Article

2025 International Conference on Agricultural Sciences, Economics, Biomedical and Environmental Sciences (SEMBE 2025)

Response of Pepper Growth to Water Deficit in a Cold and Arid Environment

Hengjia Zhang [1,*], Shijie Wang [2,3], Xietian Chen [1,2,3] and Haiyan Li [2]

[1] College of Agriculture and Biology, Liaocheng University, Liaocheng, Shandong, 252059, China
[2] College of Water Conservancy and Hydropower Engineering, Gansu Agricultural University, Lanzhou, Gansu, 730070, China
[3] Yimin Irrigation Experimental Station, Hongshui River Management Office, Zhangye, Gansu, 734500, China
* Correspondence: Hengjia Zhang, College of Agriculture and Biology, Liaocheng University, Liaocheng, Shandong, 252059, China

Abstract: To assess the response of chilli growth and dry matter to water deficit in sub-film drip irrigation, a field experiment was conducted in a cold and arid region of Northwest China in 2016. The experiment was designed with three water deficit (WD) levels: mild deficit (65%-75% in the field capacity, FC), medium deficit (55%-65% in FC) and severe (45%-55% in FC). Water deficit treatments were applied during the seedling, flowering and fruiting, full fruiting, and later fruiting stages. Full irrigation (75%-85% of field capacity) throughout the entire growing season was used as the control (CK). The results showed that different WD at seedling, flowering and fruiting, and full fruit of pepper significantly ($P < 0.05$) decreased plant height, stem diameter and leaf area index than CK. WD applied either at the seedling stage or during the flowering and fruiting stage decreased the above-ground biomass and root mass. Additionally, the reduction in aboveground biomass and root mass became more significant as the severity of WD increased.

Keywords: water deficit; pepper; plant height; stem diameter; leaf area index; dry matter accumulation; root-shoot ratio

Received: 03 March 2025
Revised: 09 March 2025
Accepted: 15 April 2025
Published: 13 May 2025

1. Introduction

Pepper (Capsicum annuum L.) is a spice crop that is widely grown throughout the world for its nutritional value and delicious taste [1]. However, due to the scarcity and uneven temporal and spatial distribution of water resources, agricultural economic losses from crop water stress ranked first among all abiotic stresses. Therefore, the development of agricultural water-saving technologies is considered an important direction for improving agricultural sustainability in China [2,3].

Numerous studies have confirmed that agricultural water use efficiency can be significantly enhanced through techniques such as drip irrigation, mulching, and conservation tillage, primarily by minimizing water losses from runoff and evapotranspiration [4-6]. Despite these benefits, the adoption rate of current drip irrigation systems remains relatively low, indicating room for further improvements through the implementation of more advanced irrigation methods. Among these, deficit irrigation strategies stand out for their potential to conserve water resources while sustaining crop yield and enhancing both water use efficiency and fruit quality. This method has already been successfully employed in the cultivation of various horticultural crops, including grapevines, orchard fruits, and certain vegetables [7-9]. Nevertheless, when it comes to leafy vegetables, the effectiveness of deficit irrigation remains less well established compared to its application in fruit crops [5]. Even so, the strategy becomes increasingly viable due to its benefits in water conservation, enhanced nitrogen utilization, reduced nutrient and pesticide leaching, and cost efficiency under rising water prices [10].

A more integrated solution — known as drip irrigation under mulch with regulated deficit irrigation (RDI) — combines subsurface drip irrigation with Israeli-style plastic mulching and RDI principles. This composite technology optimizes water application by delivering controlled irrigation beneath the film, thereby achieving more efficient water and fertilizer use, increased yield, and better economic returns than conventional deficit irrigation methods. In the present research, we assessed how varying levels of water deficit across different growth stages influence pepper plant development, specifically examining parameters such as plant height, stem thickness, leaf area index, and dry matter accumulation. The findings aim to support the development of optimized irrigation regimes and promote the practical application of regulated deficit irrigation in pepper production.

2. Materials and Methods

2.1. Overview of Experimental Site

The field experiment took place between March and September 2016 at the Yimin Irrigation Experimental Station, located in Minle County, Gansu Province, northwestern China (longitude 100°47′ E, latitude 38°35′ N). The site experiences a temperate continental climate, with an annual mean temperature of approximately 6°C. Solar radiation ranges from 558.6 to 672 kJ cm^{-2}, while the yearly precipitation averages between 183 and 285 mm. The site also exhibits high evaporation levels, with pan evaporation (uncorrected by pan coefficient) reaching around 2048 mm annually. The accumulated temperature above 10°C varies between 183 and 2870°C, and the region has an average frost-free period of roughly 165 days. The groundwater table lies deeper than 20 meters. The experimental soil, classified as loam, has a bulk density of 1.45 g cm^{-3} within the top 60 cm. This soil layer is composed of 12.5 g kg^{-1} of total organic matter, 0.88 g kg^{-1} each of total nitrogen and phosphate, and 13.97 g kg^{-1} of potassium. Additionally, it contains 64.33 mg kg^{-1} of available nitrogen and 97 mg kg^{-1} of available phosphorus.

2.2. Experimental Design and Field Management

The pepper variety "Jinjiao No. 6" was selected in the experiment. It was cultivated in the greenhouse on March 20, 2016, and the seedlings were transplanted on May 11. The seedling height was approximately 15 cm, with a row spacing of 45 cm and a planting distance of 35 cm. The ridges were made artificially Artificial ridges 80 cm wide were constructed, and sufficient sulfur-based NPK compound fertilizer was applied into two shallow ditches, each located 5 cm from the center of the ridge. In order to discharge the excessive accumulated filed water caused by rainfall as soon as possible, which would seep into the soil and influence the control of field soil water content, then A drip irrigation belt was installed along the center of each ridge, with emitters spaced 30 cm apart and an average flow rate of 2.5 L/h per emitter. The sides of the ridges were 10 cm high, while the center of each ridge was raised to 13 cm. Each plot was separated by a furrow in which a 60-cm-wide plastic film was vertically embedded below the bottom. Each furrow was constructed as a drainage ditch with a width of 40 cm and a depth of 15 cm.

The experiment was conducted in a one-way randomized block design with each plot size of 14.4 m^2 (2.4 m×6 m). To prevent horizontal permeation of soil water Each plot was isolated by embedding plastic film vertically to a depth of 2 meters in the soil profile. According to growing characteristics, the whole pepper growth period can be divided into four periods: seedling (May 11 to June 9), flowering and fruiting (June 10 to July 5), full fruit (July 6 to Aug 5) and later fruiting (August 6 to August 29) stages. Soil moisture was controlled by four levels, namely, full irrigation (75%-85% in field capacity, FC) mild water deficit: (65%-75% in FC), moderate water deficit: (55%-65% in FC) and severe water deficit (45%-55% in FC). In the first two growth stages, three levels of water deficit (mild, moderate, and severe) were applied. In the last two stages, only mild and moderate water deficits were implemented. Full irrigation was used throughout the growth period in the control treatment (CK). Therefore, a total of 11 water treatments were set up and each treatment included three replications. The design of soil water content in each treatment during the different pepper growth periods are shown 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

Following transplantation, five pepper plants were randomly chosen and tagged in each plot to monitor changes in plant height and leaf area throughout the various growth stages. Plant height and stem diameter were recorded at the conclusion of each stage using a steel tape (±1 mm accuracy) and a vernier caliper (±0.02 mm accuracy), respectively. The leaf area index was estimated using the coefficient method, which relies on actual measurements of leaf dimensions. Additionally, five plants were randomly sampled from each plot at the end of each growth period for biomass analysis. These samples were separated into roots, stems, leaves, and fruits, after which each component was oven-dried — initially at 105°C for one hour, followed by further drying at 85°C for eight hours. The final dry mass of each organ was then measured and recorded.

2.4. Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) using the Statistical Package for the Social Sciences (SPSS; IBM Corp., Armonk, NY, USA). Graphical representations were created using Microsoft Excel (Microsoft Corp., Redmond, WA, USA). To identify statistically significant differences among treatment means, the least significant difference (LSD) method was applied for multiple comparisons. Statistical significance was considered at the level of $P < 0.05$.

3. Results

3.1. Plant Height

The plant height in control group remained the highest level at the whole pepper growth period and growth rate of plant height in different growth period were in descending order, it goes: in descending order: flowering and fruiting, seedling, full fruit, and later fruiting periods, in which the plant height growth were 19.14 cm, 13.13 cm, 7.10

cm and 3.35 cm, respectively (Table 2). Water deficits during the seedling and flowering-fruit setting periods significantly inhibited plant height ($P < 0.05$), with greater water deficits leading to smaller plant heights compared to the control. During the full fruit period, plant height under mild water deficit showed no significant difference ($P > 0.05$) compared to the control, while moderate and severe deficits significantly reduced plant height. It may be mainly because that drought resistance capability of pepper was improved due to root growth. To the later fruiting period, vegetative growth of pepper was basically completed, water deficit for this period had no significant effect on pepper plant height, and the pepper with mild water deficit at seedling period had the same level of plant height with controls, This suggests that compensatory growth may have occurred after rewatering, particularly when mild water deficit was applied during the seedling stage.

Table 2. The Variation of Pepper Plant Height (CM) during the Whole Growth Period.

Treatment	Pepper growth period			
	Seedling	Flowering and fruiting	Full fruit	Later fruiting
SRD-1	19.43b	40.07ab	48.33ab	51.37a
SRD-2	17.23bc	34.73c	41.98b	44.90b
SRD-3	16.17c	27.17d	32.34c	33.80c
BRD-1	23.47a	39.23b	45.51b	48.10b
BRD-2	23.70a	35.40bc	42.03b	44.37b
BRD-3	24.47a	26.27d	31.43c	33.37c
FRD-1	24.47a	43.71a	48.26ab	50.23a
FRD-2	24.47a	45.21a	45.22b	46.87b
LRD-1	24.47a	46.33a	53.48a	54.22a
LRD-2	24.47a	45.23a	52.64a	53.67a
CK	25.13a	44.27a	51.37a	54.73a

Note: Different Lowercase Letters Indicate Significant Differences between Treatments at $P < 0.05$, the Same Below.

3.2. Stem Diameter

During the growth period the pepper stem diameter was increasing and the greatest increase in stem diameter was 5.19 mm during the full fruit period, flowering fruit-bearing period take second with stem diameter growth of 3.24 mm (Table 3). seedling period and later fruit period were 1.66 mm and 1.95 mm, respectively. At the whole pepper period, the stem diameter of control treatment remained the highest level. Stem diameter was all significantly ($P < 0.05$) less than control when water deficit was composed at seedling, flowering and fruit period and full fruit period, respectively and the stem diameter decreased with the increase of degree of water deficit. But water deficit had no significant ($P > 0.05$) influence on pepper stem diameter at later fruiting period. In the end of pepper growth period, pepper stem diameter in treatments with mild water deficit at seedling period and mild or moderate water deficit at later fruiting period were no significant difference with controls. Nevertheless, stem diameter of pepper in the other water deficit water treatment were significantly less than the control. Therefore, it showed that if water deficit applied at seedling period, blossom and fruit period or full fruit period, pepper stem growth would be affected greatly.

Table 3. The Variation of Pepper Stem Diameter (MM) during the Whole Growth Period.

Treatment	Pepper growth period			
	Seedling	Flowering and fruiting	Full fruit	Later fruiting
SRD-1	5.08b	8.34 ab	13.38ab	15.25ab
SRD-2	4.51c	7.67b	12.73b	14.60b
SRD-3	4.21c	6.39c	10.72c	12.59c

FRD-1	5.55a	6.97b	12.07b	13.24bc
FRD-2	5.67a	6.62c	11.23c	12.62c
FRD-3	5.57a	6.14d	9.57d	10.77d
ERD-1	5.54a	8.82a	12.24b	15.67ab
ERD-2	5.62a	8.86a	10.84c	13.22b
LRD-1	5.58a	8.78a	14.52a	15.67a
LRD-2	5.46a	8.86a	14.23a	15.23ab
CK	5.68a	8.92a	14.11a	16.06a

3.3. Leaf Area Index

Pepper leaf area index (LAI) refers to the ratio of pepper leaf area to the ground area it covers. At the time of transplanting, the average leaf area index (LAI) of pepper across all test plots was approximately 0.054, and the LAI in each water treatment was increasing with the growth of pepper (Table 4). Throughout the pepper growth period, the LAI under the control treatment remained the highest. All water deficit treatments, except those with mild water deficit, had significantly lower LAI values than the control ($P < 0.05$). And The reduction in LAI became more pronounced with increasing severity of water deficit. By the end of the pepper growth period, treatments with mild water deficit applied during the seedling and later fruiting stages showed LAI values comparable to the control. In the end of growth period, the LIA in treatments with mild water deficit at seedling period and later fruiting period respectively were in the highest level with control and had no significant difference ($P > 0.05$) compared with the control. However, the LAI in the treatments with severe deficit at flowering fruit-setting period and moderate water deficit at full fruit period were in the lowest level LAI at the lowest levels and significantly less than other treatments. The rest of LAI of other water deficit treatment were all at the same level and had no significant difference with each other. These results indicate that water deficits at different growth stages inhibited pepper leaf development. Rewatering after applying mild water deficit during the seedling stage led to compensatory growth, resulting in LAI levels similar to the control at maturity.

Table 4. The Variation of Pepper Leaf Area Index (CM^2/CM^2) during the Whole Growth Period.

Treatment	Pepper growth period			
	Seedling	Flowering and fruiting	Full fruit	Later fruiting
SRD-1	0.098b	0.468b	0.981a	1.203a
SRD-2	0.082bc	0.393c	0.854b	0.986b
SRD-3	0.070c	0.365c	0.755b	0.897b
FRD-1	0.113a	0.454b	0.823b	0.864b
FRD-2	0.117a	0.366b	0.700b	0.855b
FRD-3	0.119a	0.316d	0.515c	0.623c
ERD-1	0.112a	0.508a	0.788b	0.812b
ERD-2	0.115a	0.512a	0.622c	0.656c
LRD-1	0.117a	0.503a	1.045a	1.227a
LRD-2	0.116a	0.498a	0.987a	1.056b
CK	0.120a	0.518a	1.145a	1.277a

3.4. Dry Matter Accumulation

The pepper dry matter was studied only during seedling period and blossom and fruit period considering the influences caused by the picking of fruit both at full fruit period and later fruit period. Water deficit at seedling period and blossom and fruit period make the dry biomass of both above-ground parts and roots decreased, and the dry biomass decreased with increase in the degree of water deficit (Figure 1). At seedling period, the ground biomass in treatments under mild, moderate and severe water deficit were significantly (P < 0.05) less than control by 17.21%, 40.32% and 56.42%, respectively, and root dry weight were significantly decreased by 10.88%, 10.88% and 50.42%, respectively. Therefore, it showed that ground biomass decreased more than root biomass at the same degree of water deficit. At blossom and fruit period, the mild, moderate and severe water deficit decreased ground biomass by 23.47%, 53.48% and 68.32% respectively compared with the control, and root dry weight decreased by 12.20%, 35.70%, and 57.23%, respectively. This indicates that water deficits during the flowering and fruit-setting stage reduced both shoot and root biomass more severely than similar deficits during the seedling stage. As a consequence, the water deficit at blossom and fruit period had greater influence on the accumulation in dry mater of pepper.

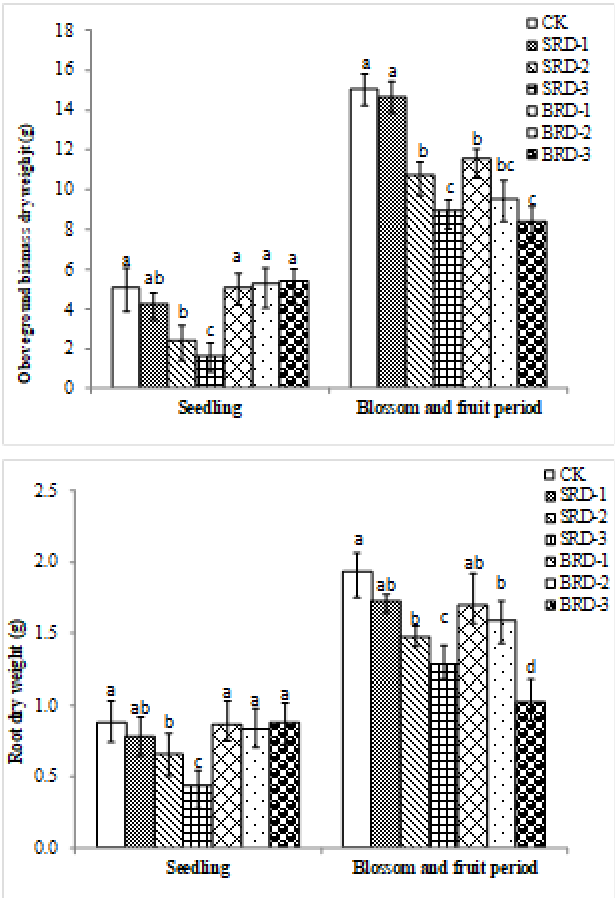

Figure 1. Effect of Water Deficit on the Dry Matter of Chilli Peppers, Different Lowercase Letters Indicate Significant Differences between Treatments at P < 0.05.

3.5. Root-Shoot Ratio

The root-shoot ratios of pepper were also studied only during seedling period and blossom and fruit period considering the influences caused by the picking of fruit both at full fruit period and later fruiting period. At the seedling stage, the root-shoot ratios under different water treatments were all above 0.23, and higher than those observed at the flowering and fruit-setting stage, due to the rapid growth of above-ground biomass during the latter (Figure 2). Water deficit at both seedling period and blossom and fruit period can significantly (P < 0.05) influence pepper root-shoot ratio. Compared with sufficient water treatment (CK, for example), a certain degree of water deficit at both seedling period and blossom and fruit period increased pepper root-shoot ratio. At seedling period, root-shoot ratio in water deficit treatments were significantly greater than the control, with SRD-2 showing the highest value, significantly greater than both SRD-1 and SRD-3, but there was no significant (P > 0.05) difference between SRD-1 and SRD-3. At blossom and fruit period, the root-shoot ratio of FRD-1 and FRD-2 were significantly greater than CK, but there was no significant difference between FRD-3 and CK. At the end of blossom and fruit period, the root-shoot ratio of SRD-2, FRD-1 and FRD-2 were significantly greater than CK, SRD-2 and FRD-1 had similar values, both significantly higher than FRD-2, and there were no significant difference among the rest of water treatments. This showed that moderate water stress during the seedling or flowering stage was beneficial to the improvement of the root-shoot ratio of pepper, especially the moderate water stress in seedling period and mild water stress at blossom and fruit period enhanced root-shoot ratio significantly, which may enhance the pepper plant's resistance to later-stage drought and improve nutrient uptake.

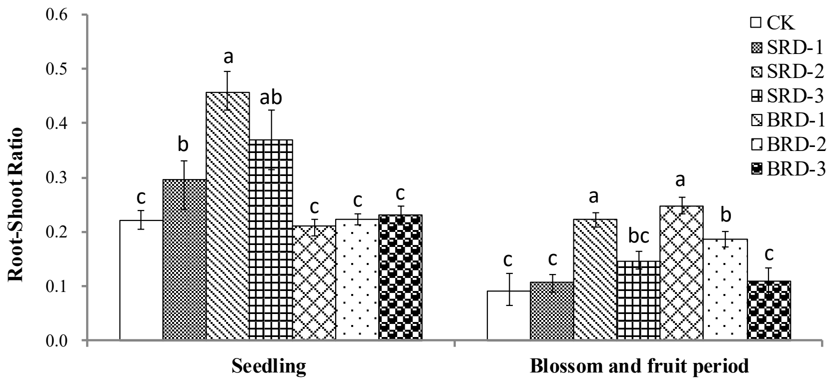

Figure 2. The Effects of Water Deficit on Root-Shoot Ratio of Pepper. Different Lowercase Letters Indicate Significant Differences between Treatments at P < 0.05.

4. Discussion

Plant height, stem diameter, leaf area and biomass of pepper all presented a trend of decline with increase in degree of drought stress, but growth indicators such as plant height and stem diameter approached the values under full irrigation due to the compensatory growth effect after rewatering of pepper after rewatering [11]. The results showed that different extents of water deficit during the seedling period, blossom and fruit period and full fruit all resulted in the significant (P < 0.05) drops of pepper plant height, stem diameter and leaf area index and these declines became more pronounced as the severity of water deficit increased.

According to the balance theory of root-shoot, both root and shoot are interdependent and competitive. Under certain environmental conditions, the root-shoot ratio has a relatively stable range determined by the crop's genetic characteristics. When environmental conditions change, roots and shoots compete for resources, and plants can automatically allocate the obtained nutrients to the organs that can best alleviate resource stress [12]. Mahmood et al. showed that water at the seedling stage of pepper could stimulate the growth of pepper root, especially the growth of taproot, and increase the absorption and synthesis capacity of the root [13]. The results of this study showed that after water stress at seedling stage and flowering stage, the root-shoot ratio of pepper increased compared with the control group, especially at seedling stage, the root-shoot ratio of pepper under different water stress treatment was significantly higher than CK.

5. Conclusions

Under the conditions of drip irrigation under film, the plant height, stem diameter and leaf area index under full irrigation were always at the highest level. Plant height, stem diameter, and leaf area index decreased significantly under water deficit at the seedling, flowering and fruiting, and full fruiting stages, and the higher the water deficit, the greater the decrease. In addition, with the increase of water deficit, the decrease of aboveground and root biomass increased at both seedling and flowering stages. In addition, water deficit significantly affected the root-shoot ratio of pepper, but moderate water deficit during the seedling stage significantly increased the root-shoot ratio, which may enhance the plant's drought resilience and nutrient uptake capacity.

Funding: This work was mutually supported by the National Natural Science Foundation of China (No. 52269008, 51669001), the Industrial Support Plan Project of Gansu Provincial Department of Education (No. 2022CYZC-51), the Key Research and Planning Projects of Gansu Province (No. 18YF1NA073), the Scientific Research Foundation for High-level Talented Scholars (No. 318042401) of Liaocheng Universtiy, and the Open Project of Liaocheng Universtiy Landscape Architecture Discipline (No. 31946221236).

References

1. Z. Zou and X. Zou, "Geographical and ecological differences in pepper cultivation and consumption in China," *Front. Nutr.*, vol. 8, p. 718517, 2021, doi: 10.3389/fnut.2021.718517.
2. H. Wang, C. Liu, and L. Zhang, "Water-saving agriculture in China: an overview," *Adv. Agron.*, vol. 75, pp. 135–171, 2002, doi: 10.1016/S0065-2113(02)75004-9.
3. L. Zhao, L. Zhang, N. Cui, C. Liang, and Y. Feng, "The evaluation of regional water-saving irrigation development level in humid regions of Southern China," *Water*, vol. 11, no. 1, p. 172, 2019, doi: 10.3390/w11010172.
4. C. Stanghellini, F. L. K. Kempkes, and P. Knies, "Enhancing environmental quality in agricultural systems," *Acta Hortic.*, vol. 609, pp. 277–283, Jul. 2003, doi: 10.17660/ActaHortic.2003.609.41.
5. H. G. Jones, "Irrigation scheduling: advantages and pitfalls of plant-based methods," *J. Exp. Bot.*, vol. 55, no. 407, pp. 2427–2436, 2004, doi: 10.1093/jxb/erh213.
6. H. Kirnak and M. N. Demirtas, "Effects of different irrigation regimes and mulches on yield and macronutrition levels of drip-irrigated cucumber under open field conditions," *J. Plant Nutr.*, vol. 29, no. 9, pp. 1675–1690, 2006, doi: 10.1080/01904160600851619.
7. I. Goodwin and A. M. Boland, "Scheduling deficit irrigation of fruit trees for optimizing water use efficiency," in *Deficit Irrigation Practices*, 2002. ISBN: 9251047685.
8. S. Kang and J. Zhang, "Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency," *J. Exp. Bot.*, vol. 55, no. 407, pp. 2437–2446, 2004, doi: 10.1093/jxb/erh249.
9. B. A. Bravdo, "Physiological mechanisms involved in the production of non-hydraulic root signals by partial rootzone drying—A review," in *VII Int. Symp. Grapevine Physiol. Biotechnol.*, *Acta Hortic.*, vol. 689, pp. 267–276, Jun. 2005, doi: 10.17660/ActaHortic.2005.689.31.
10. E. Fereres and M. A. Soriano, "Deficit irrigation for reducing agricultural water use," *J. Exp. Bot.*, vol. 58, no. 2, pp. 147–159, 2007, doi: 10.1093/jxb/erl165.
11. M. Celebi, "The effects of water stress on yield performance of drip-irrigated pepper (*Capsicum annum* L. cv. Capya var. Yalova yağlık 28) in the Central Anatolian region of Turkey," *Arab. J. Geosci.*, vol. 11, no. 23, p. 758, 2018, doi: 10.1007/s12517-018-4086-1.
12. A. M. Boland, P. D. Mitchell, P. H. Jerie, and I. Goodwin, "The effect of regulated deficit irrigation on tree water use and growth of peach," *J. Hortic. Sci.*, vol. 68, no. 2, pp. 261–274, 1993, doi: 10.1080/00221589.1993.11516351.
13. T. Mahmood, R. M. Rana, S. Ahmar, S. Saeed, A. Gulzar, M. A. Khan, F. M. Wattoo, X. Wang, F. Branca, F. Mora-Poblete, et al., "Effect of drought stress on capsaicin and antioxidant contents in pepper genotypes at reproductive stage," *Plants*, vol. 10, no. 7, p. 1286, 2021, doi: 10.3390/plants10071286.