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Effects of Deficit Mulched Drip Irrigation on Water Productivity of Pepper in a Cold and Arid Environment

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Abstract: To assess the impact of water deficit (WD) under film-mulched drip irrigation on pepper yield and water use efficiency (WUE), a field experiment was conducted with three levels of WD: mild (65%-75% field capacity, FC), moderate (55%-65% FC), and severe (45%-55% FC). WD treatments were applied during the seedling, flowering and fruiting, full fruiting, and late fruiting stages, with full irrigation (75%-85% FC) throughout the growing season serving as the control (CK). Results showed that WD during the flowering and fruiting stages significantly reduced pepper yield by 11.68%-25.56%, fruit number per plant by 18.18%-45.45%, and single fruit weight by 17.33%-19.94% compared to CK. However, moderate WD at the seedling stage and mild or moderate WD at the later fruiting stage significantly improved WUE by 6.25%-11.61% without significantly reducing fruit yield or harvest index relative to CK. The Jensen-based crop water production function revealed that the flowering and fruiting stages, with a water sensitivity index of 0.517, are critical for pepper's water needs, emphasizing the importance of adequate irrigation during this period for higher yields. Thus, water-saving and efficient pepper production can be achieved through deficit irrigation with under-membrane drip irrigation.

Keywords: water deficit; water consumption; water use efficiency; Jensen model

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1. Introduction

Previous research has demonstrated that utilizing deficit drip irrigation beneath plastic film can effectively enhance crop resilience against environmental stresses such as drought, salinity, and low temperatures [1,2]. However, if the regulated deficit irrigation is improperly timed or mismatched with the crop's water sensitivity during specific growth stages, it may severely compromise both yield and quality [3]. Constructing distinct crop water-yield relationships not only facilitates predictions of output under varying irrigation regimes but also quantifies the impact of water availability during different developmental phases on final yield outcomes [4]. Numerous studies have confirmed that both Blank's additive model and Jensen's multiplicative model are effective in estimating crop yields under varying irrigation conditions, while also capturing the effects of water stress during specific growth periods [5].

This study proposes that a well-controlled water deficit may simultaneously enhance water use efficiency (WUE) and boost yield under arid conditions. Accordingly, the study aimed to:

1) Assess the effects of water deficit (WD) on fresh fruit yield and WUE.
2) Evaluate the sensitivity of pepper to water shortage across growth stages using Jensen's water production function.

The findings are expected to inform strategies for water-efficient pepper cultivation in Northwest China.

2. Materials and Methods

2.1. Overview of Experimental Site

The experiment took place in 2016 at the Yimin Irrigation Experiment Station (100°47′ E, 38°35′ N) in Minle County, Gansu Province. The area is characterized by a dry climate with limited water resources and a continental desert-steppe climate. The region receives an average annual rainfall of 183-285 mm, with an average temperature of 6°C, a frost-free period of 140 days, and about 3,000 hours of sunshine annually. The soil in the experimental area has a bulk density of 1.45 g/cm³, a field water capacity (mass moisture content) of 24%, and the groundwater table is located 20 meters below the surface.

2.2. Experimental Design

The study followed a one-way experimental design. The growth stages of pepper were categorized into four fertility periods: the seedling period (11 May to 9 June), the flowering and fruiting period (10 June to 5 July), the fruiting period (6 July to 5 August), and the late fruiting period (6 August to 29 August). Three levels of water deficit were tested: full irrigation (75%-85% of field capacity, FC), mild deficit (65%-75% FC), and moderate deficit (55%-65% FC). Mild and moderate water deficits were applied during the seedling and flowering/fruiting stages, while mild deficits were used during the full and late fruiting stages. The control treatment (CK) received full irrigation (75%-85% FC) throughout the entire growing season. A total of seven treatments were implemented, with three replications per treatment, resulting in 21 plots (each 2.4 m × 6.0 m). When the soil moisture in the plots fell below the lower design threshold, irrigation was applied to raise the moisture level to the upper design limit using under-membrane drip irrigation. The detailed experimental setup is summarized in Table 1.

Table 1. Experimental Design.

Treatment	Relative soil moisture content (% in field capacity, FC)			
	Seedling	Flowering and fruiting	Full fruit	Later fruiting
CK	75-85	75-85	75-85	75-85
SRD-1	65-75	75-85	75-85	75-85
SRD-2	55-65	75-85	75-85	75-85
SRD-3	45-55	75-85	75-85	75-85
BRD-1	75-85	65-75	75-85	75-85
BRD-2	75-85	55-65	75-85	75-85
BRD-3	75-85	45-55	75-85	75-85
ERD-1	75-85	75-85	65-75	75-85
FRD-2	75-85	75-85	55-65	75-85
LRD-1	75-85	75-85	75-85	65-75
LRD-2	75-85	75-85	75-85	55-65

2.3. Measurements and Calculations

2.3.1. Soil Moisture Content

Soil moisture content was measured using the conventional drying method. Samples were taken randomly from the midpoint of the line connecting two consecutive pepper plants in each plot using a soil auger, from the following soil depths: 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, and 50-60 cm. Based on the root distribution of the pepper plants, the 0-30 cm soil layer was considered the primary wet layer for calculating irrigation volumes, while the soil moisture content from the 0-60 cm layer was used to determine crop water consumption. Soil moisture was measured every 10 days after transplanting, and when the moisture level fell below the lower design threshold, irrigation was applied to bring it up to the upper design limit.

2.3.2. Yield

For yield measurement, five uniformly growing pepper plants were randomly selected from each plot and marked. Upon ripening, the fruit yield from these marked plants was recorded, and the average yield per plant was calculated. This was then converted into yield per hectare. The total yield was the sum of the yields from three separate harvests.

2.3.3. Water Use Efficiency

Water use efficiency (WUE) is calculated using the following formula:

$$WUE = \frac{Y}{ET} \quad (1)$$

Where Y is the total fresh fruit yield of pepper (kg hm^{-2}), ET is the total water consumption (mm).

2.3.4. Jensen Model

The Jensen model is internationally recognized as the most widely used crop water production function model. In this study, Jensen model is also used to solve the water production, the Jensen model equation is expressed as below:

$$\frac{Y}{Y_m} = \prod_{i=1}^{n} \left(\frac{ET_{ai}}{ET_{mi}} \right)^{\lambda_i} \quad (2)$$

where Y is the actual yield (t ha^{-1}), Y_m is the maximum yield (t ha^{-1}), ET_{ai} is the code of crop growth period, n is the number of crop growth period, m is the number of water treatments, ET_{ai} is the actual evapotranspiration (mm) and ET_{mi} is the maximum evapotranspiration (mm) in the crop growth period, λ_i is the water sensitive index indicating the response of crop yield to water deficit.

2.4. Statistical Analysis

The data were analyzed using analysis of variance (ANOVA) with the Solutions Statistical Package for the Social Sciences (IBM Inc., Armonk, New York, USA), and mapping was done using Microsoft Excel (Microsoft Corporation Inc., Redmond, Washington, USA). Multiple comparisons were carried out using the Least Significant Difference (LSD) method, and the mean effects were calculated. Differences were considered significant at $P < 0.05$.

3. Results

3.1. Yield and Its Components

3.1.1. Yield

The total fresh fruit yield of pepper was the sum of the yields from three separate harvests. The control treatment with full irrigation produced the highest yield of 36,203.9 kg/hm^2. Various levels of water deficit applied during different growth stages resulted in a decrease in total fresh fruit yield (Table 2). The yields of SRD-1, SRD-2, FRD-1, ERD-1, LRD-1, and LRD-2 were 0.22%, 7.16%, 11.69%, 8.79%, 2.18%, and 2.76% lower than the CK, respectively, but no significant differences ($P > 0.05$) were observed compared to the control. In contrast, the total fresh fruit yield of SRD-3, FRD-2, FRD-3, and ERD-2 were significantly reduced by 13.20%, 13.32%, 17.34%, and 25.56%, respectively, when compared to the CK. These results suggest that while water deficit has a notable impact on pepper yield, applying deficit irrigation at appropriate levels and timings does not cause a drastic reduction in yield.

Table 2. Fruit Yield and Water Use under Different Water Treatment.

Treatment	Fruit number per plant	Single fruit weight (g)	Fresh pepper water content (%)	Yield (kg/hm²)	Total water consumption (mm)	Water use efficiency (kg/hm²·mm)
SRD-1	19abc	53.64a	92.07a	36131.48a	285.59a	129.18cd
SRD-2	18abc	55.45a	92.25a	33022.79abc	259.55bc	143.02a
SRD-3	16bcd	38.19bc	91.93a	29927.59cd	239.10c	142.02a
FRD-1	18abc	51.67a	91.56a	31973.16abc	259.93bc	129.02cd
FRD-2	15cd	38.19cd	91.11ab	31379.76bcd	253.44c	123.30d
FRD-3	12d	35.26d	91.37ab	26951.42d	218.97d	122.86d
ERD-1	20ab	52.78a	90.32bc	33619.64abc	257.74bc	130.32cd
ERD-2	16bcd	43.00bc	89.86c	31425.94bcd	252.17c	133.3bc
LRD-1	20ab	53.41a	90.31bc	35203.75ab	279.24ab	145.90a
LRD-2	18abc	44.15ab	89.89c	35777.66ab	275.77ab	138.9b
CK	22a	44.04bc	92.07a	36203.90a	288.50a	130.73cd

Note: Different lowercase letters indicate significant differences between treatments at $P < 0.05$.

3.1.2. Yield Components

Water-regulated deficit drip irrigation under film had a significant ($P < 0.05$) effect on the fresh fruit number per pepper plant, measured as the total from three pickings (Table 3). As shown in Table 2, the control treatment with full water supply throughout the growing season resulted in the highest fruit number per plant. The fruit numbers in SRD-3, FRD-2, FRD-3, and ERD-2 were significantly lower than CK by 27.27%, 31.82%, 45.46%, and 27.27%, respectively, while no significant differences ($P > 0.05$) were observed for the other water deficit treatments compared to CK. Across all growth stages, mild water deficit significantly increased the single fruit weight by 17.33%-21.80% compared to CK, whereas moderate water deficit led to a significant decrease in fruit weight by 13.28%-19.94%. The moderate water deficit treatment (FRD-2) during the flowering and fruiting stages significantly reduced single fruit weight compared to CK, but no significant differences were found in fruit weight at other stages with moderate water deficit. Moreover, water deficits during the full-fruit and late fruiting stages significantly decreased fresh fruit water content by 1.90%-2.40% compared to CK, while no significant changes in fruit water content were observed during other periods compared to CK.

Table 3. Water Sensitive Index during Different Pepper Growth Periods.

Water sensitive index	Pepper growth period				
	Seedling	flowering and fruiting	Full fruit	Later fruiting	Correlation coefficient
λ	0.219	0.517	0.273	0.157	0.947

3.2. Water Use Efficiency

Water use efficiency (WUE) of pepper represents the fresh fruit yield produced per unit of water consumed (Table 2). Compared to the control (CK), water deficits during the seedling and late fruiting periods enhanced the WUE of pepper. The WUE of CK was

130.73 kg/(hm²·mm), while the WUE of SRD-2, SRD-3, LRD-1, and LRD-2 increased significantly by 9.40%, 8.64%, 9.40%, and 8.64%, respectively ($P < 0.05$). No significant differences ($P > 0.05$) were observed in other water treatments compared to CK. These results suggest that moderate to severe water deficits during the seedling period or mild to moderate deficits during the later fruiting period significantly improve the WUE of pepper.

3.3. Harvest Index

The harvest index (HI) is the ratio of economic yield (such as fruit or grain) to total biological yield at harvest. It reflects the proportion of assimilated carbon allocated from the source (photosynthetic tissues) to the reproductive organs (e.g., fruits or seeds). Water deficit impacted the harvest index of pepper. The treatment with moderate water deficit during the seedling period achieved the highest harvest index (0.68), which was significantly higher than the control ($P < 0.05$). On the other hand, severe water deficit during the flowering and fruit-setting stages resulted in the lowest harvest index (0.38), significantly lower than CK (Figure 1). The harvest indices for SRD-2, ERD-1, SRD-1, LRD-1, and LRD-2 treatments were similar to CK, with no significant differences ($P > 0.05$). The harvest indices for FRD-2, FRD-3, and ERD-2 were significantly lower than CK, while FRD-1 was nearly identical to CK. These findings indicate that the effect of water deficit on the harvest index of pepper is related to both the timing and severity of water deficit under drip irrigation with plastic film. Moderate and severe water deficits during the blossom and fruiting stages significantly reduced the harvest index, while moderate water deficit during the seedling period increased it, suggesting that nutrient allocation to the fruit was promoted under this condition.

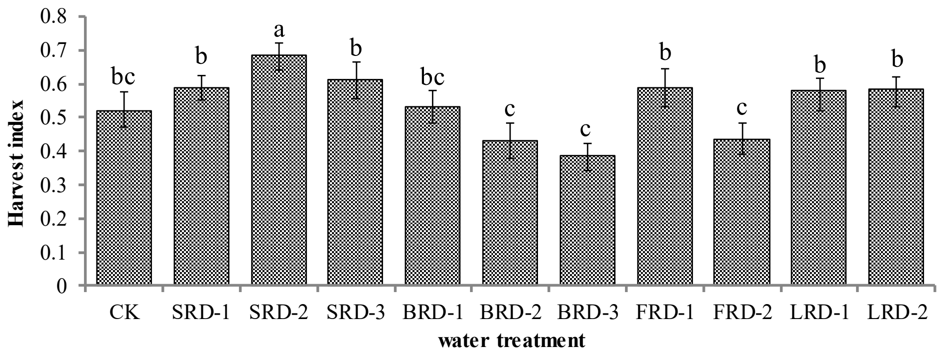

Figure 1. The Effects of Water Deficit on Pepper Harvest Index of Pepper, Different Lowercase Letters Indicate Significant Differences between Treatments at $P < 0.05$.

3.4. Water Production Function of Peppers

The Jensen water production function effectively captures the relationship between fruit yield and water consumption in peppers across different growth stages. The water sensitivity coefficients of pepper ranged from a maximum of 0.517 during the flowering and fruit-setting period to a minimum of 0.157 during the later fruiting period (Table 3). To achieve optimal fruit yield, it is essential to maintain soil moisture in the root zone at 75%-85% of field capacity during the flowering and fruit-bearing stages. Therefore, full irrigation should be applied during these critical periods.

Therefore, the Jensen water production function of pepper can be represented by equation (3) with the water sensitive index solved under the experimental conditions.

$$\frac{Y}{Y_m} = \left(\frac{ET_1}{ET_{m1}}\right)^{0.219} \times \left(\frac{ET_2}{ET_{m2}}\right)^{0.517} \times \left(\frac{ET_3}{ET_{m3}}\right)^{0.271} \times \left(\frac{ET_4}{ET_{m4}}\right)^{0.157} \quad (3)$$

Where the number 1, 2, 3 and 4 represent the four growth periods of pepper, namely, seedling period, blossom and fruit period, full fruit period and later fruit period respectively.

4. Discussion

Water use efficiency (WUE) was evaluated to assess irrigation productivity, a crucial factor in optimizing water use in crop production [6]. In this study, WUE was defined as the net economic yield (fresh fruit) per unit of water consumed by pepper. Previous studies on regulated deficit irrigation (RDI) combined with drip irrigation under mulch for crops such as pepper, potato, and corn have demonstrated that moderate water deficits can reduce water consumption while enhancing WUE [7,8].

The current results show that moderate water deficits during the seedling stage or mild to moderate deficits during the late fruiting stage significantly ($P < 0.05$) reduced water consumption and improved WUE without significantly affecting the fresh fruit yield compared to the control treatment.

Higher irrigation levels near the upper limit of soil moisture were found to enhance fruit-setting rate, early yield, and WUE of pepper [9]. On the other hand, excessive water stress during the flowering and fruit-setting stages of sweet pepper caused significant ($P < 0.05$) flower and fruit drop, leading to a reduced yield [10]. Specifically, moderate to severe water deficits during the flowering and fruit-setting stages resulted in a significant decrease of 13.32% in the number of fruits per plant and a reduction of 13.32% in fresh fruit yield compared to the control. This reduction may be linked to a decrease in pollen quantity and viability due to water shortages during flowering [11].

5. Conclusions

Water deficits during the flowering and fruiting stages led to significant reductions in pepper yield by 11.68%-25.56%, the number of fruits per plant by 18.18%-45.45%, and average fruit weight by 17.33%-19.94% compared to plants receiving full irrigation throughout the growing season. In contrast, moderate water deficits during the seedling stage and mild to moderate deficits during the late fruiting stage increased WUE by 6.25%-11.61%, without a significant reduction in fruit yield or harvest index. The crop water production function, based on the Jensen model, showed that the highest water sensitivity indices occurred during the flowering and fruiting stages, indicating that water stress during this period is particularly harmful to yield formation. Thus, adequate irrigation during these stages is critical for achieving optimal pepper yield.

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