https://doi.org/10.17221/31/2025-RAE

Optimisation of the irrigation requirement of okra under protected cultivation using a digital lysimeter

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Citation: Elango S., Madasamy N., Annamalai V., Arumugam V. (2025): Optimisation of the irrigation requirement of okra under protected cultivation using a digital lysimeter. Res. Agr. Eng., 71: 200–212.

Abstract: A field experiment was conducted in 2023 and 2024 to determine stage-specific crop coefficient values of okra (*Abelmoschus esculentus*) using the popular F1 hybrid Arka Nikita. Six evapotranspiration (ET_c) based treatments were applied: five under a forced ventilated greenhouse (T_1 = 120% ET_c, T_2 = 100% ET_c, T_3 = 80% ET_c, T_4 = 60% ET_c, T_5 = 100% ET_c in lysimeter) and one under open field (T_6 = 100% ET_c) arranged in a completely randomised block design with three replications. The results showed that T_2 had higher growth parameters, while T_4 and T_6 performed poorly. The yield was significantly higher in T_2 (23.8 t/ha in 2023 and 23.3 t/ha in 2024), whereas T_6 had a lower yield (9.5 t/ha in 2023 and 8.6 t/ha in 2024). Higher water productivity was observed in T_3 (9.85 kg/m^3 in 2023 and 8.35 kg/m^3 in 2024), while T_6 had lower water productivity (1.83 kg/m^3 in 2023 and 1.35 kg/m^3 in 2024). Hence, this study recommends using stage-specific crop coefficients of 0.32, 0.63, 0.78, and 0.41 during the initial, development, mid and final stages of 80% ET_c to optimise the water productivity and maximise the yield in the greenhouse-grown okra, respectively.

Keywords: lysimeter; precision agriculture; soil moisture sensor; water use efficiency

Greenhouse vegetable production is essential for global agriculture, contributing approximately 20% of the total vegetable output. Okra (*Abelmoschus esculentus* L.) is one of the major vegetable crops in India, producing 6.42 million tonnes annually and ranking it first globally. With a productivity of approximately 12.26 t/ha average for India 8.93 t/ha average for Tamil Nadu (Kohima et al. 2023). Compared to traditional open-field cultivation, greenhouses offer significant advantages, achieving 35–40% higher yields on average and using up to 70% less water (Awang Bono et al. 2024). The controlled environment in greenhouses allows for extended growing seasons and supports the cultivation of a wider variety of crops, which is vital for meeting rising global food demands while promoting sustainability and efficiency. Open-field cultivation, in contrast, typically consumes more water and is limited by seasonal constraints, making year-round production challenging. Greenhouse systems

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mitigate these limitations, providing continuous, efficient production with better water management and protection against adverse weather conditions (Awang Bono et al. 2024). This makes greenhouse cultivation an increasingly attractive, sustainable choice for high-quality vegetable production.

The demand for water has steadily been rising due to the growing agricultural needs, making it essential to use the available water resources judiciously. Conventional surface irrigation methods, commonly practiced in agriculture, have proven inefficient, often leading to unproductive water use by crops (Yang et al. 2023). Modern, efficient irrigation methods, such as drip irrigation, have become essential as they supply precise water amounts at regular intervals based on crop requirements, improving the yield and water efficiency. Accurate water management thus becomes critical, requiring the precise evaluation of water needs for each crop to optimise the productivity. Advanced technologies, recognised for providing reliable real-time data across diverse soil types, are increasingly used to ensure accurate water assessments by measuring the evapotranspiration. The actual evapotranspiration (ET_c) is determined as the product of the reference evapotranspiration (ET_o) and the crop coefficient (K_c), which varies with the crop type and growth stage (Subedi et al. 2017).

Recent studies have approached using different methods to measure the evapotranspiration in greenhouses. The digital weighing lysimeter is one of them, utilised by many researchers to automatically record the changes in the water along with crop conditions and calculate the daily evapotranspiration (ET_c) (Kumari et al. 2022; Awari et al. 2023; Shi et al. 2023).

Despite okra's economic and agricultural significance, there is currently no crop coefficient specific to okra under greenhouse conditions. This lack of data poses challenges in optimising the irrigation for controlled environments, necessitating an integrated approach that considers the climate, soil moisture, and crop growth stages to estimate the crop coefficients (Buttaro et al. 2015).

Therefore, an effort has been made in this study to evaluate the water requirements and crop coefficient of okra under drip irrigation. By assessing okra's performance at different irrigation levels in a greenhouse compared to open-field conditions, the study seeks to optimise irrigation schedules for maximising the yield and water productivity.

MATERIAL AND METHODS

The study was conducted during the years 2023 and 2024 in a forced ventilated unheated greenhouse, with an area of 200 m^2 (10 m long, 20 m wide, 3.5 m ridge height), oriented in a north-south direction and covered with a polythene film (200 microns) at the Agricultural Engineering College and Research Institute, Kumulur. It geographically lies between 10.9329° N latitude and 78.8269° E longitude and at an altitude of 70 m above mean sea level. The study area's average temperature, average evaporation, and mean annual rainfall are 28.8 °C, 8 mm/day and 860 mm, respectively.

Treatment details. The experiment was carried out in sandy loam soil using Okra seeds (F1 hybrid – Arka Nikita) following a Complete Randomised Block Design and replicated (R) three times. The treatments adopted with the soil moisture sensors (TEROS 10) are T_1 = 120% ET_c, T_2 = 100% ET_c, T_3 = 80% ET_c, T_4 = 60% ET_c, T_5 = 100% ET_c with lysimeter, T_6 = 100% ET_c (open field) with the recommended dose of fertiliser. Single seeds were placed per hill with 30 cm × 45 cm spacing in February 2023 and 2024. The laterals were laid with in-line drippers with a 4 lph capacity at an interval of 45 cm (Figure 1). The drip fertigation system was used to apply the recommended dose of fertiliser to the plot after the establishment of the plants, repeated once a week and ended one week before the last harvest.

In the establishment phase (10 days from sowing), all the treatment plots were irrigated uniformly at the level of the field capacity (21%) with an interval of two days to facilitate the rooting and establishment of plants within the experimental plots. The irrigation scheduling method proposed in this study is used to determine the amount of irrigation water and the time of irrigation based on the soil moisture content and evaporation rate.

Estimation of the actual crop evapotranspiration (ET_c). The soil moisture content of the treatments (T_1, T_2, T_3, T_4, and T_6) was estimated using the METER Group TEROS 10 soil moisture sensor. It is generally recognised for its efficiency and accuracy of up to ±1%. Compared to conventional moisture measuring methods, the TEROS 10 sensor is less susceptible to external interference and has a higher temporal resolution, making it ideal for dynamic field situations (Ghiat Ikhlas et al. 2021). The sensors were placed at 15 cm and 30 cm depths near the crop root zone in all five treatments. The

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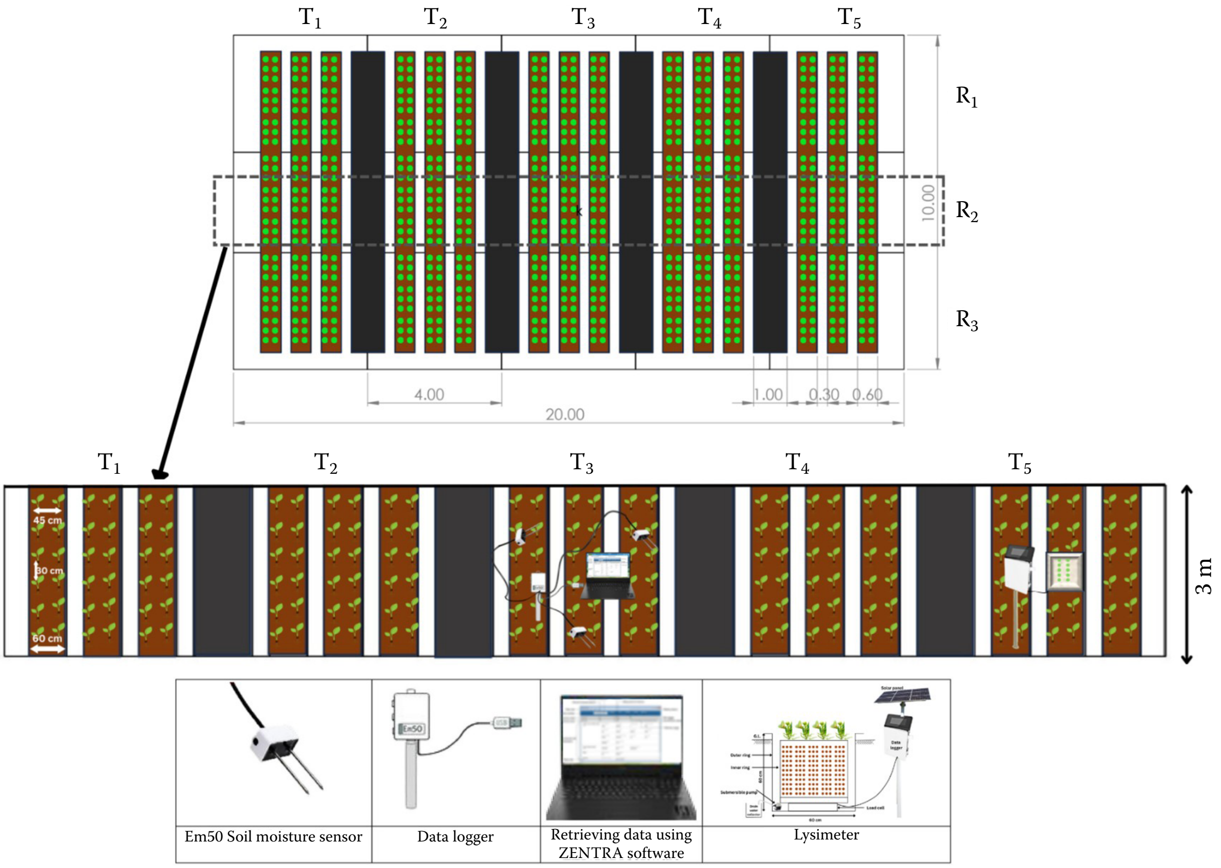

Figure 1. Layout of the experimental plot (T = treatment and R = replication)

quantity of water depleted (ΔW) by the crop was determined by the volumetric moisture content from the sensor (TEROS 10) through the Em50 data logger via the ZENTRA utility software at every one-hour interval.

The actual crop evapotranspiration was estimated by the soil water balance method with the following formula (Kumari et al. 2022) applied as irrigation at one-day intervals.

$$ET_c = P + I - R - D \pm \Delta W \quad (1)$$

where: P – precipitation (mm); I – irrigation water depth (mm); R – surface runoff (mm); D – amount of water drained from the root zone (mm); ΔW – change in the soil water storage (mm).

Runoff, drainage, and precipitation are not applicable in drip-irrigated greenhouses and were assumed to be zero. Hence, the difference in the irrigation and changes in the soil moisture content were taken as the actual crop evapotranspiration of okra (Imrana Farhan and Sugirtharan 2023).

The crop evapotranspiration of treatment 5 (100% ET_c) was estimated with the gravimetric lysimeter with a 500 kg capacity. It was erected and placed into the soil surface by maintaining the bulk density of the soil. The weight can be read with an accuracy of 50 g. The amount of water lost is only by means of evapotranspiration (Awari et al. 2023; Shi et al. 2023) and was measured in kilograms as follows:

$$ET_c = (\Delta W \times CF) + RF \quad (2)$$

where: ET_c – amount water lost, mm (i.e. crop evapotranspiration); ΔW – difference in weight, kg; CF – conversion factor (1 kg = 2.77 mm); RF – rainfall, mm (in the case of the greenhouse, the rainfall is considered to be zero).

Estimation of the reference evapotranspiration (ET_o). The Penman-Monteith (PM) model utilises the ET_o calculator FAO 56 (Subedi et al. 2017). The PM model considers multiple meteorological factors, such as the air temperature, humidity, wind

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speed, and net radiation, to estimate ET_o. The data were obtained from meteorological observation stations located 10 m from the experimental plot. The calculation of ET_o is as follows:

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \frac{900\gamma U(e_s - e_a)}{T + 273.15}}{\Delta + \gamma\left(1 - 0.34U\right)} \tag{3}$$

where: ET_o – reference crop evapotranspiration (mm/d); R_n – net radiation (MJ/m^2/d); G – soil heat flux (MJ/m^2/d); T – air temperature (°C); U – wind speed (m/s); e_s – saturation vapour pressure (kPa); e_a – actual vapour pressure (kPa); Δ – slope of the saturation vapour pressure-temperature relationship (kPa/°C); γ – psychometric constant (kPa/°C).

Estimation of crop coefficient (K_c). The following equation was given by Patil (2010) to calculate the stage-specific crop coefficient:

$$K_c = \frac{ET_c}{ET_o} \tag{4}$$

where: K_c – crop coefficient.

Morphometric observations of growth parameters, yield and water productivity. Growth parameters were recorded 20, 40, 60, 80, 100, and 110 days after sowing to assess the crop performance at different irrigation levels. The greatest leaf width and breadth were measured with a ruler, and the product was multiplied by a correction factor of 0.62 to calculate the leaf area (Elings 2000).

The Leaf area index (LAI) was determined by Elings (2000):

$$LAI = \frac{0.62 \times L \times W \times NP \times NL}{\text{Land area covered}} \tag{5}$$

where: L – leaf length (cm); W – leaf width (cm); NP – number of plants; NL – number of leaves.

Water use efficiency (WUE) was calculated as follows (Moursy et al. 2023):

$$WUE = \frac{\text{Yield (kg/ha)}}{ET_c \text{ (mm)}} \tag{6}$$

Water productivity was calculated by Jayapiratha et al. (2010):

$$\text{Water productivity (kg/m}^3\text{)} = \frac{\text{Yield (kg/ha)}}{ET_c\,(\text{m}^3/\text{ha})} \tag{7}$$

Statistical analysis. The data observed from the experiments were analysed using R (version 4.2.2) (de Mendiburu 2019). Analyses of variance (ANOVA) were conducted to determine variations among the treatments, followed by the Least significant difference (LSD) method at a significance level of α = 0.05 for the mean comparisons. Additionally, Pearson correlation analyses were performed to evaluate the relationships among the growth parameters, providing insights into the strength and direction of the associations. A heat map was generated to visually represent the correlations of the treatments, particularly highlighting patterns across the yield and water use efficiency (WUE) over both years.

RESULTS AND DISCUSSION

The observed minimum and maximum temperature in the greenhouse for the year 2023 and 2024 ranged from 26.4 °C to 40.1 °C and 28.9 °C to 41.6 °C, respectively. The minimum and maximum relative humidity was observed as 66.2% to 84.9% and 71.4% to 88.3%, respectively. Figures 2 and 3 show the monthly average evapotranspiration, temperature and relative humidity of both seasons.

The reference evapotranspiration (ET_{o-i} and ET_o) was calculated inside and outside greenhouse using the ET_o calculator (Ghiat Ikhlas et al. 2021)

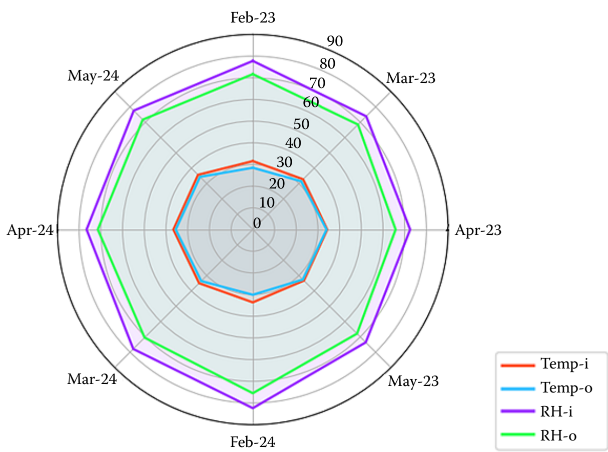

Figure 2. Radar chart of the climatic parameters during the growing period

The radar chart of climatic parameters during the growing period shows the inside and outside temperature (Temp-i, Temp-o; °C) and relative humidity (RH-i, RH-o, %) respectively

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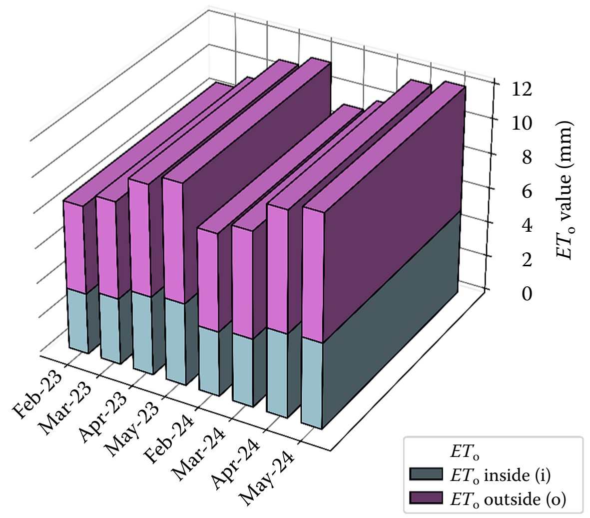

Figure 3. 3D stacked bar of the evapotranspiration during the growing period

ET_o – reference crop evapotranspiration

and it is varied from 3.3 to 5.2 mm/day (2023), 3.4 to 5.5 mm/day (2024) and 4.2 to 7.2 mm (2023), 5.2 to 7.6 mm (2024), respectively, during the growing period. The stage wise estimated ET_o value for the both years are given in Table 1.

The reference evapotranspiration estimated in both years was at a minimum during the initial stage and at a maximum in the mid-stage due to respective vegetation growth at the stage. However, these results are not new, but give confidence to the subsequent results findings (Subedi et al. 2017). The same evapotranspiration trend has been reported by several researchers for okra (Tiwari et al. 1998; Ahmet and Ali 2009; Jayapiratha et al. 2010)

Actual crop evapotranspiration (ET_c). The actual crop evapotranspiration, ET_c (mm/day), was calculated by the soil water balance using soil moisture sensors (TEROS 10) and a lysimeter. A similar methodology was followed by Jayapiratha et al. (2010), Moursy et al. (2023), Shi et al. (2023). Each of these studies demonstrates the utility of advanced monitoring techniques to assess evapotranspiration rates accurately under varying conditions. In this study, the initial, mid, development, and final stages of the actual crop evapotranspiration (ET_c) were observed through the use of a TEROS 10 sensor for the five treatments (T_1, T_2, T_3, T_4, and T_6) and lysimeter for T_5 in both years (2023 and 2024) as depicted in Table 1. The volume of irrigation was calculated from the depleted moisture content through the sensors and lysimeter for the respec-

Table 1. Stage-wise reference evapotranspiration and actual crop evapotranspiration for 2023 and 2024

DAS	ET_o (mm)		ET_{o-i} (mm)		ETC_1 (mm)		ETC_2 (mm)		ETC_3 (mm)		ETC_4 (mm)		ETC_5 (mm)		ETC_6 (mm)	
	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2	S_1	S_2
0–19	98.70	108.65	70.32	75.68	32.92	37.86	27.44	31.55	21.95	25.24	16.46	18.93	23.78	26.54	47.29	53.84
20–50	159.50	176.36	113.26	119.00	105.70	114.12	88.08	95.10	70.47	76.08	52.85	57.06	75.13	79.75	151.89	182.39
51–80	178.30	195.59	128.22	135.30	139.73	167.95	116.44	139.96	93.15	111.97	69.87	83.97	100.81	116.01	198.44	251.94
80–110	207.20	221.29	145.78	152.96	84.45	98.46	70.38	82.05	56.30	65.64	42.23	49.23	60.25	67.94	122.40	152.64
Total	643.7	701.89	457.58	482.94	362.8	418.39	302.34	348.66	241.87	278.93	181.41	209.19	259.97	290.24	520.02	640.81

DAS – days after sowing; S_1 – first season (2023); S_2 – second season (2024); ET_o – reference evapotranspiration in the open field; ET_{o-i} – reference evapotranspiration in the greenhouse; ET_c – crop evapotranspiration

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tive treatment. Irrigation was followed on the alternative days. In all the treatments, higher water consumption was observed during the mid-stage; it may be due to the maximum vegetative growth and optimum amount of water and fertiliser application. The total amount of water consumed by the okra was 363 mm, 302 mm, 242 mm, 181 mm, 260 mm, and 520 mm (2023) and 418 mm, 349 mm, 279 mm, 209 mm, 290 mm, and 641 mm (2024) in treatment T_1, T_2, T_3, T_4, T_5, and T_6, respectively. The crop evapotranspiration of okra observed with 100% ET_c in open field conditions by Patil (2010) was reported to be 547 mm and by Awari et al. (2023) was reported to be 610 mm, which are in line with the result of this study.

Plant growth parameters. The plant growth parameters showed distinct differences across all the treatments based on the irrigation levels and environmental conditions, as depicted in Table 2. Different crop growth stages under the greenhouse are shown in Figures 4, 5, 6, 7, 8 and 9. Treatment T_2 consistently exhibited superior results for the plant height, recording heights of 1.15 m in 2023 and 1.14 m in 2024, indicating optimal irrigation conditions that likely supported better nutrient uptake and photosynthesis (Graamans et al. 2018). Treatments T_1, T_3, and T_5, with heights of 1.01, 1.06, and 1.06 m in 2023 and 0.98, 1.04, and 1.09 m in 2024, respectively, demonstrated statistically similar performance as per the LSD test.

The letter groupings shown in Table 2 demonstrate that the treatments have roughly similar plant heights, signifying generally proper water availability across irrigation regimes, as reported by Ahmet and Ali (2009). In 2023, only T6 had a statistically lower plant height of 0.74 m, as shown by the letter "b". In 2024, all T1–T6 were in a single statistical group "a", confirming no significant differences in plant height within the same season. This height reduction for T6 could be explained by its outdoor growing conditions; given the fluctuations in temperature and the generally low humidity, plant development was constrained (Graamans et al. 2018).

Regarding the stem girth, treatments T_1, T_2, T_3, and T_5 recorded higher values and exhibited statistically under the same group. It shows that maintaining a sufficient water supply facilitates optimal carbohydrate distribution within the controlled environment, resulting in thicker stems (Moursy et al. 2023). T_6 had lower girth values (1.46 cm in 2023 and 1.40 cm in 2024), likely due to the stress of the

Table 2. Statistical analysis of the plant growth performance with various levels of irrigation under different climatic conditions

Source of variation	2023										2024									
	SS	*df*	*F*	*P*-value	means of the treatment						SS	*df*	*F*	*P*-value	means of the treatment					
					T_1	T_2	T_3	T_4	T_5	T_6					T_1	T_2	T_3	T_4	T_5	T_6
Plant height (m)	0.3	12	60.9	$4.1e^{-8}$	1.01^{ab}	1.15^{a}	1.06^{ab}	0.83^{ab}	1.06^{ab}	0.74^{b}	0.2	12	34.8	$9.5e^{-7}$	0.98^{a}	1.14^{a}	1.04^{a}	0.88^{a}	1.09^{a}	0.82^{a}
Girth (cm)	2.1	12	17.0	$4.4e^{-5}$	2.20^{a}	2.43^{a}	2.36^{a}	2.13^{b}	2.46^{a}	1.46^{b}	2.6	12	21.1	$1.5e^{-5}$	2.26^{ab}	2.53^{a}	2.36^{ab}	2.13^{b}	2.46^{ab}	1.40^{c}
Branches (Nos.)	224.5	12	67.4	$2.3e^{-8}$	11^{c}	16.0^{b}	16^{b}	11.0^{c}	17^{a}	7.0^{d}	236.2	12	40.5	$4.1e^{-7}$	10^{e}	16^{b}	14^{c}	11^{d}	17^{a}	6^{f}
Harvest (Nos.)	375.3	12	103.9	$1.8e^{-9}$	16^{d}	21^{b}	20^{c}	15^{e}	23.0^{a}	9.0^{f}	394.6	12	71.04	$1.7e^{-8}$	17^{e}	22^{b}	20^{c}	18^{d}	22^{a}	8^{f}
Flowering (days)	199.6	12	32.6	$1.4e^{-6}$	34^{b}	33^{a}	34^{b}	38^{c}	33^{a}	42^{d}	153.1	12	30.6	$1.9e^{-6}$	34^{b}	33^{a}	33^{a}	38^{c}	33^{a}	40^{e}
Fruiting (days)	207.2	12	43.9	$2.7e^{-7}$	39^{c}	38^{a}	38^{ab}	43^{c}	38^{a}	47^{d}	168.4	12	28.8	$2.7e^{-6}$	40^{c}	38^{a}	38^{ab}	43^{d}	38^{b}	46^{e}
Harvesting (days)	209.7	12	34.3	$1.0e^{-6}$	44^{c}	42^{a}	44^{c}	48^{d}	43^{b}	52^{e}	191.3	12	36.2	$7.7e^{-7}$	45^{d}	42^{a}	43^{b}	48^{e}	44^{c}	52^{f}
LAI	15.1	12	199.6	$4.1e^{-11}$	2.2^{c}	4.0^{a}	2.6^{b}	2.1^{cd}	4.0^{a}	1.7^{d}	16.3	12	101.4	$2.2e^{-9}$	2.0^{c}	3.9^{a}	2.6^{b}	2.1^{c}	4.0^{a}	1.6^{d}
Yield (t/ha)	551.3	12	554	$9.4e^{-14}$	18.9^{d}	23.8^{a}	22.2^{c}	12.1^{e}	23.1^{b}	9.5^{f}	578.1	12	901.2	$5.12e^{-15}$	17.8^{c}	23.3^{a}	22.2^{b}	12.2^{d}	23.1^{a}	8.6^{e}
WUE (kg/ha.mm)	11 442.5	12	1 655	$1.3e^{-16}$	52.08^{e}	78.8^{c}	91.6^{a}	66.9^{d}	88.8^{b}	18.2^{f}	9 630.2	12	1 178	$8.7e^{-17}$	48.9^{e}	66.7^{b}	79.4^{a}	58.3^{c}	79.6^{a}	13.1^{e}

An analysis of Variance (ANOVA) on the effect of the treatments on the agronomic parameters was conducted. [a–f]The mean values in the columns with different letters are significantly different based on the LSD test at $P < 0.05$; *df* – degrees of freedom; *F* – table value; *LAI* – the Leaf area index; SS – sum of square; *WUE* – water use efficiency

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Figure 4. Sensor installed in the crop root zone

Figure 5. Crop developed stage in the greenhouse along with lysimeter grown

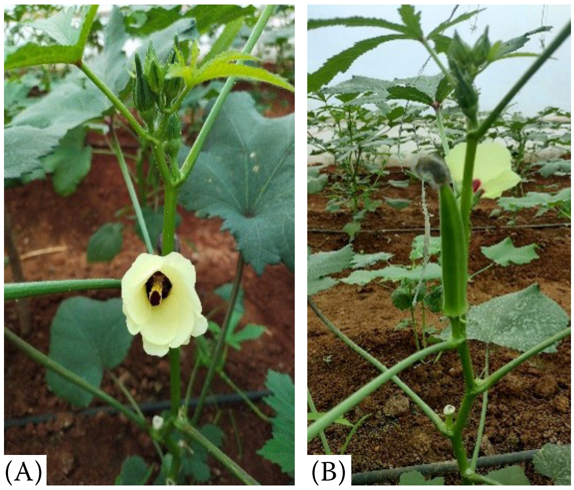

Figure 6. (A) Flowering and (B) fruiting of Okra

Figure 7. Final stage of okra crop

Figure 8. Yield Per plant during 1st harvest of T3 treatment

Figure 9. Yield per 54 Nos. of plant per harvest of T3 treatment

fluctuating outdoor conditions, which hindered the growth (Buttaro et al. 2015).

For the number of branches, T_5 recorded the most (17 branches in both years), reflecting the benefits of the precise irrigation management in promoting vegetative growth and healthy branching (Ali et al. 2024) T_2 and T_3 also performed well, with branch numbers statistically comparable to T_5. T_6, with the fewest branches (7 in 2023 and 6 in 2024), demonstrated the environmental stress's adverse impact on the vegetative growth (Mandal et al. 2018).

Finally, the Leaf area index (*LAI*) was higher in T_2 and T_5, at 4.0 in both years, indicating that the optimal irrigation facilitated more efficient photosynthesis under greenhouse conditions (Moursy et al. 2023). Similar *LAI* values were observed in T_1 and T_3, all of which performed comparably according to the statistical analysis. However, T_6, with the lower *LAI* values (1.7 in 2023 and 1.6 in 2024), continued to show reduced photosynthetic capacity due to the stress from the environmental conditions (Yang et al. 2023).

The number of harvests further highlighted the advantages of greenhouse-based irrigation. T_5 achieved higher harvests (23 in 2023 and 22 in 2024), showcasing the importance of controlled conditions for maximising the productivity. T_1, T_2, and T_3 followed closely behind with similar performances, while T_4 and T_6, with their fewer harvests, likely suffered from either under- or over-irrigation, leading to reduced yields (Awang Bono et al. 2024).

Flowering and harvesting days. The flowering and harvesting durations showed apparent differences based on the treatments. T_2 and T_5 exhibited the shortest time to flowering (33 days

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in both years) and fruiting (38 days in both years). Meanwhile, T_3 very closely follows and is on par with T_2 and T_5, indicating how stable the greenhouse irrigation promotes the timely floral development (Imrana Farhan and Sugirtharan 2023). In contrast, T_6, which was grown outdoors, experienced delays in flowering (42 days in 2023 and 40 days in 2024) and fruiting (47 days in 2023 and 46 days in 2024) due to the higher stress levels caused by the fluctuating environmental conditions (Yang et al. 2023). The number of days to harvest followed a similar trend, with T_2 showing the shortest time to harvest (42 days in both years), compared to T_6, which required 52 days to harvest in both years. These results highlight the advantage of controlled greenhouse environments in expediting crop development and achieving faster harvests (Donato et al. 2015).

Cultivating crops in a greenhouse minimised the pesticide use, with no applications needed, unlike the three required in the open-field conditions. This pesticide-free approach reduces the chemical residue, promoting sustainable practices (Möhring et al. 2023). Labour-intensive tasks like weeding were also reduced, with greenhouse crops needing only one weeding compared to four in the field. This decrease in inter-cultivation activities conserves labour and energy, enhancing the sustainability of greenhouse production systems.

Heat map: *Yield*, water use efficiency (*WUE*), and water productivity (*WP*). The heat map analysis of the yield (tonnes), water use efficiency (*WUE*, kg/ha.mm), and water productivity (*WP*, kg/mm^3) across the treatments revealed significant variations, underscoring the advantages of greenhouse cultivation (Figure 10). The heatmap effectively visualises the treatment performance, using a colour gradient that ranges from light to dark to represent values from lower to higher. Lighter shades indicate treatments with lower performance, while darker shades highlight higher performance levels. In both 2023 and 2024, Treatment 2 achieved the highest yields, with 23.8 t/ha and 23.3 t/ha, respectively, followed closely by Treatment 5, which recorded 23.1 t/ha yields. In contrast, the outdoor Treatment 6 showed considerably lower yields of 9.5 t/ha and 8.6 t/ha in 2023 and 2024, respectively, marking an approximate 60% reduction compared to the greenhouse treatments, highlighting the efficacy of controlled greenhouse conditions in enhancing the crop yield. Consistent with Shi et al. (2023), these findings highlight how optimised greenhouse conditions reduce the environmental stress, boosting both the growth and productivity.

The *WUE* analysis indicated T_3 as the most efficient, achieving 91.6 and 79.6 kg/ha·mm, while T_6 lagged with 18.2 kg/ha·mm and 13.1 kg/ha·mm, aligning with Hashemi et al. (2024) on the importance of precise irrigation in controlled environments (Table 3). The *WP* results similarly favoured T_3, showing values of 9.85 kg/m^3 in 2023 and 8.35 kg/m^3 in 2024, contrasting sharply with T_6 as 1.83 kg/m^3 and 1.35 kg/m^3 across the two years.

These results demonstrate how controlled environments promote more efficient water use, leading to higher economic returns per unit of water used (El-Naggar et al. 2020). The analysis reinforced a clear treatment hierarchy with the greenhouse (T_1–T_5) outperforming the outdoor (T_6), stable parameter correlations, particularly between *WUE* and *WP* in T_2 and T_3, and temporal consistency between years, underscoring the greenhouse reliability. These results point to significant environmental and economic implications, advocating for greenhouse cultivation to enhance the productivity and water efficiency, critical for sustainable agricultural practices, addressing water scarcity, and supporting food security. The observed consistency and superior performance of T_2 and T_3 underscore the potential for controlled environment agriculture to drive sustainable intensification strategies in future planning and resource management.

Stage-specific crop coefficient (K_c). The crop coefficient (K_c) patterns across various irrigation

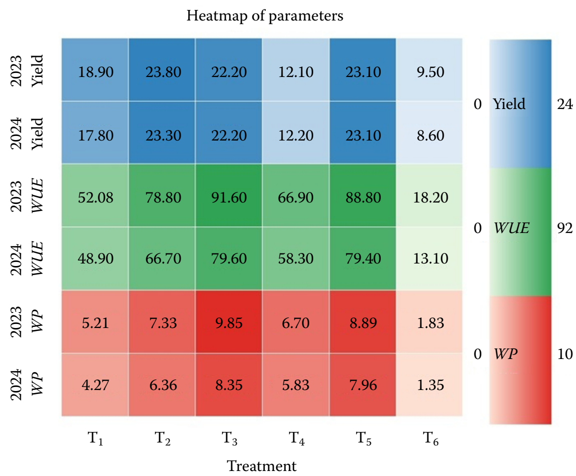

Figure 10. Heat map for the Yield, (kg), *WUE* (kg/ha. mm), and *WP* (kg/m^3)

WP – water productivity; *WUE* – water use efficiency

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Table 3. Evapotranspiration and water productivity for all the treatments

Treatment	Evapotranspiration (ET_o; mm)		Crop evapotranspiration (ET_c; mm)		Water productivity (kg/m^3)	
	2023	2024	2023	2024	2023	2024
T_1	457.6	482.9	362.80	418.38	5.21	4.27
T_2	457.6	482.9	302.34	348.65	7.33	6.36
T_3	457.6	482.9	241.87	278.90	9.85	8.35
T_4	457.6	482.9	181.40	209.19	6.70	5.83
T_5	457.6	482.9	260.00	290.00	8.89	7.96
T_6	643.7	701.9	520.01	640.80	1.83	1.35

regimes exhibited clear distinctions throughout the okra growing season, as mentioned in Table 4. Fourth-order polynomial regression equations were applied to model the average K_c as a function of days after sowing (DAS), which is valuable for estimating the crop water requirements under greenhouse and outdoor conditions. The K_c data for 2023 and 2024 showed an initial increasing trend from 0 DAS to 48 DAS, stabilising during the mid-growth stage (49–72 DAS) and declining during the late stage (80–110 DAS) across both environments. The higher average K_c within the greenhouse was recorded at 1.17 during the mid-stage in Treatment 1 followed by Treatment 2 (0.98), while the lower average, at 0.79, was observed in Treatment 4. In open-field condition with 100% ET_c recorded a peak K_c of 1.2 during the mid-stage and a low of 0.49 in the initial stage, which is higher than the 120% ET_c in the greenhouse. This consistent trend across all the treatments is attributable to the reduced transpiration during the early stage, a gradual increase towards the mid-stage as the plant canopy expands, and a decline during the late stage due to crop maturation and reduced water uptake.

The notably higher K_c values in the outdoor conditions compared to the greenhouse treatments indicate the increased evapotranspiration driven by the direct solar radiation and more pronounced climatic fluctuations that enhance water loss. This aligns with the findings by Möhring et al. (2023), which demonstrated that open-field crops experience higher transpiration rates due to direct exposure to variable environmental conditions. Moursy et al. (2023) also emphasised that increased radiation and temperature outside controlled environments contribute to greater water demand and potential soil surface evaporation.

These variations in the K_c across the treatments underline the significance of adapting irrigation practices to different growth stages and environmental conditions to optimise water use. All the treatments followed a polynomial pattern ($R^2 > 0.96$) with three distinct phases: an initial increase during vegetative growth (K_c values starting around 0.3–0.5), peak values during flowering and fruiting (0.7–1.4 depending on the treatment), and a decline during maturity. The polynomial equations derived for each treatment, with R^2 values ranging from 0.969 to 0.994, (Table 5). Furthermore, the calculated polynomial equations can be a useful tool for future irrigation planning since they make it possible to calculate the daily water requirements, which enhances the water usage

Table 4. Stage-wise crop coefficient (K_c) of various irrigation levels

Stage	K_{c1}			K_{c2}			K_{c3}			K_{c4}			K_{c5}			K_{c6}		
	S_1	S_2	Avg.	S_1	S_2	Avg.	S_1	S_2	Avg.	S_1	S_2	Avg.	S_1	S_2	Avg.	S_1	S_2	Avg.
Initial	0.47	0.50	0.48	0.39	0.42	0.40	0.31	0.33	0.32	0.23	0.25	0.24	0.34	0.35	0.34	0.48	0.50	0.49
Development	0.93	0.95	0.94	0.77	0.79	0.78	0.62	0.64	0.63	0.46	0.48	0.47	0.66	0.67	0.66	0.95	1.03	0.99
Mid	1.09	1.25	1.17	0.91	1.04	0.98	0.73	0.83	0.78	0.55	0.63	0.59	0.79	0.86	0.83	1.12	1.29	1.20
Final	0.58	0.64	0.61	0.48	0.53	0.51	0.38	0.43	0.41	0.29	0.32	0.30	0.41	0.44	0.43	0.59	0.69	0.64

K_{c1}, K_{c2}, K_{c3}, K_{c4}, K_{c5} and K_{c6} – stage-specific crop coefficient of the treatments; Avg. – average value of the crop coefficient of two seasons

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Table 5. Fourth-order polynomial equation for all the treatments

Treatment	Polynomial equation	Coefficient of determination (R^2)
T_1	y = 1E-07x^4 – 3E-05x^3 + 0.0021x^2 – 0.0305x + 0.5552	0.9719
T_2	y = 1E-07x^4 – 3E-05x^3 + 0.0017x^2 – 0.0254x + 0.4627	0.9719
T_3	y = 8E-08x^4 – 2E-05x^3 + 0.0013x^2 – 0.016x + 0.342	0.9739
T_4	y = 7E-08x^4 – 2E-05x^3 + 0.001x^2 – 0.0153x + 0.2776	0.9719
T_5	y = 9E-08x^4 – 2E-05x^3 + 0.0015x^2 – 0.0216x + 0.3946	0.9693
T_6	y = 1E-07x^4 – 3E-05x^3 + 0.0017x^2 – 0.0216x + 0.5116	0.9854

Pearson correlation was performed for the morphometric parameters of all the treatments; x – days after sowing; y – crop coefficient

efficiency and promotes sustainable crop production under various irrigation regimes.

To more explicitly describe the stage of crop–treatment–weather relationship, a mean crop coefficient (K_c) pattern 3D surface plot was generated (Figure 11). This graph provides an easily interpretable presentation of the K_c variation with the days after sowing and between treatments such that the phases of the highest and lowest water requirement can be ascertained, comparisons of the treatments for effect made easily, and stage-specific irrigation planning optimised. In summarising the tabular data with regression data into a single graphic, it allows for the easier interpretation of data as well as making prudent water-use efficient choices.

Comparison of the evapotranspiration of the 100% ET_c inside and outside the greenhouse. The scatter plot analysis comparing the soil moisture sensor-based evapotranspiration (ET_{c2}) with the lysimeter-based (ET_{c5}) and meteorological-based (ET_{c6}) ET measurements highlighted critical insights into the ET estimation methods as depicted in Figure 12. The strong correlation (R^2 = 0.999) between ET_{c2} and ET_{c5} indicates the reliability of using the lysimeter or soil moisture sensor for measuring ET in greenhouse environments, in agreement with Tayyaba et al. (2022). However, the correlation between ET_{c2} and ET_{c6} (R^2 = 0.989) also showed a good relationship since ET_{c6} measured outdoors had a 44% higher value than ET_{c2} due to the increased environmental variability, such as higher solar radiation and wind. This difference underscores the impact of outdoor climatic conditions on the evapotranspiration measurement.

The correlation matrices from the study reveal complex relationships between the irrigation water (IW) and various crop growth parameters, highlighting critical insights into the effects of irrigation on the crop performance. The matrices consistently show strong positive correlations among the growth parameters and yield. Yet, IW is negatively correlated with these factors, as de-

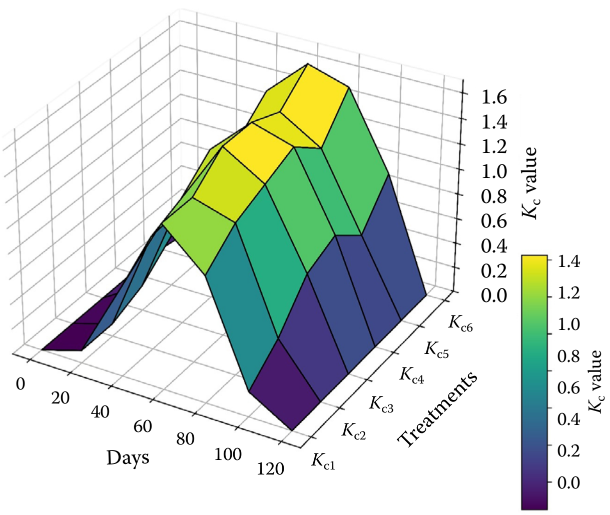

Figure 11. 3D Surface graph of the average crop coefficient (K_c) versus the days after sowing for 2023 and 2024 seasons under the open field and greenhouse conditions

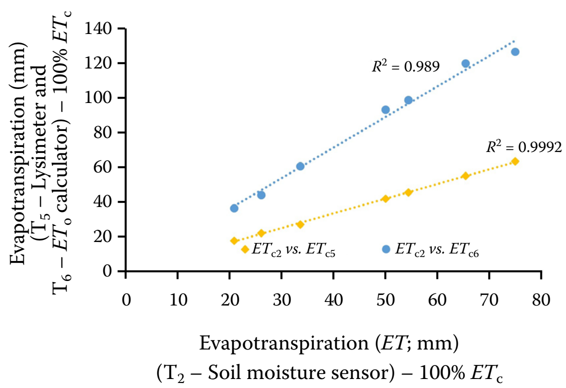

Figure 12. Scatter plot of the evapotranspiration performed for crops grown under different environments

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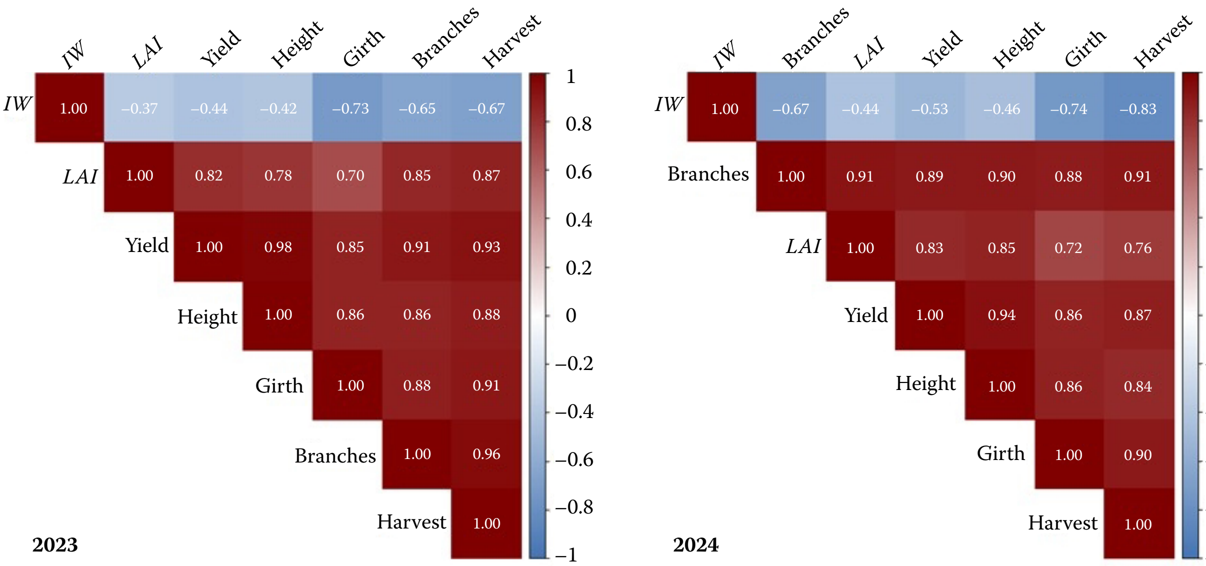

Figure 13. Pearson correlation performed for the morphometric parameters of all the treatments
IW – irrigation water; *LAI* – Leaf area index

picted in Figure 13. In particular, stronger negative correlations are observed in one dataset compared to the other, with values like the harvest (–0.67 *vs.* –0.83) and yield (–0.44 *vs.* –0.53). These negative correlations suggest that higher irrigation levels may be associated with decreased growth and yield, potentially indicating issues such as over-irrigation, leading to waterlogging or nutrient leaching, or the possibility of a non-linear relationship where mild water stress promotes more substantial growth (Awang Bono et al. 2024).

Conversely, the Leaf area index (*LAI*) exhibits strong positive correlations with the growth parameters and yield in both datasets (yield: 0.82 and 0.83; branches: 0.85 to 0.91), underscoring the critical role of canopy development in determining the crop productivity (Kohima et al. 2023). The strong positive correlations between the yield and other growth parameters (height: 0.94 to 0.98; branches: 0.89 to 0.91) further emphasise the interconnected nature of plant growth and yield, suggesting that management practices that enhance the plant structure will likely improve the overall crop productivity (Mandal et al. 2018).

Yield response factor (k_y) to water stress. The yield response factor (k_y) analyses for 2023 and 2024 and the average factor of the seasons illustrate the sensitivity of the crop yield to the evapotranspiration deficits across various treatments, underscoring the importance of strategic irrigation in maintaining the yield stability under water-limited conditions. Treatment T_5, with a k_y value of 0.13, demonstrated a low yield response to the water deficit. This indicates that the lysimeter-based irrigation significantly enhances the water use efficiency by sustaining yields even with reduced water availability. This is consistent with the findings of Ali et al. (2024), who highlighted the resilience associated with precise irrigation methods. Similarly, T_3, which recorded a k_y value of 0.29, showed moderate sensitivity to water stress, aligning with deficit irrigation strategies designed to conserve water while minimising the yield loss. This aligns with the work of Geerts and Raes (2009), who noted that deficit irrigation can optimise the water use while maintaining reasonable yield levels.

Conversely, treatments T_2 and T_4, with a k_y value of 1.00 and 1.2, respectively, exhibited a substantial or amplified decrease in the yield when faced with water deficits (Figure 14). This indicates a higher vulnerability to water stress and emphasises the necessity for consistent irrigation. These observations align with Graamans et al. (2018), who found that traditional irrigation methods are more susceptible to water stress than controlled irrigation approaches. The analyses for both years collectively emphasise the advantage of precise, sensor-controlled irrigation, as exemplified by T_5, which supports sustained productivity with reduced water input followed by T_3. In contrast, treatments such as T_2 and T_4 underscore the challenges faced with irrigation, leading to yield penalties.

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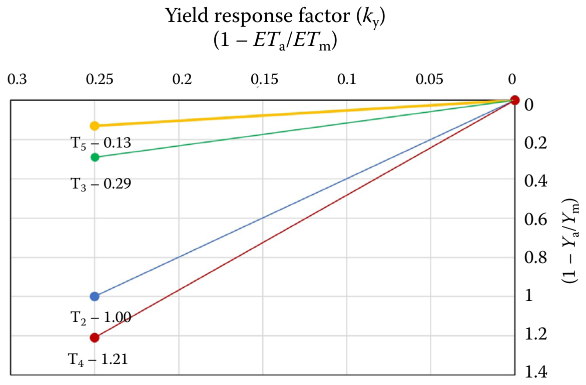

Figure 14. Average Yield response factor of both season
Y_a – actual yield of the crop; Y_m – maximum yield of the crop

The current study makes a novel contribution to precise irrigation management by assessing the crop coefficient (K_c) of greenhouse-grown okra using advanced soil water sensors (TEROS 10) and a digital lysimeter for greenhouse-grown okra. Stage-specific evapotranspiration patterns with clear changes in K_c from the initial through the middle to late growth phases validate the superior water use efficiency and yield potential under optimised drip irrigation regimes (T_2 and T_3 specifically). Controlled greenhouse conditions are shown to improve the water use efficiency (*WUE*) considerably while repressing the pesticide and labour use compared with open-field conditions. The findings also offer broader relevance for crop production in water-limited environments, demonstrating that precision-agriculture technologies in commercial greenhouses can enhance resource-use efficiency with environmental protection.

CONCLUSION

The analysis revealed that T_2 achieved a higher yield, followed closely by T_5, highlighting the effectiveness of optimal irrigation strategies under greenhouse conditions for maximising the productivity. Notably, T_3 exhibited higher water use efficiency (*WUE*) and water productivity (*WP*), showcasing the benefits of balanced water management practices that conserve water while sustaining the output. It was observed that crop water consumption recorded by sensors was, on average, 15% higher than that measured by the lysimeters. Despite this difference in the recorded water use, the yield showed negligible variation between the sensor-based and lysimeter-based irrigation. This finding underscores that both methods can be effectively utilised for precise water applications in greenhouse okra production. Adopting the crop coefficient (K_c) values from T_3 could enhance the *WP* and contribute to more sustainable water use. These results support using either sensors or lysimeters for irrigation management, ensuring economic efficiency and environmental sustainability. Therefore, incorporating the K_c pattern observed in T_3 as a guide during the initial (0.32), development (0.63), mid (0.78), and final stage (0.41) for irrigation scheduling offers a strategic approach to optimise the water productivity and maintain high productivity while addressing water conservation needs.

REFERENCES

Ahmet K., Ali U. (2009): Growth, yield, and water use of okra (*Abelmoschus esculentus*) and eggplant (*Solanum melongena*) are influenced by rooting volume. New Zealand Journal of Crop and Horticultural Science, 37: 201–210.

Ali N., Dong Y., Lavely E. (2024): Impact of irrigation scheduling on yield and water use efficiency of apples, peaches, and sweet cherries: A global meta-analysis. Agricultural Water Management, 306: 109148.

Awang Bono I.A., Kastaman R., Suryadi E., Rubiyanti Y. (2024): A study of irrigation management in smart farming and IoT for greenhouse tomato production. Journal of Electrical Systems, 20: 2616–2630.

Awari H.W., Ingle V.K., Khodke U.M., Balore K.A. (2023): Determination of crop coefficient of okra crop using lysimeter for semi-arid climatic condition of Parbhani, Maharashtra. Journal of Agricultural Engineering (India), 60: 311–319.

Buttaro D., Santamaria P., Signore A., Cantore V., Boari F., Montesano F.F., Parente A. (2015): Irrigation management of greenhouse tomato and cucumber using tensiometer: Effects on yield, quality and water use. Agriculture and Agricultural Science Procedia, 4: 440–444.

de Mendiburu F. (2019): Agricolae: Statistical procedures for agricultural research. R package version 1.3.

Elings A. (2000): Estimation of leaf area in tropical maize. Agronomy Journal, 92: 436–444.

El-Naggar A.G., Hedley C.B., Horne D., Roudier P., Clothier B.E. (2020): Soil sensing technology improves the application of irrigation water. Agricultural Water Management, 228: 105901.

https://doi.org/10.17221/31/2025-RAE

Geerts S., Raes D. (2009): Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agricultural Water Management, 96: 1275–1284.

Ghiat I., Mackey H.R., Al-Ansari T. (2021): A review of evapotranspiration measurements models, techniques, and methods for open and closed agriculture. Water, 13: 2523.

Graamans L., Baeza E., van den Dobbelsteen A., Tsafaras I., Stanghellini C. (2018): Plant factories versus greenhouses: Comparison of resource use efficiency. Agricultural Systems, 160: 31–43.

Hashemi S.Z., DarzNaftchali A., Karandish F., Ritzema H., Solaimani K. (2024): Enhancing agricultural sustainability with water and crop management strategies in modern irrigation and drainage networks. Agricultural Water Management, 305: 109110.

Imrana Farhan I., Sugirtharan M. (2023): Effect of surface and drip irrigation on growth, yield and water use efficiency of okra (*Abelmoschus esculentus*) – A review. Advances in Technology, 3: 1–19.

Jayapiratha V., Thushyanthy M., Sivakumar S. (2010): Performance evaluation of okra (*Abelmoschus esculentus*) under drip irrigation system. Asian Journal of Agricultural Research, 4: 139–147.

Kohima N., Samnotra R.K., Kumar S. (2023): Influence of okra (*Abelmoschus esculentus*) genotypes on growth, yield, and biochemical traits. Indian Journal of Agricultural Sciences, 93: 57–61.

Kumari A., Upadhyaya A., Jeet P., Al-Ansari N., Rajput J., Sundaram P.K., Saurabh K., Prakash V., Singh A.K., Raman R.K., Gaddikeri V., Kuriqi A. (2022): Estimation of actual evapotranspiration and crop coefficient of transplanted puddled rice using a modified non-weighing paddy lysimeter. Agronomy, 12: 2850.

Mandal K.G., Thakur A.K., Mohanty S. (2018): Planting techniques and irrigation influenced crop growth, light interception, and yield-evapotranspiration relationship of potatoes. International Journal of Plant Production, 12: 285–296.

Möhring N., Kanter D., Aziz T., Castro I.B., Maggi F., Schulte-Uebbing L., Seufert V., Tang F.H.M., Zhang X., Leadley P. (2023): Successful implementation of global targets to reduce nutrient and pesticide pollution requires suitable indicators. Nature Ecology and Evolution, 7: 1556–1559.

Moursy M.A.M., Abdel Kareem Nessrien S., Mustafa E.F., Elfetyany M. (2023): Assessing the application of modern irrigation systems under greenhouse and open field conditions on the productivity of different crops (eggplants case). Alexandria Engineering Journal, 77: 435–442.

Patil C.S. (2010): Crop coefficient and water requirement of okra (*Abelmoschus Esculentus* L. Moench). Mausam, 61: 121–124.

Shi W., Zhang X., Xue X., Feng F., Zheng W., Chen L. (2023): Analyzing evapotranspiration in greenhouses: A lysimeter-based calculation and evaluation approach. Agronomy, 13: 3059.

Subedi A., Chávez J.L., Andales A.A. (2017): ASCE-EWRI Standardized Penman-Monteith evapotranspiration (ET) equation performance in southeastern Colorado. Agricultural Water Management, 179: 74–80.

Tayyaba S., Ahmad M., Baig M.T., Kanwal S., Nazir M.Z., Sidra-Tul-Muntaha (2022): Remote sensing in precision agriculture for irrigation management. Environmental Sciences Proceedings – The 1st International Precision Agriculture Pakistan Conference 2022 (PAPC 2022) – Change the Culture of Agriculture, 23: 31.

Tiwari K.N., Mal P.K., Singh R.M., Chattopadhyay A. (1998): Response of okra [*Abelmoschus esculentus* (L.) Moench.] to drip irrigation under mulch and non-mulch conditions. Agricultural Water Management, 38: 91–102.

Yang P., Wu L., Cheng M., Fan J., Li S., Wang H., Qian L. (2023): Review on drip irrigation: Impact on crop yield, quality, and water productivity in China. Water, 15: 1–18.

Received: March 20, 2025
Accepted: August 8, 2025
Published online: December 15, 2025