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Research Paper

Empirically derived crop coefficient values for tomatoes grown in protected structure under climatic condition of Jalandhar, Punjab

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ABSTRACT

In modern agriculture, calculating the Crop Water Requirement (CWR) for tomato crops under protected cultivation often relies on FAO-56 crop coefficient (Kc) values. However, these values may not fully account for the unique microclimatic variations within protected structures, creating a need for adjusted Kc values. This study aimed to develop growth-stage-specific Kc values for tomatoes grown under protected conditions in Jalandhar, Punjab. Results showed that daily microclimatic parameters, excluding relative humidity, were consistently higher in open-field conditions and lowest within protected environments. Pooled data indicated growth-stage-specific Kc values of 0.51, 1.05, and 0.61 for shed net houses; 0.53, 1.08, and 0.63 for polyhouses with insect net ventilation; and 0.51, 1.10, and 0.67 for open-field conditions, corresponding to the initial, mid, and late growth stages, respectively. Water consumption was highest during the mid-stage, decreasing progressively toward crop maturity. These empirically derived Kc values support precise CWR calculations through climatological irrigation scheduling, benefiting tomato cultivation in protected environments and similar agro-climatic regions. The development of growth-stage-specific Kc values provides a scientific foundation for improving irrigation water management and resource efficiency, offering valuable insights for farmers, policymakers, and water resource planners.

Keywords: Crop coefficient, Protected structures, Crop evapotranspiration, Reference evapotranspiration, and Growth stages.

Greenhouse tomato production provides a means to offer marketable products during periods of low supply (off-season cultivation). Tomato (*Solanum lycopersicum* L.) ranks as the second most popular vegetable crop after potato, with an annual yield of approximately 182.31 million tons across 4.848 million hectares (Anonymous, 2019). As India's population continues to rise, meeting the increasing vegetable demand poses a significant challenge. In this context, protected cultivation techniques are highly effective, as they can significantly enhance vegetable yields per unit of water and land (Singh and Singh, 2021). Given the limited availability of fresh water in India, farmers must adopt water-conserving methods such as drip irrigation within protected structures. Accurate irrigation scheduling relies heavily on understanding the crop's water requirements (Kumar and Haroon, 2021). The crop water requirement (CWR) under protected cultivation differs from that in open field conditions (Sharma and Yadav, 2021). Crop evapotranspiration (ETc) and CWR are influenced by microclimatic parameters and crop characteristics (Satpute *et al.,* 2021). The FAO-Penman-Monteith method is commonly used to estimate reference evapotranspiration (ET_0), which is then utilized to calculate CWR for various crops (Saxena *et al.,* 2020). Accurate determination of ETc using ET_0 and crop coefficients throughout the growing period is crucial for effective irrigation scheduling. Crop coefficient (Kc) is a critical parameter used to estimate crop water use and develop irrigation schedules (Ko *et al.,* 2009). Kc values represent the ratio of actual ETc to ET_0 and are essential for precise irrigation water calculations for different crops across various agro-climatic regions (Doorenbos and Pruitt, 1977). Kc values are influenced by local factors such as climatic conditions, soil characteristics, irrigation methods, and crop management practices (Rana *et al.,* 2014). Numerous studies have explored methods to develop Kc values for crops like pulses, rice, and sunflower in India, and wheat and maize in China (Ko *et al.,* 2009; Liu and Luo, 2010). However, these studies often overlook the variability of local climatic conditions. The traditional approach for determining Kc values involves using lysimeters, a method that is time-consuming and labor-intensive

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(Bhantana and Lazarovitc, 2010). While Doorenbos and Pruitt (1977) have proposed Kc values for various crops, these values may be less effective for irrigation scheduling under specific local conditions in different regions of India. Therefore, these values should only be used as approximations where local Kc data are not available. Allen *et al.,* (1998) emphasize the need for empirically derived Kc values through field experiments tailored to local conditions. Arunadevi *et al.,* (2020) estimated Kc values for capsicum in both protected and open field conditions, noting slight variations in Kc values between these conditions. In India, farmers often use Kc values from the FAO-56 guidelines to calculate CWR for vegetable crops under protected cultivation conditions. However, literature suggests that Kc values for tomato crops should differ between protected and open field conditions. Therefore, this investigation aims to develop region-specific and growth-stage-specific Kc values for tomato crops under both protected and open field cultivation in the Jalandhar region of Punjab.

MATERIALS AND METHODS

Experimental details

The study was conducted at Lovely Professional University, Jalandhar, Punjab, located at latitude 31.25° N, longitude 75.70° E, and an altitude of 280 meters above mean sea level. Tomato crops were cultivated under two types of protected structures: a shade net house and a naturally ventilated polyhouse (NVP) equipped with insect net vents.

Protected structure: 1: Shade net house (Frame covered with green net)

Protected structure: 2**:** Naturally ventilated polyhouse [frame covered with LDPE polythene (thickness 200 μ) and side ventilation through insect net].

The experiment spanned two autumn seasons, from1August to 30 November, in the years 2023 and 2024**.** The planting density was maintained at 50 x 30 cm. In both cultivation systems, irrigation was administered using a drip irrigation system. To monitor microclimatic parameters daily, four digital temperature and humidity meters were installed at a height of 2 meters above the ground. These meters were calibrated weekly using conventional dry and wet bulb thermometers (Fig. 1).

Calculation of ETo, ETc and adjusted Kc

The FAO-Penman Monteith equation was used to calculate real time ETo as per the monitored micro-climatic conditions under protected structures as well as open field condition which was further utilized to calculate the adjusted crop coefficient values of tomato with help of equations (ii) and (iii). The FAO-Penman Monteith equation is given as below:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

Where, ET_o = reference/potential evapotranspiration (mm day^{-1}), R_n= net radiation over surface of crop (MJ m^{-2} day), T = air temperature at approximately 2 m height (°C), G = heat flux density of soil (MJ m^{-2}day), u_2 = speed of wind at 2 m height (m s^{-1}), e_s - e_a = vapour pressure deficit (kPa), Y= psychrometric constant, (kPa°C^{-1}). Δ = vapour pressure curve slope (kPa°C^{-1}),

In drip irrigated plots, irrigation water was supplied on the basis of 50% depletion in field capacity of soil which was continuously monitored with the help of soil moisture meter at 15 to 30 cm depth. Water meters were installed at the starting of each plot to measure volume of irrigation water supplied during each irrigation event. The total depth of irrigation water supplied during each growth stages was estimated corresponding to area of plot.

Further, corresponding to actual depth of irrigation water supplied during each irrigation event, the crop evapotranspiration (ET_C) was estimated by water balance formula which is given as follows (Michael and Ojha, 2024);

$$ETc = \frac{\text{Irrigation Depth} + \Delta S - R}{(1-p)\times\eta} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

Where, ETc=Crop evapotranspiration (mm day^{-1}), Irrigation Depth: It is the depth of irrigation water applied (mm), ΔS: change in soil moisture content (before irrigation - after irrigation) in decimals, R: Effective rainfall (mm), : Soil moisture depletion fraction (in decimals), : Soil water extraction coefficient (in decimals) The irrigation was given to wheat crop at 50% depletion in field capacity (24%) of soil so change in soil moisture content (ΔS) was consider as (0.12-0.24) = 0.12 during each irrigation event. In order to estimate ET_c by above equation, p and η values were assumed as 0.5 (commonly used value for soil moisture depletion fraction) and 1 (for simplicity, assuming full extraction), respectively (Michael and Ojha, 2024). In the open field cultivation, effective rainfall was negligible throughout the growing period.

Finally, in existing climatic conditions of selected study area, the stage wise average crop coefficient (Kc) value for drip irrigated wheat crop was developed by dividing estimated crop evapotranspiration (as per soil water balance method) to its corresponding actual reference evapotranspiration (as computed by using equation i).

$$K_c = ETc/ETo \ldots\ldots\ldots\ldots\ldots \text{(iii)}$$

Where, K_c: Crop coefficient, ETc: Average crop evapotranspiration (mm day^{-1}), ETo: Average reference evapotranspiration (mm day^{-1}).

The growth and yield data were recorded to validate the developed Kc values for different growing condition. The obtained data were analyzed using analysis of variance (ANOVA) within a randomized block design framework.

RESULTS AND DISCUSSION

Reference evapotranspiration (ET_o) and crop evapotranspiration (ETc)

Throughout the growing season, the daily average reference evapotranspiration (ET_o) varied across growth stages, ranging from 1.1 to 2.9 mm day^{-1} in Shade net, 1.2 to 3.7 mm day-1in Polyhouse, and 1.5 to 4.2 mm day-1in open-field conditions.

Fig. 1: Experimental view of (a) Structure-1 (Shade net) and (b) Structure-2 (Polyhouse).

These findings align with Sharma and Yadav (2021), who reported similar ET_o variations for various vegetable crops under both protected and open-field cultivation. Using real-time monitored microclimatic data and the Penman-Monteith equation, the total estimated ETo was 317.8 mm, 358 mm, and 454 mm for Shade net, Polyhouse, and open-field conditions, respectively. Differences in ETo values across these environments were attributed to variations in microclimatic parameters within each structure and the open field. Mean daily maximum and minimum temperatures were lowest in Shade net, likely due to the shading effect of the shed net house, which reduced incoming solar radiation compared to the polyhouse and open field. In polyhouse, temperatures were slightly higher, potentially due to the greenhouse effect, resulting in greater shortwave radiation retention under its partially sealed conditions. Relative humidity was reduced within the polyhouse (Table 1), and daytime temperatures were observed to be elevated. These temperature and humidity differences have notable implications for physiological processes such as flowering, germination, and development, as well as on plant water status and transpiration rates influenced by stomatal behavior during photosynthesis. The unique microclimatic conditions within each environment significantly impacted ETo, underscoring the importance of structure-specific adjustments to optimize water use in both protected and open-field cultivation.

Table 1: Average air temperature and humidity data under shade net, polyhouse and outside at different growth stages of tomato crop.

Growth stages	Maximum temperature (^{0}C)			Minimum temperature (^{0}C)			Relative humidity- max. (%)			Relative humidity- min. (%)		
	Shade net	Polyhouse	Open	Shade net	Polyhouse	Open	Shade net	Polyhouse	Open	Shade net	Polyhouse	Open
Initial	27.0	30.5	34.3	21.5	22.0	27.6	86	83	81	65	61	59
Development	25.2	29.1	32.2	19.9	21.5	25.0	90	89	87	67	63	60
Mid	25.0	28.1	30.0	14.9	15.3	17.3	89	89	89	68	67	64
Late	20.4	22.9	25.6	10.5	11.0	12.3	94	92	92	69	69	66
End	21.6	22.8	24.0	11.3	12.0	13.6	94	93	92	69	68	65

Table 2: Pooled values of $ET_{0\,,}$ Kc and ETc at all the growth stages for tomato under shade net, polyhouse and open field.

Growth stages	Days after sowing	Reference evapotranspiration (ETo) (mm day^{-1})			Crop evapotranspiration (ETc) (mm day^{-1}),		
		Shade net	Polyhouse	Open	Shade net	Polyhouse	Open
Initial	1 to 26	2.9	3.7	4.2	1.18 to 1.47	1.88 to 1.96	2.35 to 3.39
Development	27 to 62	2.7	3.6	4.0	1.37 to 2.83	1.90 to 3.88	2.28 to 4.40
Mid	63 to 99	2.5	3.1	3.7	2.65 to 2.67	3.34 to 3.37	4.07 to 4.44
Late	100 to 120	1.9	2.4	2.8	2.0 to 1.15	2.61 to 1.51	3.36 to 1.87
End	More than 120	1.1	1.2	1.5	0.66	0.75	1.00

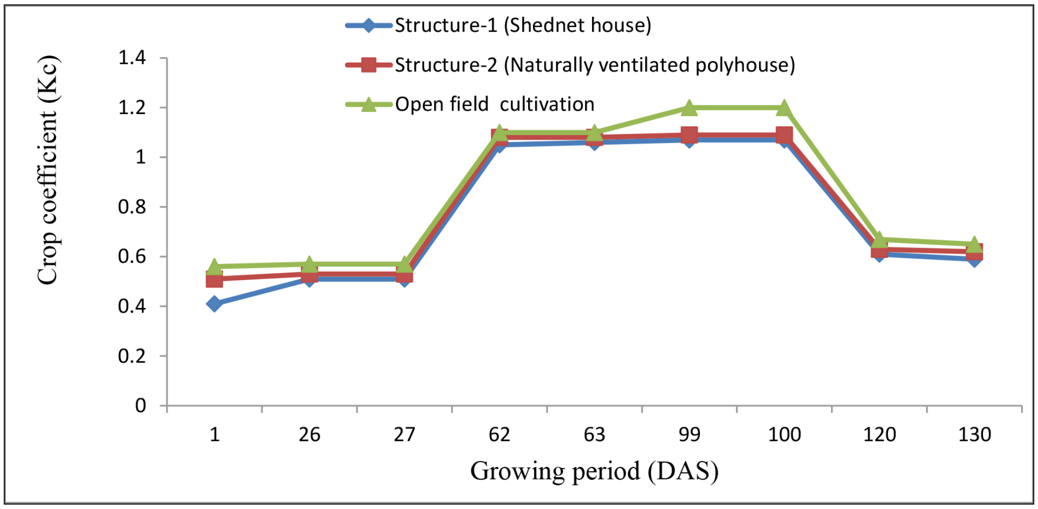

Fig. 2: Developed Kc values at different days after sowing (DAS) for shade net, polyhouse and open field.

Throughout the growing season, the daily average crop evapotranspiration (ETc) calculated using the soil water balance method was highest in open-field conditions compared to Shade net and Polyhouse, as shown in Table 2. Climatic conditions, crop characteristics, field management, and microclimatic differences influenced actual irrigation depth and ETc, consistent with findings by Sharma *et al.,* (2023), Sharma *et al.,* (2021), Satpute *et al.,* (2021), and Mehta and Pandey (2016). Following ETo and ETc estimations, crop coefficient (Kc) values were derived for each growth stage of the tomato crop, with results presented in Table 2.

Crop coefficient (Kc)

At the initial stage (1–26 days after sowing), Kc values remained relatively constant due to minimal canopy development, with values ranging from 0.41 to 0.51, 0.51 to 0.53, and 0.56 to 0.57 for Shade net, Polyhouse, and open-field conditions, respectively (Fig. 1). This stability reflects low water demand as the crop establishes its root system. During the development stage (27–62 days after sowing), Kc values increased progressively (from 0.51 to 1.05 in Shade net, 0.53 to 1.08 in Polyhouse, and 0.57 to 1.10 in the open field), corresponding to canopy expansion and rising ETc due to higher water demand for photosynthesis. This phase highlights increased water requirements essential for robust vegetative growth and efficient water use. In the mid-stage (63–100 days after sowing), Kc values reached their peak (1.06 to 1.07 for Shade net, 1.08 to 1.09 for polyhouse, and 1.1 to 1.2 in the open field) and remained stable, indicating maximum water demand associated with optimal canopy development and photosynthetic activity. This phase is critical for yield formation, requiring precise irrigation management to sustain productivity. As the crop matured in the late stage (101–120 days after sowing), Kc values gradually declined (from 1.07 to 0.61 in Shade net, 1.09 to 0.63 in Polyhouse, and 1.12 to 0.67 in the open field) due to reduced transpiration associated with canopy maturation. The end stage saw a stable Kc (0.61, 0.63, and 0.67 in shade net, polyhouse, and the open field, respectively), reflecting stabilized water requirements as the crop approached senescence.

This study underscores the importance of stage-specific irrigation management to meet the dynamic water needs of the tomato crop across different environments. By leveraging Kc values, growers can improve water use efficiency, supporting optimal crop growth and productivity. The variations in Kc values among different growing structures also emphasize the impact of microclimatic conditions on crop water requirements, guiding the development of tailored irrigation strategies for diverse cultivation environments (Fig. 2).

Plant height and yield attributes

The data on plant height, fruit yield per plant, and total fruit yield are presented in Table 3. The results indicate that crop performance was significantly influenced by the microclimatic conditions within the growing structures. The tallest plant height, reaching 121 cm, was observed under polyhouse compared to Shade net. This difference is likely due to higher CO_2 concentrations in polyhouse, attributed to the ventilation net covered by a side curtain during the night, which enhances the photosynthesis rate and promotes more rapid plant growth compared to outside field conditions. Fruit yield per plant and total fruit yield were also highest under Polyhouse, with values of 2730 g/plant and 71.2 t ha^{-1}, respectively. A similar trend was reported by Rana *et al.,* (2014), who found that tomatoes grown under the microclimatic conditions of a polyhouse produced approximately 50% higher yields (90 t ha^{-1}) compared to those grown in open field conditions (54.8 t ha^{-1}). Overall, crop performance was significantly improved under protected cultivation compared to open-field conditions. Controlled environments like polyhouses and net houses create distinct microclimates that influence temperature, humidity, and light, subsequently affecting crop water requirements. Developing accurate, a growth-stage-specific crop coefficient (Kc) value tailored to these microclimates is essential for precise irrigation scheduling, preventing over- or under-irrigation and promoting efficient water use.

Table 3: Effect of growing structures on performance of tomato crop

Structures	Plant height (cm)	Fruit yield per plant (g plant^{-1})	Crop yield (t ha^{-1})
Shade net	98	1962	53.1
Polyhouse	121	2730	71.2
Open	67	1360	41.0
SEM	3.1	4.2	2.4
CV (%)	8.4	14.2	8.1
CD (P=0.05)	8.9	6.1	5.3

Efficient water management is critical, especially in water-scarce regions. Localized Kc values for protected systems enable targeted irrigation practices, conserving water and supporting sustainable agriculture. These values also provide a scientific foundation for agricultural recommendations and support best practices for water use in protected cultivation. Developing Kc values for tomatoes in protected environments offers a reference for advancing irrigation technologies, refining crop management strategies, and fostering research, ultimately optimizing productivity and resource management in protected agriculture.

CONCLUSION

This study demonstrates that microclimatic parameters were consistently highest in open-field conditions and lowest within protected structures, with notable impacts on plant height, yield, reference evapotranspiration (ETo), crop evapotranspiration (ETc), and crop water requirements (CWR) for tomatoes grown under both protected and open-field conditions. ETo was minimized in shade net and maximized in open-field conditions, reflecting the influence of microclimatic variations on crop water demand. Growth-stage-specific crop coefficient (Kc) values were established at 0.51, 1.05, and 0.61 for Shade net; 0.53, 1.08, and 0.63 for polyhouse; and 0.51, 1.10, and 0.67 for open fields, corresponding to the initial, mid, and late stages of tomato growth, respectively. These values, lower than those recommended by FAO-56 for tomatoes, are tailored to local microclimatic conditions within protected cultivation. The developed Kc values can be effectively used by researchers and practitioners to estimate CWR for protected tomato cultivation in Jalandhar, Punjab, and similar agro-climatic zones. This study provides a scientific framework for optimizing irrigation scheduling and improving water resource management in India, underscoring the importance of environment-specific Kc values in enhancing crop productivity and water use efficiency in protected agriculture.

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