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Effects of Water Deficit on Water Consumption Characteristics of Pepper under Mulched Drip Irrigation in the Hexi Oasis Region

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Abstract: This study examined how varying degrees of water deficit influence the water consumption patterns of pepper under drip irrigation with mulch through a field trial. The experimental design included mild and moderate water deficits during the flowering and fruiting phases, as well as mild deficits during the full fruit and late fruiting stages. A fully irrigated treatment throughout the reproductive stage served as the control (CK). The findings revealed that across treatments, pepper water use characteristics — specifically water consumption modulus, rate, and total consumption — ranked as follows: full fruit stage > late fruiting stage > flowering and fruiting stage > seedling stage. Compared to CK, both water use intensity and total consumption generally declined as the severity of water deficit increased. Notably, mild water limitation at the seedling phase and water stress in the late fruiting stage had little effect on overall water use, whereas other deficit treatments significantly decreased total consumption by 9.90%-24.10% relative to CK. Overall, deficits during the seedling and late fruiting stages minimally influenced total water use, whereas reductions were most pronounced when stress occurred during the flowering and fruiting stage.

Keywords: water deficit; pepper; total water consumption; phasic water consumption; water consumption intensity; water consumption modulus

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1. Introduction

Global water scarcity is intensifying due to rising demand, inadequate management, and increasing pollution. In many regions, the anticipated rise in annual dry days is expected to worsen this challenge [1-3]. Agriculture, particularly irrigated farming, plays a central role in this issue, consuming approximately two-thirds of the freshwater extracted for human use [4]. Within this context, agriculture is often viewed as inefficient, primarily due to low irrigation water use efficiency, defined as the proportion of water effectively utilized by crops relative to the total drawn from sources [2]. As freshwater becomes scarcer and competition from sectors like tourism, industry, and urban expansion intensifies, the value of water continues to grow — especially in areas where these demands coexist [5-9].

In China, where the pace of economic development is accelerating, water shortages pose a serious obstacle to sustainable agricultural growth, particularly in arid northwestern regions [10]. China also leads the world in pepper cultivation area, with roughly 1.33 million hectares planted — about 35% of the global total [11]. However, research remains limited on how water deficits influence the water consumption behavior of pepper crops in the arid northwest. This study addresses that gap by hypothesizing that controlled water deficits, applied under mulch-covered drip irrigation, may significantly alter pepper water usage in such environments. The primary aim was to explore how different growth stages respond to water stress, offering valuable insight into the crop's water consumption dynamics in northwestern China.

2. Materials and Methods

2.1. Overview of the Experimental Site

The experiment was conducted in 2016 at Yimin Irrigation Experiment Station (100°47′ E, 38°35′ N) in Minle County, Gansu Province. The climate in this region is dry, characterized by water scarcity, with a continental desert steppe climate. The annual average temperature is 6℃, the extreme maximum temperature is 37.8℃, the extreme minimum temperature is-33.3℃, the annual total rainfall is 183-285 mm, the frost-free period is 109-174 days, and the annual sunshine duration is about 3000 h. The soil type is light loam, the soil bulk weight is 1.4 t/m^3, the field water capacity is 24% (mass moisture content), and the groundwater level is low, with no salinization.

2.2. Experimental Design

This study adopted a single-factor experimental design. Based on the growth characteristics of pepper, the growing season was divided into four distinct stages: seedling stage (May 11 to June 9), flowering and fruit-setting stage (June 10 to July 5), full fruit stage (July 6 to August 5), and late fruiting stage (August 6 to August 29). Irrigation regimes were categorized into full irrigation (75%-85% of field capacity, FC), mild deficit (65%-75% FC), and moderate deficit (55%-65% FC). Light and moderate water deficits were imposed during the seedling and flowering/fruit-setting stages, while only mild deficits were applied during the full fruit and late fruiting periods. Full irrigation throughout the entire growth cycle served as the control treatment (CK). The experiment included seven treatment combinations, each replicated three times, totaling 21 plots. Each plot measured 2.4 meters by 6.0 meters. Irrigation was triggered when soil moisture dropped below the lower threshold of the designated range, and water was supplied until the upper limit was reached. Drip irrigation under plastic mulch was employed for all treatments. Further details of the experimental setup are presented 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 water content was measured using the standard oven-drying technique. Samples were taken at random locations in each plot using a soil auger, positioned midway between two adjacent pepper plants. Sampling was conducted at six 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 characteristics of pepper, the 0-30 cm depth was identified as the effective irrigation zone for calculating water application, while soil moisture fluctuations within the 0-60 cm profile were used to estimate total crop evapotranspiration. Measurements began after transplanting and were taken every 10 days. Irrigation was carried out whenever soil moisture dropped below the preset lower threshold, replenishing it to the corresponding upper limit.

2.3.2. Pepper Water Consumption

Pepper water consumption was calculated using the water balance method, as shown in the equation below:

$$ET = P + I + K - C + \Delta W \tag{1}$$

Where ET is water consumption (mm), P is precipitation (mm), I is the irrigation amount (mm), K and C are groundwater recharge and deep seepage, respectively, and ΔW represents the change in soil water storage over a period of time.

2.4. Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using the Statistical Package for the Social Sciences (IBM SPSS, Armonk, NY, USA). Graphs were generated in Microsoft Excel (Microsoft, Redmond, WA, USA). To evaluate differences among treatments, the least significant difference (LSD) test was employed for post hoc comparisons. Statistical significance was determined at a threshold of $P < 0.05$.

3. Results

3.1. Temperature and Rainfall during the Pepper Growing Season

3.1.1. Temperature

As shown in Figure 1, the temperature variation during the pepper growth period in the experimental zone was significant. The average temperature throughout the growing season was 16.4 ℃, with a maximum of 33.8 ℃ and a minimum of 0.5 ℃, which occurred during the later fruiting and seedling stages, respectively. The average temperatures during the four growth stages of pepper were 11.9 ℃, 17.9 ℃, 17.9 ℃, and 17.1 ℃, with temperature ranges of 2.8–20.9 ℃, 6.9–18.3 ℃, 17.6–18.3 ℃, and 2.2–17.3 ℃, respectively. These results indicate large temperature fluctuations during the pepper growth period, with frequent alternations between cold and warm conditions in the study region.

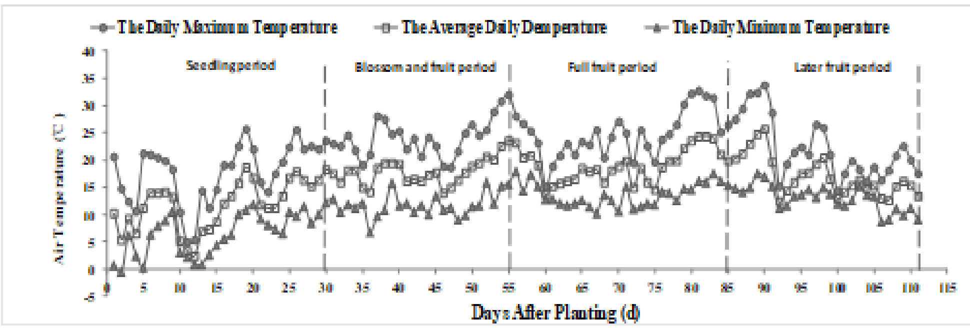

Figure 1. The variation of average temperature during different pepper growth stages.

3.1.2. Rainfall

During the pepper growing season, total rainfall reached 165.6 mm, of which 148.2 mm was considered effective precipitation (i.e., exceeding 5 mm per event) (Figure 2). The rainfall distribution across different growth periods was as follows: 20.8 mm during the seedling stage, 6.1 mm in the flowering and fruiting stage, 60.9 mm in the full fruit stage, and 75.8 mm during the later fruiting stage. These amounts represented 13.77%, 3.68%, 36.78%, and 45.77% of the total rainfall, respectively. This pattern suggests that precipitation was heavily concentrated in early July and from mid to late August, aligning with the critical stages of fruit development and ripening. As such, maintaining effective drainage during these periods is essential to ensure healthy pepper growth.

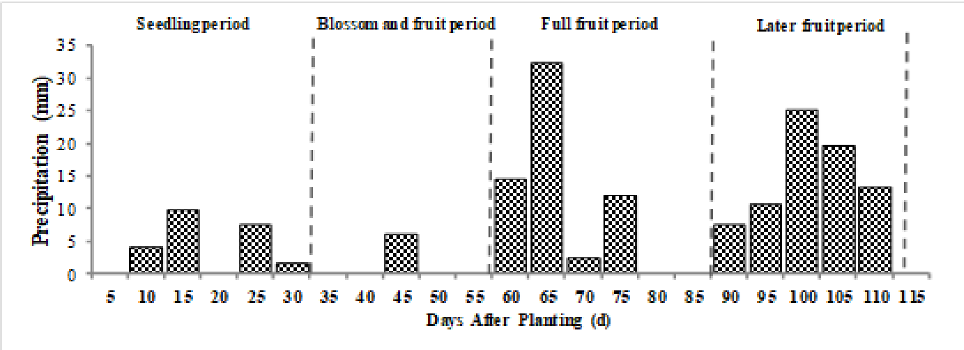

Figure 2. The precipitation distribution during different pepper growth stages.

3.2. Water Consumption Characteristics of Pepper

3.2.1. Total Water Consumption

Water deficits had a significant impact ($P < 0.05$) on the total water consumption of pepper throughout the growth cycle under drip irrigation conditions (Table 2). The control group (CK) recorded the highest overall water usage at 288.50 mm. Treatments SRD-1, LRD-1, and LRD-2 showed slightly reduced water consumption compared to CK, by 1.01%, 3.21%, and 4.41%, respectively, though these reductions were not statistically significant. On the other hand, the treatments FRD-1, SRD-2, ERD-1, FRD-2, ERD-2, SRD-3, and FRD-3 demonstrated significantly lower total water consumption than CK, with reductions of 9.90%, 10.03%, 10.66%, 12.15%, 10.66%, 17.12%, and 14.10%, respectively..

Table 2. The water consumption, intensity of water consumption and water consumption modulus in different pepper growth periods.

	Seedling			Flowering and fruiting			Full fruit			Later fruiting			
Treatment	WC (mm)	IWC (mm/d)	WCM (%)	WC (mm)	IWC (mm/d)	WCM (%)	WC (mm)	IWC (mm/d)	WCM (%)	WC (mm)	IWC (mm/d)	WCM (%)	Total
SRD-1	43.90a	1.47a	15.71de	62.16a	2.39a	21.77c	103.78a	3.34a	36.34ab	75.74a	3.03a	26.52abc	285.59a
SRD-2	39.37b	1.31b	16.86bc	55.72bc	2.14bc	21.47cd	94.41b	3.04b	36.37ab	70.05ab	2.80ab	26.99a	259.55bc
SRD-3	35.28c	1.18c	17.93b	51.82c	1.99c	21.67c	87.61b	2.82b	36.64ab	64.39bc	2.58bc	26.93a	239.10c
FRD-1	41.99ab	1.4ab	16.09cde	55.06bc	2.12bc	21.18cd	93.45b	3.02b	35.98bc	69.42ab	2.78ab	26.74ab	259.93bc
FRD-2	45.54a	1.52a	17.99b	52.08c	2.00c	20.56de	89.30b	2.88b	35.22bc	66.53bc	2.66bc	26.22ab	253.44c
FRD-3	45.60a	1.52a	20.94a	47.54d	1.67d	19.86e	74.22c	2.39c	33.85c	55.61d	2.23d	25.35de	218.97d
ERD-1	43.49ab	1.45ab	16.05cde	59.37ab	2.28ab	22.99b	88.35b	2.85b	34.37cd	66.53bc	2.66bc	25.78bcd	257.74bc
ERD-2	45.20a	1.51a	16.51cd	63.16a	2.43a	25.05a	79.40c	2.56c	31.47d	64.41bc	2.58bc	25.55cd	252.17c
LRD-1	44.82a	1.49a	15.38de	61.57a	2.37a	22.04c	102.72a	3.31a	36.79ab	70.13ab	2.80b	25.12e	279.24ab
LRD-2	45.54a	1.52a	15.17de	63.41a	2.44a	22.99b	105.22a	3.40a	38.16a	61.61c	2.47c	22.34f	275.77ab
CK	45.32a	1.51a	14.76d	62.52a	2.41a	21.67c	104.84a	3.38a	36.34ab	75.82a	3.03a	26.28ab	288.50a

Note: Different lowercase letters indicate significant differences between treatments at $P < 0.05$. WC, water consumption; IWC, intensity of water consumption; WCM, water consumption modulus.

3.2.2. Water Consumption at Different Growth Stages

Among all growth stages, the full fruit stage exhibited the highest water consumption across treatments, with each exceeding 74.22 mm (Table 2). Compared to CK, all stages under water deficit conditions showed a decline in water use, with the extent of reduction intensifying as the severity of the deficit increased. The lowest water consumption, 45.32 mm, occurred during the seedling stage, where mild and moderate deficits led to reductions of 2.65% and 13.25%, respectively, relative to CK. In contrast, even during the full fruit stage — the peak water demand period — mild and moderate deficit treatments (maximum 75.82 mm) resulted in 15.68% and 24.26% lower water consumption than CK. Following re-irrigation, treatments such as SRD-3, FRD-2, FRD-3, ERD-1, and ERD-2 consistently showed significantly ($P < 0.05$) lower water use compared to CK, while other deficit treatments exhibited no statistically significant difference.

3.2.3. Water Consumption Modulus

Under varying deficit conditions, the distribution of water consumption modulus in pepper followed the order: full fruit stage > later fruiting stage > flowering and fruiting stage > seedling stage. During the seedling phase, the FRD-3 group had the highest modulus (20.94%), whereas CK recorded the lowest (15.17%). In comparison to CK, deficit treatments increased the modulus by 27.78%–41.87%. During the flowering and fruiting phase, ERD-2 had the highest water consumption modulus at 25.05%, and other treatments at this stage showed an increase ranging from 6.09% to 8.35% over CK. In the full fruit stage, treatments FRD-3, ERD-1, and ERD-2 saw significant reductions of 6.85%, 5.42%, and 13.40%, respectively, in modulus values compared to CK, while other treatments showed no significant differences. At the later fruiting stage, LRD-1 and LRD-2 treatments exhibited significant decreases of 4.41% and 14.99%, respectively.

3.2.4. Water Consumption Intensity

Pepper's water consumption intensity under different water deficit treatments followed the descending order: full fruit stage (2.39-3.40 mm/day) > later fruiting stage (2.23-3.03 mm/day) > flowering and fruiting stage (1.67-2.44 mm/day) > seedling stage (1.31-1.52 mm/day). During the seedling period, treatments SRD-2 and SRD-23 showed significant reductions in water use intensity by 13.25% and 22.52%, respectively, compared to CK, whereas other deficit treatments showed no notable differences. In the flowering and fruiting phase, FRD-2 and FRD-23 significantly decreased water consumption intensity by 17.01% and 30.71% relative to CK. At the full fruit stage, SRD-1, LRD-1, and LRD-2 treatments exhibited similar water use intensities to CK, while other deficit treatments showed marked reductions ranging from 10.05% to 29.29%. In the later fruiting stage, FRD-1 and LRD-2 had the most pronounced decreases in water consumption intensity, dropping by 26.40% and 18.48%, respectively, when compared with the control group.

4. Discussion

Vegetable crops have high water requirements globally, and implementing deficit irrigation techniques can effectively conserve irrigation water [12]. In this study, it was found that applying water deficits at different growth stages significantly ($P < 0.05$) reduced both total water consumption and water consumption modulus in pepper. Moreover, the more water consumed during a particular stage, the greater the reduction caused by an equivalent deficit. Throughout the pepper growth cycle, water consumption followed a characteristic pattern: initially low during the seedling stage, increasing at the flowering and fruiting stage, peaking during the full fruit period, and then declining in the later fruiting phase. This trend can be attributed to the small plant size and low temperatures during the seedling period, resulting in minimal transpiration. As the crop entered the flowering and fruiting stage, both average daily temperatures and leaf area expanded rapidly, and with low rainfall and dry atmospheric conditions, water demand increased substantially. During the full fruit stage, vegetative growth was nearly complete, fruit development was at its peak, and ambient temperatures were highest, collectively leading to maximum water consumption [13].

5. Conclusions

A mild water deficit applied at the seedling stage (SRD-1) and water deficits imposed during the later fruiting stage (LRD-1 and LRD-2) did not significantly impact the total water usage of pepper plants. In contrast, all other deficit irrigation treatments led to notable reductions in water consumption, ranging from 9.90% to 24.10% compared with the control group (CK). Regardless of treatment, the distribution of water use across growth stages consistently followed the sequence: full fruit > later fruiting > flowering and fruiting > seedling stage. Specifically, the water consumption modulus surpassed 31.47%, 22.34%, 20.56%, and 14.76% at each respective stage. In general, water restriction reduced stage-specific water use, with minimal reductions observed when deficits occurred during the seedling or later fruiting periods, and the most substantial decreases recorded during the flowering and fruiting stage.

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