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Research Paper

Irrigation water requirement of drip irrigated tomato and capsicum under controlled and open-field environments

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ABSTRACT

Freshwater scarcity poses a major challenge for Indian agriculture. This study presents an optimized irrigation scheduling framework for tomato and capsicum cultivation under protected and open-field conditions in Jalandhar, Punjab, over the 2021 and 2022 seasons. The CROPWAT model was used to estimate reference evapotranspiration (ETo) and irrigation needs. Results showed that ETo and ETc values were consistently lower under protected cultivation due to microclimatic control, reducing irrigation requirements by up to 27% compared to open-field cultivation. Water use efficiency and yields improved significantly under protected cultivation, with increases of 96% and 43% for tomato, and 92.8% and 40% for capsicum. This study demonstrates that optimized irrigation scheduling and protected cultivation can conserve freshwater and enhance agricultural sustainability in water-limited regions like Punjab.

Keywords: Drip irrigation, Open field cultivation (OFC), Protected field cultivation (PFC), Crop evapotranspiration (ETc), Reference evapotranspiration (ETo), Vegetable crops.

India is facing growing freshwater scarcity, which is severely impacting its agricultural sector. As water is a critical resource for crop irrigation (Sharma and Singh, 2022), optimizing irrigation management has become crucial in regions with limited water availability. In Punjab, groundwater contamination with heavy metals has further restricted its suitability for agriculture. The increase in the number of tube wells in Punjab from 1.07 million in 2000-01 to 1.47 million in 2018-19 can be referenced from the Central Ground Water Board (CGWB) report on groundwater resources and irrigation in Punjab (Anonymous, 2022a). Currently, 95% of groundwater extracted in Punjab is used for irrigation, but excessive extraction is unsustainable, particularly for vegetable crops (Anonymous, 2022b). Drip irrigation has emerged as an efficient technique to optimize water use in vegetable production under water-limited conditions (Sharma *et al.,* 2023). This system enhances water-use efficiency by maintaining higher soil moisture levels, which reduces water stress during key plant processes such as photosynthesis (Saxena *et al.,* 2020; Garg *et al.,* 2022). Effective irrigation scheduling, which involves determining the optimal timing and amount of water to be applied, is essential for maximizing water-use efficiency in drip irrigation systems (Sharma *et al.,* 2021). Although the benefits of irrigation scheduling are well-recognized, research remains limited on its application for vegetable crops under both open-field and protected conditions. Given the rising demand for vegetables like tomato and capsicum, it is vital to assess how different cultivation techniques specifically open-field and protected cultivation can contribute to optimized water use and improved agricultural sustainability. By focusing on water-use efficiency, this study aims to develop an optimized irrigation scheduling framework for drip irrigation in Jalandhar, Punjab, based on crop water requirements under both protected and open-field conditions. This research specifically seeks to demonstrate how optimized irrigation strategies can reduce water consumption while enhancing productivity, contributing to sustainable agricultural practices in water-scarce regions.

MATERIAL AND METHODS

The study was conducted at Lovely Professional University, Jalandhar, Punjab, over a growing season (June to September) during two consecutive years 2021 and 2022, with the aim of developing irrigation scheduling for different vegetable crops, specifically tomato and capsicum. The experimental site is situated

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at latitude of 31.25° N, a longitude of 75.70° E, and an altitude of 280 meters above mean sea level. The study area features a uniform topography with a gentle slope and adequate drainage facilities. The climate of the experimental site is subtropical, characterized by prolonged hot winds during the summer, with high temperatures persisting both day and night.

Experimental details

To evaluate the performance of drip-irrigated tomato and capsicum crops during the study period, a field experiment was conducted from June 25 to September 30 in both 2021 and 2022. The primary objective was to evaluate the effectiveness of the developed irrigation scheduling framework and its suitability for future agricultural applications. The experiment was carried out under two cultivation systems: Open Field Cultivation (OFC) and Protected Field Cultivation (PFC), both of which were subjected to a randomized block design (RBD) with eight replications per system, ensuring statistically robust results. Healthy seedlings were transplanted on June 25 in both years. Each seedling was established on raised beds designed for optimal irrigation and root development. The dimensions of each raised bed were 20 meters in length and 80 centimeters in top width, with a height of 30 cm to improve drainage and soil aeration. The transplanting was performed at a plant spacing of 25 cm between plants within rows and 25 cm between rows, which resulted in a uniform plant density conducive to optimal growth and resource utilization. Drip irrigation lines were installed along the beds to facilitate precise and efficient water application. Each raised bed was equipped with two parallel drip lines, spaced 30 cm apart, to ensure uniform water distribution across the root zone. The drip lines were fitted with online emitters, each with a discharge rate of 2 L h^{-1}. In the protected cultivation system, UV-stabilized naturally ventilated poly house was employed to shield the crops from environmental stress, thereby simulating a controlled growing environment. Conversely, the open field cultivation plots were exposed to natural environmental conditions, allowing for comparative analysis of the crops' performance under varying climatic stressors. The recommended dose of fertilizer was supplied to both crops through drip fertigation in equal splits at 4-day time interval.

Micro climatic control and data collection in PFC

In the PFC system, a thermal net was deployed daily to regulate temperature, with automatic misting-controlled hourly by a digital cyclic timer to maintain humidity and temperature. Digital temperature and humidity meters were installed at multiple locations within the structure to monitor real-time microclimatic conditions. Irrigation was scheduled based on real-time climatic data and applied daily through a drip irrigation system to meet the crop's estimated water requirement. While in OFC system, irrigation was scheduled using weather data from the Jalandhar station, provided by regional station of Punjab Agricultural University, Ludhiana.

Irrigation water requirement

According to Sharma *et al.,* (2023), the irrigation water requirement is fundamentally governed by daily reference evapotranspiration (ETo) and subsequent crop evapotranspiration (ETc). To calculate ETo for both protected and open field cultivation systems, the CROPWAT model was employed on a daily basis. In this model, ETo was automatically computed using the standard equation presented by Allen *et al.,* (1998). Daily reference evapotranspiration (ETo) and crop coefficient (Kc) values were utilized to calculate crop evapotranspiration (ETc) using the following equation. The calculated ETc was then used to estimate the daily irrigation water requirement, following the relationship provided by Sharma *et al.,* (2023):

$$IWR = ETc \times Wp \times A$$

Where,

$$ETc = ETo \times Kc$$

IWR = Irrigation water requirement (liter $plant^{-1}$ day^{-1}), ETc = Crop evapotranspiration (mm day^{-1}), ET_o = reference evapotranspiration (mm day^{-1}), Kc = Crop coefficient, Wp = Wetting fraction (taken as 1 for most cases in close growing crops), A = Plant area, m^2 (i.e. spacing between rows, m x spacing between plants, m).

Growth, yield and quality parameters

Data on plant height, number of fruits per plant, yield were collected from five randomly selected plants in each replication at the time of harvesting. This sampling method ensured a representative assessment of crop performance under both cultivation systems. Water use efficiency (WUE) was calculated as the ratio of yield to the total amount of irrigation water applied. TSS content was determined using a handheld digital refractometer. Tomato juice was extracted by crushing the fruit, and a few drops of the juice were placed on the refractometer prism. The TSS value was recorded as °Brix. Ascorbic acid and Lycopene content were measured by using standard methods i.e. 2,6-dichlorophenolindophenol (DCPIP) titration method and method of extraction with hexane.

Data were analyzed using ANOVA through the CVSTAT tool, an MS Excel-based utility developed in 2007 for analyzing field experiments in designs like Randomized Block Design (RBD), Split Plot Design (SPD), and factorial RBD.

RESULTS AND DISCUSSION

The growth stage-specific, simulated average daily reference evapotranspiration (ET_0) values calculated using the CROPWAT model under both protected (controlled environment) and open-field conditions are shown in Table 1. The mean data indicate that the ET_0 values ranged from 4.1 to 6.4 mm day^{-1} under protected cultivation and from 6.3 to 8.2 mm day^{-1} in open-field cultivation. The highest ET_0 values were recorded in the open field throughout the growing season, consistent with the results reported by Abdrabbo (2001). During the mid-growth stage, the ET_0 values reached their peak, with 6.25 mm day^{-1} under protected cultivation and 8.2 mm day^{-1} in the open field. The average daily reference evapotranspiration (ET_0) during different growth stages was consistently lower under protected cultivation compared to open-field conditions. Previous studies have demonstrated that ET_0 inside greenhouses is generally lower, accounting for approximately 45% of the values observed in open-field conditions (Fernandez *et al.,* 2010).

Table 1: Average daily reference evapotranspiration (ETo) and crop evapotranspiration (ETc) under protected field cultivation (PFC) and open field cultivation (OFC)

Growth stages	ETo (mm day^{-1})						ETc (mm day^{-1})			
	PFC			OFC			Tomato		Capsicum	
	2021	2022	Mean	2021	2022	Mean	PFC	OFC	PFC	OFC
Initial	4.10	4.90	4.50	6.90	7.40	7.15	2.70	4.29	2.25	3.58
Development	5.40	5.80	5.60	7.70	7.40	7.55	3.64	4.91	3.47	4.68
Mid	6.10	6.40	6.25	8.10	8.30	8.20	7.19	9.43	6.56	8.61
Late	4.10	4.20	4.15	5.90	6.70	6.30	3.32	5.04	3.53	5.36

Table 2: Irrigation water requirement of selected vegetable crops grown open under poly house and field condition

Growing Months	Average irrigation water requirement (l plant^{-1} day^{-1})			
	Tomato		Capsicum	
	Open field	Protected	Open field	Protected
Initial	0.97	0.61	0.80	0.51
Development	1.10	0.82	1.05	0.78
Mid	2.12	1.62	1.94	1.48
Late	1.13	0.75	1.20	0.79
Total (l plant^{-1} season^{-1})	159.4	117.1	141.4	103.8

According to the mean data, the average daily ETc values for tomato ranged from 2.7 to 7.1 mm day^{-1} under protected cultivation and from 4.2 to 9.4 mm day^{-1} in open fields (Table 1). For capsicum, ETc values ranged from 2.2 to 6.5 mm day^{-1} under protected conditions and from 3.5 to 8.6 mm day^{-1} in open-field cultivation. The study revealed significant variation in ETc across different growth stages, with the highest values occurring during the mid-growth stage, which corresponds to the period of rapid crop development and increased transpiration rates. The ETc for capsicum was slightly lower than that for tomato across all growth stages, a trend influenced by multiple factors, including environmental conditions and crop-specific traits. Key determinants of ETc, such as crop growth stage and canopy coverage, affect water requirements, emphasizing the need for crop-specific irrigation scheduling.

The total irrigation water requirement for tomato over the entire growing period was estimated at 117.1 liters plant^{-1} under protected cultivation, compared to 159.4 liters plant^{-1} in open-field conditions, as presented in Table 2. Therefore, the implementation of crop-specific irrigation management practices, tailored to meet water requirements at each developmental phase, is crucial for optimizing water use efficiency and ensuring sustainable vegetable production, especially in water-scarce regions. This variation is likely due to the fact that tomatoes require significant water for optimal vegetative and reproductive development, and local weather parameters influence irrigation water requirements. Additionally, factors such as crop variety, season, and cultivation method also play a role. In capsicum cultivation, the total water requirement was similarly lower in protected cultivation (103.8 liters plant^{-1}) compared to open field conditions (144.1 liters plant^{-1}). The variation in irrigation water requirements between protected and open cultivation is attributed to the controlled microclimatic conditions in protected cultivation, where factors such as air temperature and relative humidity are partially regulated by natural ventilation and shading nets on the polyhouse surface.

This study demonstrates that vegetable crops grown under protected field cultivation can achieve significant water savings of 26-27% compared to open-field cultivation. These findings align with previous research highlighting the water-saving advantages of protected cultivation. Studies in Mediterranean climates have reported similar reductions in water use, ranging from 20-30% for crops such as tomatoes and cucumbers (Fernandez *et al.,* 2018). Additionally, Rathore *et al.,* (2017) found a 25% reduction in water use for capsicum cultivated under polyhouse conditions in semi-arid regions of India, further supporting the results of the current study. Sagar and Singh (2019) have also reported that water requirements in an open environment were approximately 30% higher than those in a polyhouse, a finding corroborated by Santosh *et al.,* (2017). Future research should aim to extend these findings to other crops and regions to further explore the effectiveness of protected cultivation in mitigating water scarcity. Numerous studies have recommended an alternate-day irrigation schedule for drip-irrigated vegetable crops in semi-arid regions (Kumar and Gupta, 2020). However, the findings from this study indicate that when irrigation is applied on an alternate-day basis (i.e., 60 irrigation events over a crop cycle of 120 days), the total operational time of the drip irrigation system under protected cultivation is consistently lower compared to that in open-field cultivation for all vegetable crops.

Performance of crops under protected and open field conditions

Protected cultivation techniques significantly enhanced plant growth, crop yield, and water use efficiency for both tomato and capsicum compared to open-field cultivation (Table 3). For tomato, lycopene content and total soluble solids (TSS) remained similar under both cultivation methods, indicating minimal influence of microclimatic variations on these parameters. However, ascorbic acid content in tomato was notably higher under protected cultivation (14.1 mg 100 g^{-1}) than in open fields, likely due to the impact of controlled environmental factors like light intensity on its biosynthesis. Crop yields and water use efficiency were

Table 3: Response of different crop to developed irrigation scheduling under protected and open field conditions (on polled data basis).

Parameters	OFC	PFC	F-Test (p=0.05)	LSD	CV (%)
Tomato					
Plant height (cm)	60	141	S	23	8.4
Number of marketable fruits plant^{-1}	15	27	-	-	-
Lycopene content (mg 100 g^{-1})	8.5	8.3	NS	0.1	6.2
TSS °B	4.47^{a}	4.46^{a}	NS	0.03	4.1
Ascorbic acid (mg 100 g^{-1})	14.1^{a}	12.2^{b}	S	0.8	6.8
Crop yield (t ha^{-1})	51	73	S	12.1	7.6
Total irrigation water applied (mm)	753.2	545.2	S	-	-
Irrigation water use efficiency (t ha^{-1}-cm)	0.677	1.33	S	0.30	-
Irrigation water saving over OFC (%)		26			
Capsicum					
Plant height (cm)	87	126	S	18	6.7
Number of fruits plant^{-1}	9	16	S	3.2	4.8
Crop yield (t ha^{-1})	35	49	S	9.1	7.8
Total irrigation water applied (mm)	695.8	504.4	S	-	-
Irrigation water use efficiency (t ha^{-1}-cm)	0.503	0.97		0.21	-
Irrigation water saving over OFC (%)		27			

OFC: Open field condition; PFC: Protected field condition; Similar letters with in a column do not differ significantly by Fischer T-test ($p \leq 0.05$)

maximized under protected conditions, with tomato yields reaching 73 t ha^{-1} and capsicum 49 t ha^{-1}, alongside water use efficiencies of 1.33 and 0.97 t ha^{-1}-cm, respectively. Protected cultivation also reduced irrigation water requirements by 27%, improving water savings and efficiency by up to 92 to 96%. These improvements are attributed to optimized microclimatic conditions within protected structures, which enhance production and photo assimilate allocation. Additionally, the greenhouse effect and consistent soil moisture levels in protected environments reduce heat and water stress, resulting in higher yields and better resource use efficiency compared to open-field systems. A comparative analysis of crop performance under Open Field Cultivation (OFC) and Protected Field Cultivation (PFC) revealed significant differences in growth, yield, and resource efficiency. Under PFC, where environmental factors like temperature, humidity, and light are regulated, crops showed improved growth metrics, including increased plant height, number of marketable fruits, and overall yield for both tomato and capsicum. Water use efficiency was notably higher in PFC due to reduced irrigation needs and minimized evaporation. Nutritional content was largely similar between systems, with lycopene and total soluble solids (TSS) remaining stable. However, ascorbic acid levels in tomatoes were higher in OFC, possibly due to stress-induced nutrient enhancement.

These results demonstrate the effectiveness of protected cultivation in enhancing crop yield and optimizing water use, making it a viable option for sustainable agriculture, particularly in water-scarce regions like Jalandhar and other parts of Punjab. Further research is recommended to refine irrigation practices for different seasons under both cultivation methods.

CONCLUSION

The study found that average daily reference evapotranspiration (ETo) and crop evapotranspiration (ETc) were consistently lower under protected cultivation (PFC) compared to open-field cultivation (OFC) throughout the growing season of selected vegetable crops. The irrigation scheduling developed indicated that open-field production requires significantly more water than protected environments. Tomatoes and capsicum in PFC realized water savings up to 27% and enhance irrigation water use efficiency by 92 to 96% over OFC in selected study area. Although lycopene and total soluble solids (TSS) remained stable across conditions, tomatoes had higher ascorbic acid content under OFC, likely due to stress-induced metabolic responses. Based on these findings, it is recommended that farmers using drip irrigation systems to irrigate tomato and capsicum crop on alternate days. This strategy enhances water management efficiency, significantly reduces freshwater consumption, and lowers operational costs.

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