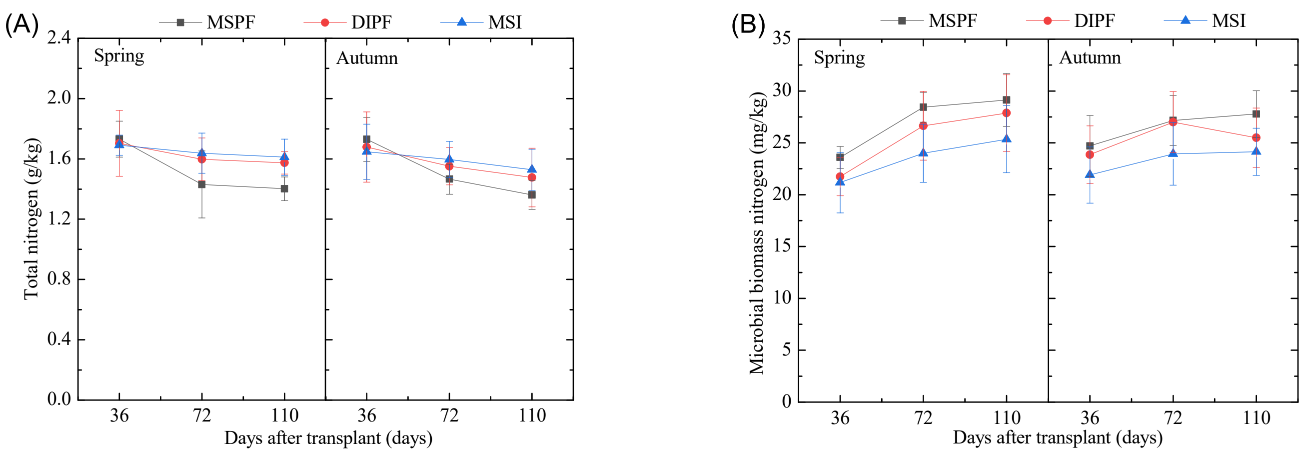

Figure 4. Response of soil total nitrogen (**A**) and soil microbial biomass nitrogen (**B**) to irrigation strategy and plastic film mulching during spring and autumn season.

3.3. Effects of Irrigation Strategy and Plastic Film Mulching on Urease and Leucine Aminopeptidase Activities in Greenhouse Tomato Rhizosphere Soil

Figure 5 shows the rhizosphere UR and LAP activities under different irrigation strategies during both spring and autumn. Both UR and LAP first increased and then decreased with the age of the plants, whereas UR and LAP reached their maximum at 72 d after tomato transplantation. The results showed that PF mulching could increase the activities of both UR and LAP. The UR activity during spring was significantly higher than that during autumn at 72 and 110 d after tomato transplantation. The average value of UR during spring and autumn increased by 13.72% and 8.27%, respectively, under the MSPF treatment compared with the DIPF treatment. In addition, they increased by 24.02% and 24.04%, respectively, under the MSPF treatment compared with the MSI treatment. The average value of LAP during spring and autumn increased by 1.66% and 5.21%, respectively, under the MSPF treatment compared with the DIPF treatment. In addition, it increased by 13.69% and 12.88%, respectively, under the MSPF treatment compared with the MSI treatment.

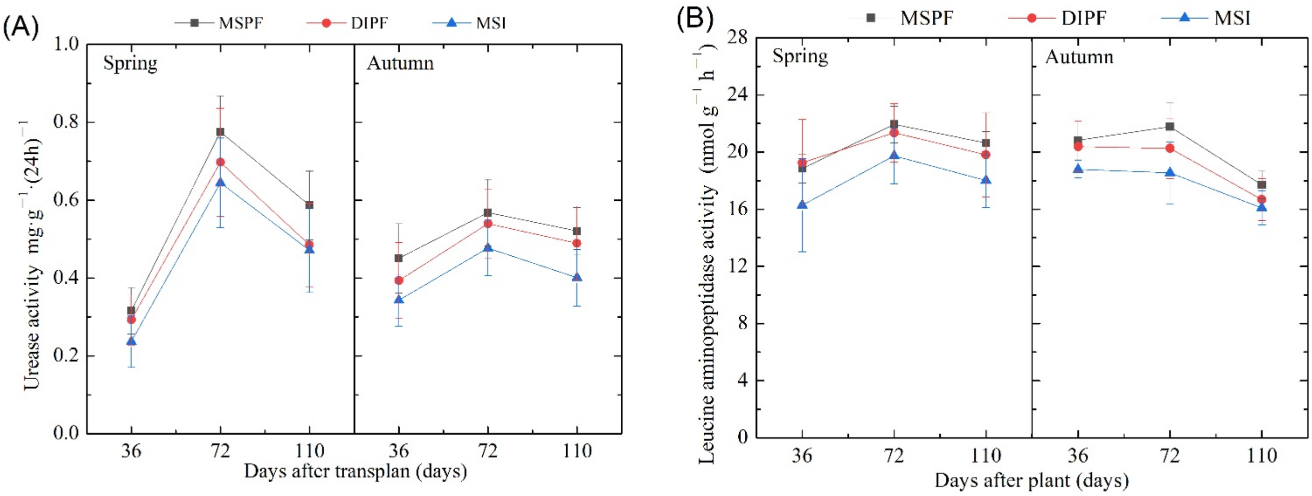

Figure 5. Rhizosphere soil urease (**A**) and leucine aminopeptidase (**B**) activities under different irrigation strategies.

3.4. Effects of Irrigation Strategy and Plastic Film Mulching on N_2O Emissions

Figure 6 shows the effects of the irrigation strategy and PF mulching on N_2O emissions. Throughout the spring growth period, the overall N_2O emissions exhibited a trend of first increasing and then decreasing, reaching a maximum at 72 d after transplant. Nevertheless, during the autumn, the N_2O emissions decreased with the age of the plants, reaching a maximum at 20 d after transplant. As shown in Figure 6, the N_2O emission rate of spring tomato in the greenhouse was greater than that in autumn. PF mulching significantly increased N_2O emissions, whereas the N_2O emission rate reached a maximum under the DIPF treatment and a minimum under the MSI treatment. During the spring growing season, the average N_2O emission rate decreased by 4.50% under the MSPF treatment compared with the DIPF treatment, but increased by 24.31% compared with the MSI treatment. During the autumn growing season, the average N_2O emission rate decreased by 4.43% under the MSPF treatment compared with the DIPF treatment, but increased by 22.99% compared with the MSI treatment.

3.5. Effects of Irrigation Strategy and Plastic Film Mulching on the nirS-Type Denitrifying Bacterial Community in Tomato Rhizosphere Soil

As shown in Table 2, we analyzed the diversity indices of the denitrifying bacterial community under different treatments. The results showed that irrigation strategy and PF mulching had a significant impact on the ACE, Chao richness indices, and Sobs and Shannon diversity indices of the rhizosphere-denitrifying bacteria. The ACE, Chao, Sobs and Shannon indices for the MSI treatment were lower than those for the MSPF and DIPF treatments (Table 2). However, there were no significant differences in any of the diversity indices of denitrifying bacteria between the MSPF and DIPF treatments. In addition, the ANOVA F values for the main effects showed that the Sobs, Shannon, and ACE indices during spring were more significant than those during autumn. The results indicate that PF mulching significantly improved the denitrifying bacterial community and that the irrigation strategy had no significant effect on the denitrifying bacterial community.

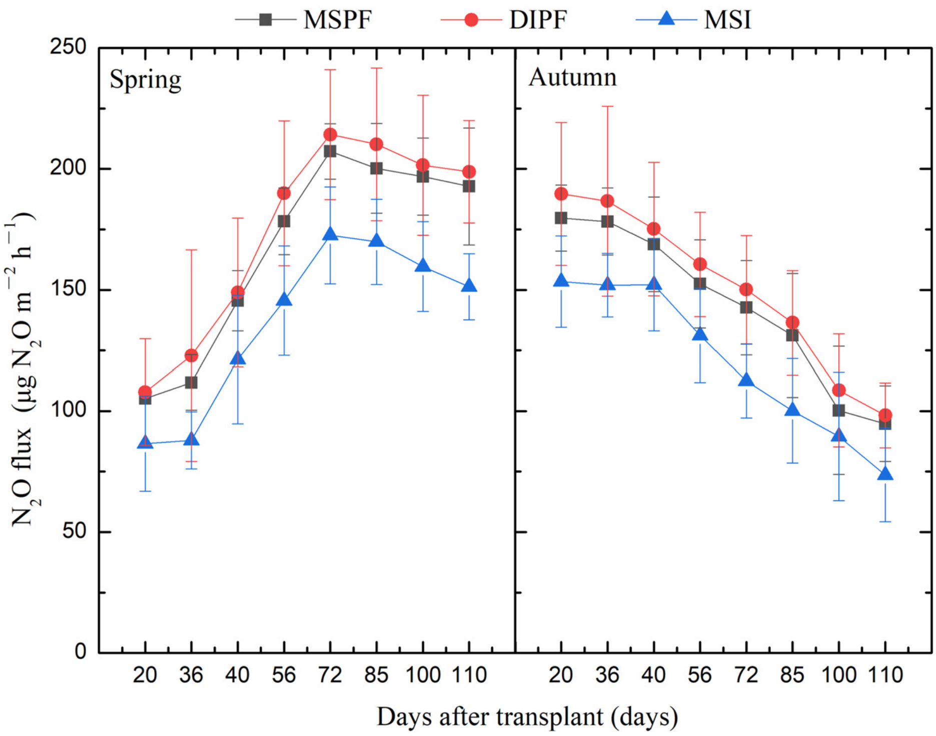

Figure 6. N_2O emission rate in response to irrigation strategy and plastic film mulching.

Table 2. Diversity indices of the denitrifying bacterial community under different irrigation strategies and PF mulching.

Growing Season	Treatment	Sobs	Shannon	Simpson	Ace	Chao	Coverage
Spring	MSPF	440.333 ± 18.009 a	4.074 ± 0.066 ab	0.044 ± 0.008 a	549.428 ± 19.646 a	531.713 ± 11.074 a	0.9921 ± 0.001 a
	DIPF	463.667 ± 58.347 a	4.192 ± 0.334 a	0.039 ± 0.014 a	560.432 ± 69.79 a	545.986 ± 69.462 a	0.9921 ± 0.002 a
	MSI	316 ± 35.679 b	3.67 ± 0.258 b	0.059 ± 0.015 a	409.457 ± 52.667 b	402.954 ± 52.067 b	0.9925 ± 0.0015 a
	F-value	11.339 **	3.694 **	2.008 ns	7.940 *	7.294 *	0.091 ns
Autumn	MSPF	449 ± 101.946 a	3.616 ± 0.468 ab	0.072 ± 0.023 a	574.282 ± 112.76 a	548.788 ± 109.586 a	0.9927 ± 0.0009 ab
	DIPF	504 ± 106.86 a	3.947 ± 0.364 a	0.057 ± 0.031 a	603.154 ± 116.073 a	585.874 ± 110.158 a	0.9918 ± 0.0006 b
	MSI	236 ± 41.761 b	2.801 ± 0.485 b	0.176 ± 0.094 a	335.344 ± 123.487 b	297.574 ± 72.131 b	0.9946 ± 0.002 a
	F-value	7.655 *	5.340 *	3.675 ns	4.693 *	7.544 *	3.589 ns

Note: The values with the same letter within rows are statistically non-significant by Duncan's test at $p < 5\%$. ns, not significant. * ANOVA F value for main effect was not significant or significant at ≤5% level; ** ANOVA F value for main effect was not significant or significant at ≤1% level.

Venn diagrams were constructed to examine unique and shared operational taxonomic units (OTUs) of denitrifying bacteria among the different irrigation treatments during both seasons (Figure 7). In general, the shared OTUs accounted for 26.72% and 42.78% of the total OTUs in the rhizosphere soil for all the treatments during spring and autumn, respectively, which illustrated that some of the *nirS*-type denitrifying bacteria were able to exist in all the treatments in each soil. During the spring, the number of unique OTUs in the MSPF, DIPF, and MSI treatments was 13.40%, 23.08% and 3.89% of the total OTUs in the soil samples, respectively. During the autumn, these values were 8.87%, 12.17% and 3.30%, respectively. Additionally, 23.66% and 20.25% of the OTUs in the soil samples were common to both the MSPF and the DIPF treatments during spring and autumn, respectively. The results indicate that a large number of bacteria coexisted under the PF mulching treatment.

As shown in Figure 8, we analyzed the microbial composition of *nirS*-type denitrifying bacteria under different irrigation treatments at the phylum and class classification levels. Proteobacteria accounted for 6.43–24.83% of the community abundance at the phylum level, and the DIPF treatment resulted in higher Proteobacteria richness than that in the MSPF and MSI treatments during both seasons. The dominant bacterial classes found in the analyzed rhizosphere soil were unclassified_k__norank_d__Bacteria, unclassified_p__Proteobacteria, Alphaproteobacteria, Betaproteobacteria and Gammaproteobacteria. The community abundance of unclassified_p__Proteobacteria in the DIPF treatment was higher than that in the MSPF and MSI treatments. In addition, the abundance of species was higher in spring than autumn, and it was always DIPF that had the higher species abundance (Figure 8C,D).

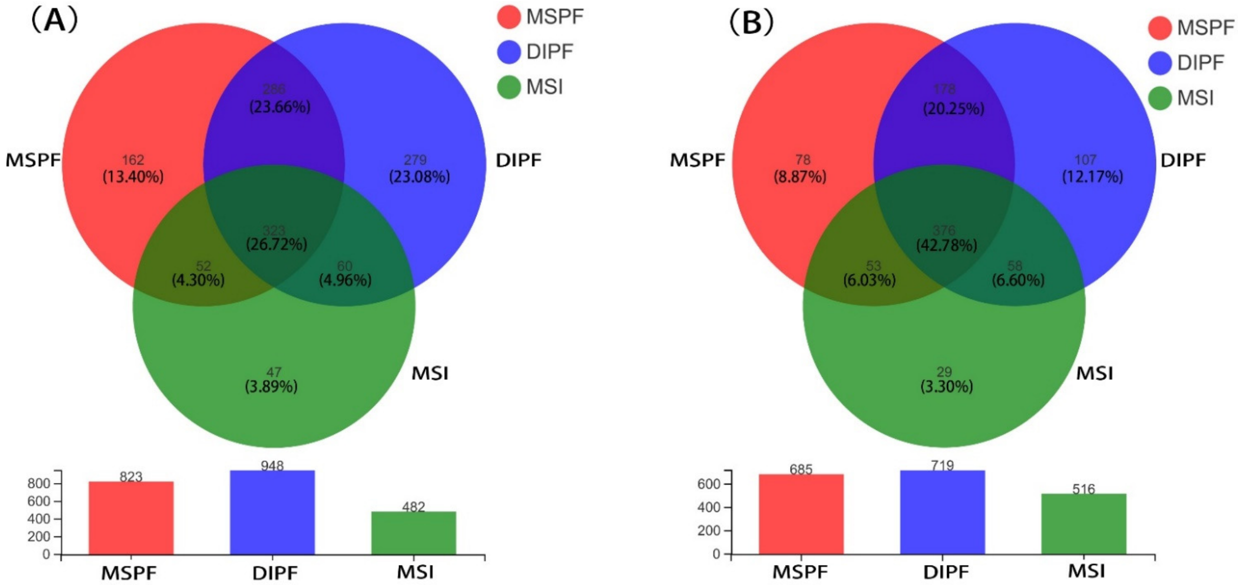

Figure 7. Venn diagram showing the unique and shared *nirS*-type denitrifying bacteria in rhizosphere soil samples at the OTU classification level under different irrigation strategies and PF during spring (**A**) and autumn (**B**).

As shown in Figure 9, during the spring, the contribution rates of the principal components (PCs) PC1 and PC2 to denitrifying bacterial community differences among the different treatments were 49.6% and 42.75%, respectively. Under the PC1 condition in spring, the effects of the DIPF and MSI treatments were similar, whereas the effects of the MSPF treatment were significantly different from those of the other treatments. Under the PC2 condition, the effects of the DIPF and MSPF treatments were similar, whereas the effects of the MSI treatment were significantly different. During autumn, the contribution rates of PC1 and PC2 to denitrifying bacterial community differences among the different treatments were 38.37% and 29.46%, respectively. Under the PC1 condition, the effects of the MSPF and DIPF treatments were similar, whereas the effects of the MSI treatment were significantly different from those of the other treatments. Under the PC2 condition, the effects of the MSI and MSPF treatments were similar, whereas the effects of the DIPF treatment were significantly different.

3.6. Effects of Irrigation Strategy and Plastic Film Mulching on Fruit Yield and Water Use Efficiency of Tomato

The effects of different irrigation strategies and PF mulching on the fruit yield, water consumption and water use efficiency of spring and autumn tomatoes are shown in Table 3. The results showed that different treatments had a significant effect on fruit yield, water consumption and water use efficiency. The fruit yield and water use efficiency in the MSI treatments were significantly lower than those in the MSPF and DIPF treatments during both seasons, and the water consumption was also significantly higher than that of the other treatments. During the spring, although water consumption was higher under the MSPF treatment than under the DIPF treatment, the fruit yield was higher than that under the DIPF treatment. However, there was no significant difference in water consumption and fruit yield between the MSPF and DIPF treatments in autumn. The results showed that PF mulching could significantly improve water use efficiency and fruit yield.

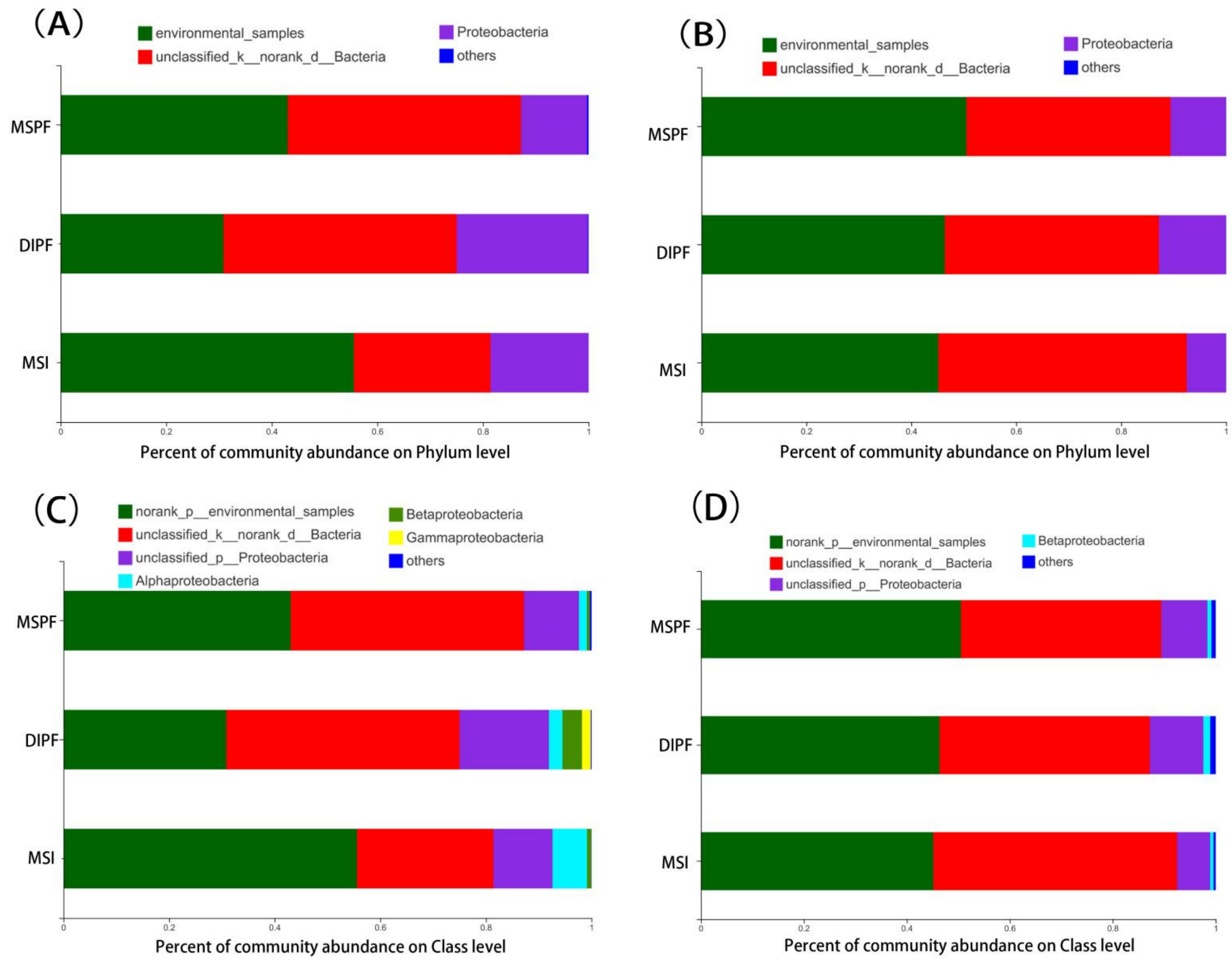

Figure 8. Microbial structure composition of *nirS*-type denitrifying bacteria under different irrigation treatments. Note: (**A**) community structure at the phylum level during spring; (**B**) community structure at the phylum level during autumn; (**C**) community structure at the Class level during spring; (**D**) community structure at the Class level during autumn.

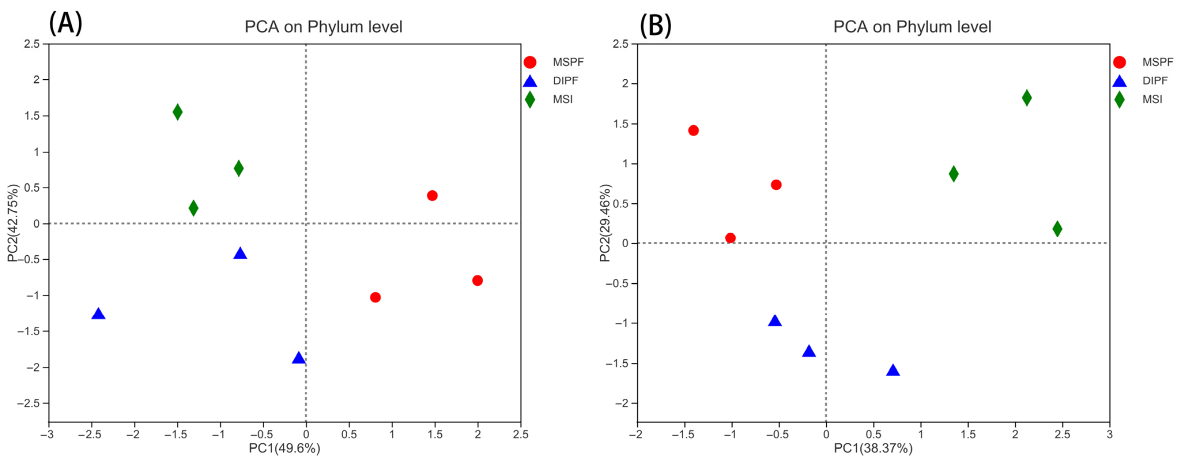

Figure 9. Principal component analysis (PCA) of denitrifying bacterial communities under different irrigation treatments during spring (**A**) and autumn (**B**). The points with the same color and shape indicate replicate samples for each treatment.

Table 3. Effects of different irrigation strategies and PF mulching on the fruit yield and water use efficiency of tomato.

Growing Season	Observation Variable	MSPF	DIPF	MSI	F-Value
Spring	Yield (kg/ha)	119,961.18 ± 15,863.47 a	100,482.01 ± 10,345.32 b	99,582.82 ± 11,169.57 b	9.873 **
	Water consumption (mm)	374.12 ± 15.82 b	344.94 ± 22.42 c	406.69 ± 22 a	27.764 **
	Water use efficiency (kg/m^3)	32.16 ± 4.75 a	29.23 ± 3.38 a	24.54 ± 3.03 b	12.315 **
Autumn	Yield (kg/ha)	97,979.17 ± 12,550.56 a	93,722.22 ± 18,965.42 a	65,659.72 ± 12,688.55 b	16.368 **
	Water consumption (mm)	266.97 ± 7.57 b	260.18 ± 14.67 b	282.85 ± 18.46 a	7.950 **
	Water use efficiency (kg/m^3)	36.73 ± 4.83 a	35.9 ± 6.41 a	23.24 ± 4.51 b	24.249 **

Note: The values with the same letter within rows are statistically non-significant by Duncan's test at $p < 5\%$.
** ANOVA F value for main effect was not significant or significant at ≤1% level.

4. Discussion

4.1. Effect of Irrigation Strategy and Plastic Film Mulching on Soil Water, Temperature and nirS-Type Denitrifying Bacteria Abundances

Soil water is a key factor affecting soil microbial activity, N_2O emissions, and nutrient utilization in farmland [35,36]. The results of this study showed that the MSPF treatment could significantly increase the soil water content at depths of 0–40 cm during spring and improve the uniformity of soil water in the 0–80 cm soil layer (Figure 2). Micro-sprinkler irrigation resulted in a larger surface wet area than that in drip irrigation. In addition, this study found that PF mulching could increase soil moisture at deeper depths (40–80 cm). We speculate that PF mulching significantly reduced the ineffective evaporation of surface soil water, and this phenomenon decreased the migration of water from deep soil to the surface. Therefore, the water content of the deep soil decreased. In this study, PF mulching enhanced the soil temperature at depths of 5–25 cm, and the results were consistent with those of previous studies [37].

The soil microbial community is a major driver of nutrient availability and cycling, and it is well characterized to be influenced by the microenvironment [38]. Different irrigation strategies can alter the soil bacterial community structure and the activity of soil nitrogen [39]. Wu's study confirmed that PF mulching interfered with the complexity of soil bacterial symbiosis networks [40]. Nevertheless, few studies have focused on *nirS*-type denitrifying bacterial communities under different irrigation strategies. In this study, we found that the Sobs, Chao and Ace indices of the rhizosphere denitrifying bacteria under the DIPF and MSPF treatments were significantly higher than those under the MSI treatment. However, there was no significant difference in the diversity indices of the denitrifying bacterial community between the MSPF and DIPF treatments. The Sobs, Chao and Ace indices were reduced by 4.47%, 3.38% and 10.08%, respectively, with the MSPF treatment compared to the DIPF treatment (Table 2). The results indicated that PF mulching was the main influencing factor of the diversity indices of denitrifying bacteria compared with the irrigation strategy. This results indicate that PF mulching has a greater impact on the *nirS*-type denitrifying bacterial community than does the irrigation strategy. Moreover, the results of Venn diagrams strongly support the aforementioned viewpoints, in which a large number of bacteria coexisted under the PF mulching treatments (Figure 7).

4.2. Effects of Irrigation Strategy and Plastic Film Mulching on Soil Enzyme Activities and N_2O Emissions

Soil enzyme activity is proven to be a key indicator of microbial function in the nutrient cycle and is associated with soil quality [41]. As reported in our previous study, soil enzymes are secreted by plant roots and rhizospheric microorganisms [42]. Irrigation strategies and PF mulching inevitably influence the microenvironment, plant roots and rhizospheric microorganisms. UR is an enzyme that catalyzes the hydrolysis of urea, which is related to the transformations of nitrogenous compounds in ammonium. Drought led to a significant decrease in UR activity [43]. It is generally reported that the process of amide-linked polypeptide degradation and nitrogen circulation is controlled by LAP [44]. In the present case, both UR and LAP were significantly increased by the MSPF treatment

(Figure 5). Compared with the MSI treatment, the DIPF treatment also improved enzyme activity, but the effect was not as significant as that of the MSPF treatment (Figure 5). This difference may be because the MSPF treatment improved the soil water content and was uniform in the plough layer, thereby increasing the activities of UR and LAP. The results indicate that PF mulching and micro-sprinkler irrigation could increase the activities of UR and LAP, thereby indirectly accelerating nitrogen cycling.

Nitrification is the main process of N_2O production under aerobic conditions, and the denitrification process dominates N_2O emissions under anaerobic conditions [45]. Irrigation increases the soil water content and displaces gas between soil pores, and this process creates an anaerobic environment for the soil. Furthermore, soil water plays important roles in regulating N_2O to a great extent through substrate mineralization to stimulate microbial activity [46]. The results of this study demonstrate that the N_2O emissions under the MSPF treatment were lower than those under the DIPF treatment (Figure 6). However, no previous reports focused on the N_2O fluxes under the MSPF and DIPF treatments. In terms of irrigation strategy, the flow rate of the MSPF treatment droppers was approximately 45 times higher than that of the DIPF treatment, and the irrigation duration was shorter for the MSPF treatment [47]. Therefore, the ratio of the horizontal to vertical migration distance of soil water increased under the MSPF treatment [47]. In this study, the MSPF treatment decreased the alternate rate of wetting and drying of soil and improved the water distribution uniformity in the 0–80 cm soil layer (Figure 2). Previous studies have confirmed that a relatively stable soil microenvironment can reduce N_2O emissions [35], and alternate wetting and drying irrigation can significantly increase N_2O emissions [48]. Therefore, we speculate that the MSPF treatment results in significantly decreased N_2O emissions through improved water distribution uniformity.

4.3. Effects of Irrigation Strategy and Plastic Film Mulching on Water Use Efficiency, Fruit Yield and Economic Effectiveness

Previous studies showed that both drip irrigation and PF mulching increased fruit yield and water use efficiency [37,39]. In the present case, compared with the MSI treatment, the average soil water content of the MSPF treatment at 0–40 cm increased by 8.30%, and the 5, 15, and 25 cm soil temperatures increased by 3.83%, 5.85% and 1.68%, respectively. The PF mulching treatment could not only restrain water loss caused by water spray atomization but also effectively reduce ineffective water evapotranspiration and increase soil water content. Our results showed that both the MSPF and the DIPF treatments significantly increased fruit yield compared with the MSI treatment (Table 2). This result suggests that fruit yield can be increased by PF mulching. These findings are in line with previous results [37,49]. This is mainly because the soil temperature and soil moisture increased in response to the PF mulching treatment [50]. Furthermore, during the spring and autumn, the fruit yield under the MSPF treatment was increased by 19.39% and 18.21%, respectively, compared with that under the DIPF treatment (Table 2). This result is mainly because the MSPF treatment created a more stable hydrothermal environment for the rhizosphere (Figures 2 and 3). The improved microenvironment under the MSPF treatment increased the MBN (Figure 4), UR and LAP (Figure 5) in the rhizosphere soil. The increased enzyme activity sped up the circulation of nitrogen in the soil and increased production [50].

Based on the local labor price, the labor cost for film mulching in a 50 m long greenhouse is approximately CNY 500. The costs of micro-spraying and drip irrigation pipes are approximately CNY 700 and CNY 1300, respectively. The cost of mulching film is approximately CNY 300. Because the spacing between each plot was quite large, the total fruit yield for each treatment was lower than that under normal cultivation practices. The tomato price can vary greatly from year to year, and the average price over several years was approximately 4.0 CNY/kg. The additional income for each treatment is shown in Table 4. The calculated maximum total income was approximately 19,192 CNY/greenhouse for the MSPF treatment during the spring. The results showed that the comprehensive benefit order for the treatment combination was MSPF > DIPF > MSI. The results showed that both the MSPF and the DIPF treatments could improve the fruit yield of greenhouse tomato differently, but the comprehensive benefit of the MSPF treatment was more profitable than that of the DIPF treatment because of the lower cost of micro-spraying pipes. The MSPF treatment is appropriate for configuring commercially available installation and operation.

Table 4. Economic effectiveness of irrigation strategies and plastic film mulching in each greenhouse.

Growing Season	Treatments	Additional Labor Cost (CNY)	Irrigation Pipe Cost CNY)	Mulching Film Cost (CNY)	Fruit Yield (Kg)	Total Income (CNY)	Additional Cost Compared with MSI (CNY)	Additional Income Compared with MSI (CNY)
Spring	MSPF	500	700	300	4798	19,192	800	4452
	DIPF	500	1300	300	4019	16,076	1400	736
	MSI	0	700	0	3983	15,932	0	1992
Autumn	MSPF	500	700	300	3919	15,676	800	5685
	DIPF	500	1300	300	3749	14,996	1400	4405
	MSI	0	700	0	2626	10,504	0	1313

5. Conclusions

Our results demonstrated the following:

(1) The MSPF treatment could improve the uniformity of soil water in the 0–80 cm soil layer and the water content at 0–40 cm. Film mulching could increase the soil temperature at depths of 5–25 cm.
(2) The MSPF and DIPF treatments could increase microbial nitrogen, promote the activities of rhizosphere UR and LAP, accelerate the turnover of soil nutrients, and increase the N_2O emission rate. However, there were no significant differences between the MSPF and DIPF treatments in terms of the N_2O emissions.
(3) Both the MSPF and the DIPF treatments improved yield and water use efficiency, but there were no significant differences between the MSPF and DIPF treatments.
(4) Both the MSPF and the DIPF treatments could improve tomato fruit yield in greenhouses. MSPF could be used to configure commercially available installation and operation. The comprehensive benefit of MSPF treatment is that it is more profitable than that of DIPF.

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