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RESEARCH ARTICLE

Quantitative assessment of cotton evapotranspiration, irrigation requirements and water productivity from weather-based estimations

Gnanasekaran Madhavan[1], Sellaperumal Pazhanivelan[2]*, A P Sivamurugan[3], Dhanaraju Muthumanickam[4], Selvaraj Selvakumar[2] & Kaliaperumal Ragunath[2]

[1]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Centre for Water and Geospatial Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Department of Rice, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Department of Remote Sensing & GIS, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - pazhanivelans@tnau.ac.in

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Abstract

This study investigates the water requirements, evapotranspiration dynamics and water productivity of cotton (CO 17) under semi-arid climatic conditions across three cropping seasons (2023-2025) at Agricultural Research Station, Bhavanisagar. Field experiments were conducted on sandy loam soils with continuous monitoring of weather, soil moisture and crop parameters. The standardized FAO Penman-Monteith equation was used to compute daily reference evapotranspiration (ETo), while actual crop evapotranspiration (ETc) was estimated using both locally developed and FAO-based crop coefficient (Kc) curves derived as functions of thermal units. Seasonal ETc ranged from 386 to 607 mm and irrigation applied varied between 170 and 336 mm. Seed cotton yield ranged from 1997 to 2237 kg/ha and lint yield from 678.8 to 761.7 kg/ha, with corresponding water use efficiency (WUE) values between 0.107 and 0.155 kg/m^3 and water productivity (WP) from 0.32 to 0.46 kg/m^3. Statistical analyses, including paired t-tests and regression, confirmed no significant difference ($p > 0.05$) between local and FAO-based ETc estimates, while a strong linear relationship ($R^2 = 0.93$) was observed between adjusted ETc and irrigation applied. The locally calibrated Kc improved ETc estimation by better representing canopy development and climatic variability. Precisely scheduled irrigation and site-specific Kc calibration enhanced yield, water productivity and resource-use efficiency, emphasizing the importance of ET-based irrigation management for sustainable cotton production in water-limited environments.

Keywords: Cotton; crop coefficient; evapotranspiration; irrigation scheduling; Penman-Monteith ETo; water management; water use efficiency

Introduction

Cotton (*Gossypium hirsutum*) is the king of fibres, sustaining textile industries, contributing to rural livelihoods and serving as a critical driver of trade and agricultural development. Beyond lint, cotton by-products such as cottonseed oil and protein provide raw materials for biofuels and animal feed, enhancing its economic value (1). In India, cotton is a major cash crop that provides employment and income to millions of farmers, significantly contributing to the national economy through domestic textile markets and international exports (2). The role of cotton is particularly pronounced in Tamil Nadu, where cultivation supports rural households and the regional textile industry. The crop's adaptability across diverse soils and climatic zones strengthens its importance to the state's agricultural economy (3).

Globally, cotton covers about 29.6 million ha in 2025, with a projected output of 25.9 million tonnes (117 million bales) (4, 5). Major producers include China (24-26 %), India (20-21 %), followed by Brazil, the U.S. and Pakistan. The global average yield is around 875 kg/ha, with China and the U.S. leading in productivity, while India, despite having the largest area, records comparatively lower yields (Fig. 1-3) (6, 7). In India (2024), cotton covered 12.69 Mha, producing 32.52 million bales at an average yield of 436 kg/ha. Maharashtra had the largest area (4.23 Mha), while Gujarat achieved the highest productivity (574 kg/ha) and production (9.05 million bales) whereas Tamil Nadu recorded lower productivity (330 kg/ha) from 0.13 Mha (8).

Water availability is a decisive factor shaping cotton productivity, especially in arid and semi-arid regions where irrigation is indispensable. Cotton's crop water requirement and evapotranspiration (ETc) are strongly influenced by climate change, population growth and competing demands on water resources. Rising air temperatures induced by climate change elevate ETc and irrigation needs while simultaneously lowering effective rainfall and groundwater recharge (10, 11). This threatens the sustainability of cotton cultivation in water-limited environments. Future projections suggest that irrigation demand may increase from 163 mm to 192 mm under changing climate scenarios (12, 13). Meanwhile,

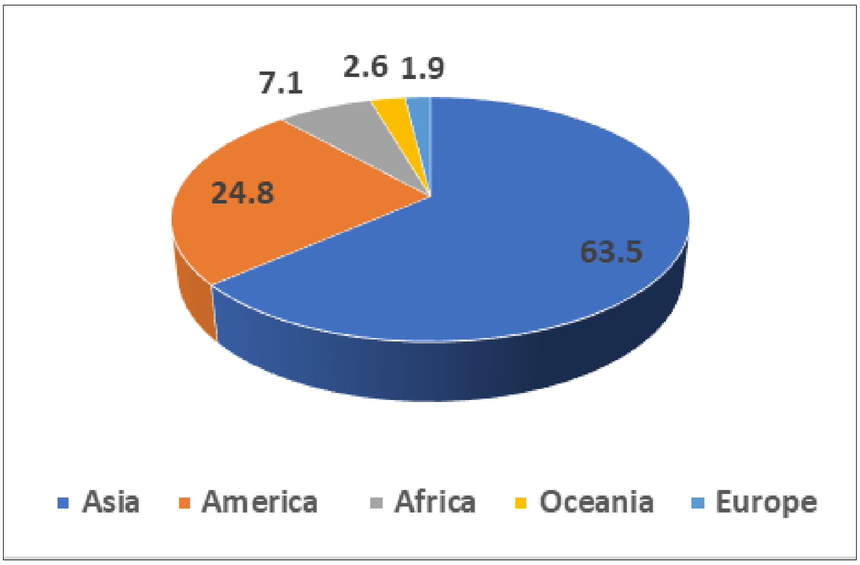


Fig. 1. Continental distribution of global cotton production (%) (9).

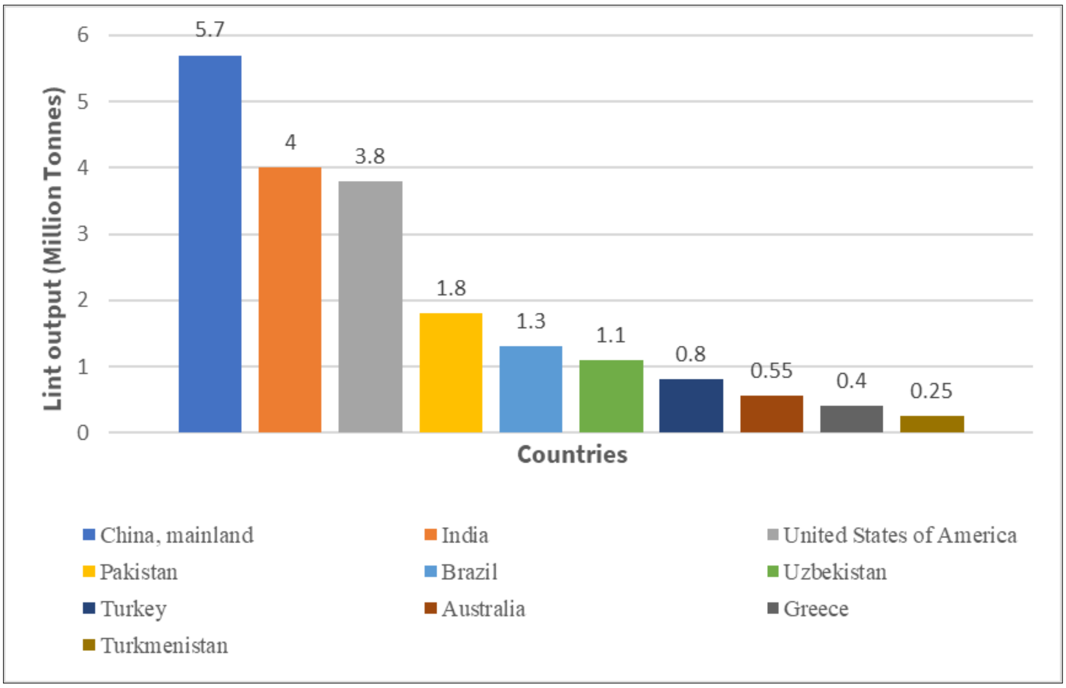


Fig. 2. Top cotton-producing countries (million tonnes) (9).

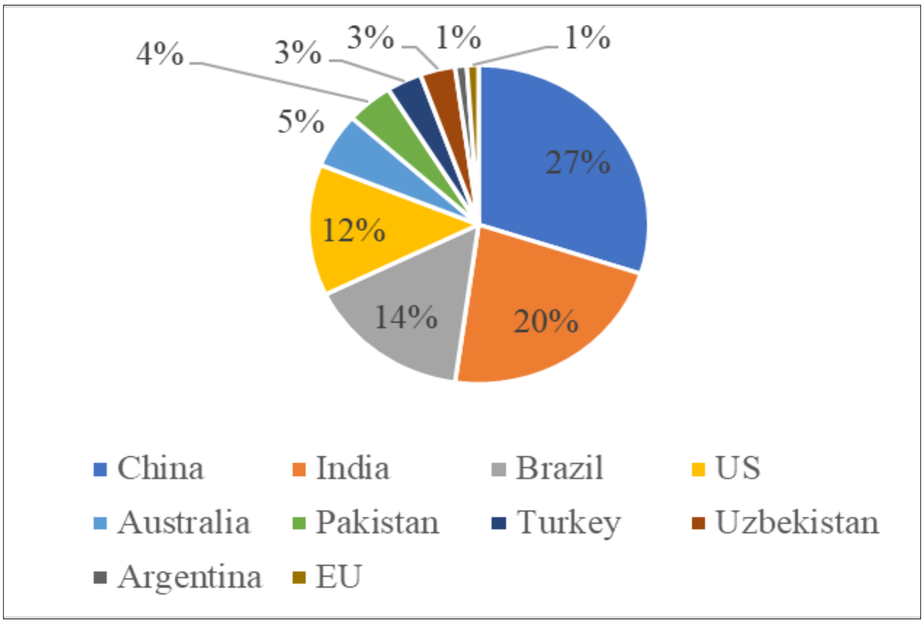


Fig. 3. Leading cotton producing countries by total production and global share (2024-2025) (9).

population growth and rising demand for food and fiber intensify competition for limited water, expanding cotton cultivation areas and heightening resource pressures.

To address these challenges, research highlights the importance of efficient irrigation strategies. Techniques such as deficit irrigation, mulching and improved irrigation scheduling have been proposed to save water while maintaining yield levels (14, 15). However, spatial and temporal variability in ETc complicates irrigation planning, as warming and droughts raise water demand in some regions, while altered or shortened growing seasons impact others (15). This underscores the need for precise estimation of evapotranspiration and irrigation water requirement. Evapotranspiration (ET) the combined process of soil water evaporation and plant transpiration represents the primary pathway of agricultural water use (16). Irrigation water requirement (IWR) is defined as the additional water needed to supplement effective rainfall to fully satisfy crop water demand (17). Accurate ET and IWR estimates are essential to conserve groundwater, prevent over-irrigation and reduce environmental stresses.

Equally significant is water productivity, often assessed using water use efficiency (WUE). Crop WUE, defined as yield per unit of total water use, reflects the ability of the plant to convert water into biomass (18). ET-WUE, which relates yield to evapotranspiration, captures the effectiveness of ET in producing output (16). Irrigation WUE, in contrast, measures yield per unit of irrigation applied, considering rainfall and effective rainfall in the cropping season (19). Lint yield, the main cotton product, best reflects economic value, profitability and irrigation efficiency, providing a standardized basis for water use efficiency. Enhancing all forms of WUE is fundamental to sustaining cotton productivity under water scarcity.

The accuracy of cotton water use estimation depends largely on crop coefficients (Kc), which link reference evapotranspiration (ETo) to actual ETc. While FAO Kc values, derived from global data under standard conditions, serve as guidelines, they may not fully capture local agro-climatic contexts. Locally derived Kc values better represent site-specific conditions such as climate, soil type, crop variety and management practices. To refine irrigation planning, statistical approaches such as regression analysis and t-tests are frequently employed to compare FAO and local Kc values (16, 20). Validation and calibration of Kc values are thus critical to ensuring accurate and locally relevant predictions of water use.

This study bridges the existing gap by providing site-specific validation and calibration of the FAO-56 crop coefficient (Kc), as the original coefficients were mainly developed under sub-humid to humid climatic conditions and may not accurately represent semi-arid environments like Tamil Nadu. Sustainable cotton production in water-scarce environments requires a quantitative understanding of crop water use, irrigation demand and water productivity (21). It is hypothesized that weather-based estimation of evapotranspiration (ETc), supported by locally calibrated crop coefficients (Kc), can accurately quantify cotton water use and irrigation requirements, thereby improving water productivity under the semi-arid climatic conditions of Tamil Nadu (22). Therefore, the study aims to quantitatively assess cotton water use and productivity under semi-arid conditions through weather-based estimations. Specifically, it seeks to estimate crop evapotranspiration (ETc) and irrigation water requirement (IWR) by integrating climatic variability and effective rainfall, evaluate water productivity under full irrigation and validate locally derived crop coefficient (Kc) values against FAO standards.

Materials and Methods

The field experiments were conducted at Agricultural Research Station (ARS), Bhavanisagar, Tamil Nadu Agricultural University (272 m above mean sea level). The soil is sandy loam with a bulk density of 1.36 g/cm^3, field capacity 21 %, permanent wilting point 10.2 %, hydraulic conductivity 0.40 cm/h, organic carbon 0.46 %, pH 6.9 and electrical conductivity 0.34 dS/m. Climate parameters including Tmax, Tmin, RHmax, RHmin, wind speed (2 m height) and solar radiation were recorded daily by meteorological observatory and automatic weather station at ARS, Bhavanisagar for three crop seasons and presented in Fig. 4. The trials were carried out for three cotton-growing seasons: Season 1 (25.08.2023-16.01.2025), Season 2 (09.03.2024-18.07.2024) and Season 3 (04.10.2024-21.02.2025). The site is characterized by a semiarid climate with seasonal variability in rainfall, temperature, relative humidity, wind speed and solar radiation. Cotton variety CO 17 was cultivated following the recommended practices as per the crop production guide (CPG), TNAU. The field experiment was laid out in a Randomized Block Design (RBD) with three replications. A spacing of 90 cm × 15 cm was adopted to maintain an optimum plant population of approximately 18,500 plants/hectare. The crop received a recommended dose of fertilizers (RDF) of 120:60:60 NPK kg/ha, applied as per standard agronomic practices to ensure uniform nutrient availability and optimal crop growth. Irrigation was scheduled through drip automation to maintain soil moisture depletion at 40-45 % of total available water, ensuring an optimal balance between crop growth, yield and water use. Based on the evidence reported by (23) for cotton, this threshold was adopted for CO 17 cultivated in sandy loam soils.

Reference evapotranspiration estimation

Daily grass-reference evapotranspiration (ETo) was calculated using the ASCE standardized Penman-Monteith equation (Eqn. 1) (24). The model incorporated parameters such as net radiation (Rn, MJ/m^2/day), soil heat flux density (G, MJ/m^2/day), mean air temperature (T, °C), wind speed at 2 m height (u_2, m/s), saturation vapor pressure (e_s, kPa), actual vapor pressure (e_a, kPa), slope of the saturation vapor pressure curve (Δ, kPa/°C) and the psychrometric constant (γ, kPa/°C).

$$ETo = \frac{0.408\,\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{(Eqn. 1)}$$

where ETo = reference evapotranspiration (mm/day), Cn = 900, Cd = 0.34. Net radiation (Rn) was calculated from solar radiation using standard relationships. Soil heat flux (G) was assumed as 0.1-0.2 × Rn during the cropping season based on (16, 25). Missing weather data (<2 % of daily records) was estimated using an interpolation method and sensor calibration was verified weekly against standard meteorological instruments.

Crop coefficients and actual ET estimation

Daily actual crop evapotranspiration (ETc) (Eqn. 2) was estimated by multiplying the crop coefficient (Kc) with the reference evapotranspiration (ETo) (Eqn. 1 and 3) (25).

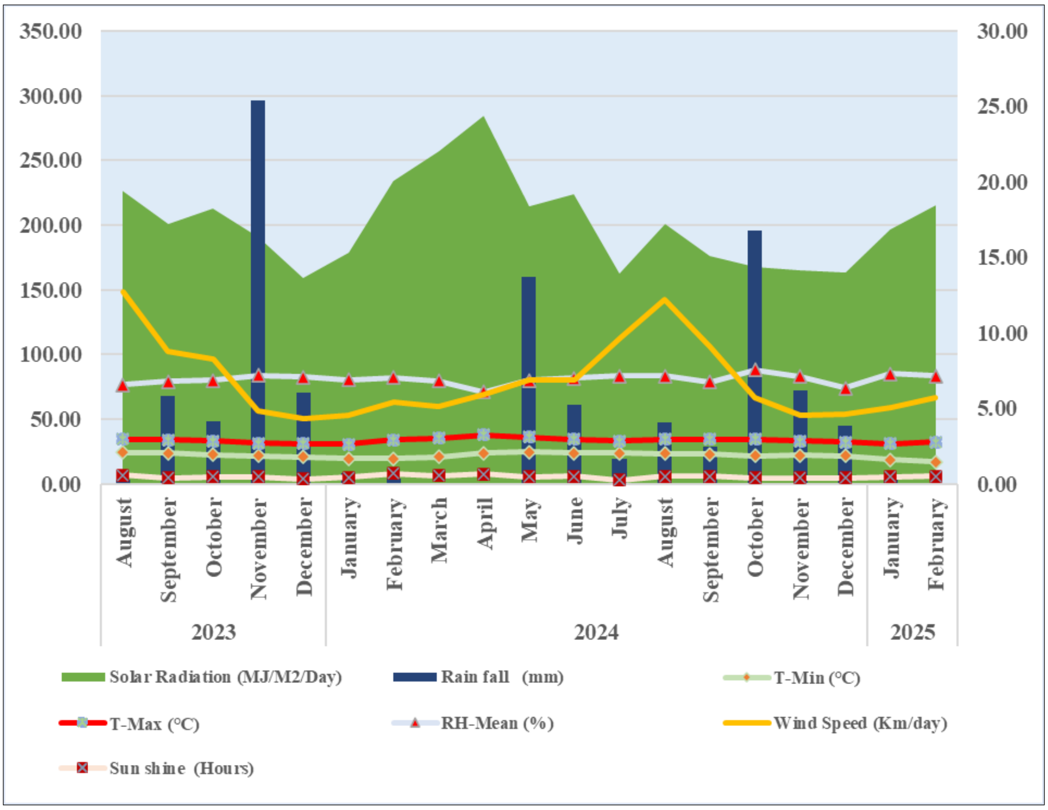


Fig. 4. Monthly weather trends across three cotton growing seasons

$$ETc = K_c \times ETo \qquad \text{(Eqn. 2)}$$

A locally developed Kc curve, based on thermal units (TU), was applied daily and compared with the FAO-56 standardized Kc values adjusted for local climatic conditions and crop height. The FAO Kc value for cotton initial stage (Kc_{ini}), mid-season (Kc_{mid}) and late season (Kc_{end}) is 0.35, 1.15 and 0.70, respectively (25). The locally developed Kc function was expressed as:

$$K_c = 0.12 + 0.00168 \times TU - 2.45 \times 10^{-7} \times TU^2 - 4.37 \times 10^{-10} \times TU^3 \qquad \text{(Eqn. 3)}$$

Where, K_c = daily crop coefficient, TU = thermal units (°C). A locally developed cotton crop coefficient curve was used based on accumulated thermal units (TU), adjusting the FAO-56 Kc values for local climate and crop height (Eqn. 4) (25). Adjusted FAO crop coefficient for mid and late growth stages:

Where: u_2 = wind speed at 2 m height (m/s), RH_{min} = minimum relative humidity (%), h = plant height (m). The adjustment factor $[0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \times (h/3)^{0.3}$

$$K_{c\_adj} = K_c + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \times \left(\frac{h}{3}\right)^{0.3} \qquad \text{(Eqn. 4)}$$

modifies the standard FAO crop coefficient (Kc) to account for the effects of local microclimate and crop canopy structure on evapotranspiration. The term $[0.04(u_2 - 2) - 0.004(RH_{min} - 45)]$ corrects for deviations in wind speed and minimum relative humidity from standard reference conditions (u_2 = 2 m/s and RHmin = 45 %), reflecting their influence on vapor pressure deficit and aerodynamic resistance. The multiplicative component $(h/3)^{0.3}$ adjusts for crop height, representing the non-linear increase in aerodynamic conductance with taller canopies. The exponent 0.3 is derived from boundary layer theory, which describes how turbulence and roughness elements within the canopy affect momentum and vapor transfer (16, 25).

Thermal units (TU) or growing degree days (GDD) (Eqn. 5) were calculated using daily maximum and minimum temperatures with a base temperature (T_{base}) as follows:

$$TU = \sum \frac{T_{max} + T_{min}}{2} - T_{base} \qquad \text{(Eqn. 5)}$$

Where, T_{max} = daily maximum temperature (°C), T_{min} = daily minimum temperature (°C), T_{base} = base temperature (15 °C for cotton). A base temperature (T_{base}) of 15 °C for cotton is crucial as crop growth and development markedly slow or cease below this threshold, making it the minimum temperature for accurate thermal time and growing degree day calculations (24).

Irrigation water requirement (IWR) is the amount of water that must be supplied through irrigation to meet the crop's evapotranspiration demand after accounting for effective rainfall for optimal growth and yield which is expressed as an equation 6:

$$IWR = ET_{crop} - P_e \qquad \text{(Eqn. 6)}$$

Where, IWR (mm/ha), ET_{crop} = Crop evapotranspiration (mm), P_e = Effective rainfall (mm). Effective rainfall (P_e) was estimated using the USDA Soil Conservation Service method (P_e = 0.8P - 0.2), suitable for semi-arid sandy loam soils. The calculated P_e showed strong agreement with gravimetric soil moisture data (R^2 = 0.84), confirming the method's reliability. (25, 26).

Water use efficiency and water productivity

Water use efficiency (WUE) and water productivity (WP) of cotton were computed using yield, seasonal evapotranspiration, irrigation water use and total water supply (Eqn. 7-10). Crop Water Use Efficiency (CWUE) was calculated as the ratio of lint yield (kg/ha) to the total water supply (m^3). Evapotranspiration Water Use Efficiency (ETWUE) was determined by dividing the lint yield (kg/ha) by the adjusted crop evapotranspiration (Adj. Kc ETc, m^3). Irrigation Water Use Efficiency (IWUE) was computed as the lint yield (kg/ha) per unit of irrigation water applied (m^3).

Water Productivity (WP), expressed in kg/ha-m^3, was obtained as the ratio of lint yield (kg/ha) to the total water supply (m^3). All WUE metrics have units of kg/m^3 (yield per unit water) (25, 27, 28). Lint yield was selected as it is the primary marketable product of cotton, directly reflecting economic value, profitability and irrigation efficiency, thereby providing a realistic and standardized basis for assessing water use efficiency and productivity (29). The following indices were calculated:

$$\text{Crop water use efficiency: CWUE} = \frac{\text{Lint yield (kg/ha)}}{\text{Total water supply (m}^3\text{)}} \quad \text{(Eqn. 7)}$$

$$\text{Evapotranspiration water use efficiency: ETWUE} = \frac{\text{Lint yield (kg/ha)}}{\text{Adj. Kc ETc(m3)}} \quad \text{(Eqn. 8)}$$

$$\text{Irrigation water use efficiency: IWUE} = \frac{\text{Lint yield (kg/ha)}}{\text{Irrigation applied(m}^3\text{)}} \quad \text{(Eqn. 9)}$$

$$\text{Water Productivity(kg/ha-m}^3\text{): WP} = \frac{\text{Lint yield (kg/ha)}}{\text{Total water supply (m}^3\text{)}} \quad \text{(Eqn. 10)}$$

Lint yield was determined from 1 kg representative seed cotton samples, calibrated with hand-ginned references (r = 0.98). Water volumes were converted (1 mm/ha = 10 m^3/ha).

Evaluation criteria

Preliminary analyses verified that the data met parametric assumptions: the Shapiro-Wilk test confirmed normality ($p > 0.05$) and Levene's test verified homogeneity of variances ($p > 0.05$). No outliers exceeding three standard deviations were detected. Paired t-tests were conducted on three seasonal ETc observations derived from locally calibrated and FAO Kc values, while regression analyses included 45 daily ETc data points from three cotton seasons. Given three regression analyses were performed, Bonferroni correction was applied with an adjusted significance level of $\alpha = 0.0167$. (20, 30).

Results and Discussion

The three cotton crop seasons (Table 1) showed distinct water supply and evapotranspiration patterns. In Season 1, the total water supply was 663.2 mm (170 mm irrigation + 493.2 mm rainfall), with effective rainfall of 332.1 mm. FAO-based crop evapotranspiration (ETc) was 410.9 mm, while the adjusted ETc (Adj Kc) was higher at 473.6 mm. Season 2 received 577 mm (336.1 mm irrigation + 240.9 mm rainfall), with effective rainfall 187 mm. FAO ETc was 495.7 mm, whereas adjusted ETc reached 607.2 mm. Despite the highest irrigation and adjusted ETc in Season 2, the lint yield and ET-WUE were lower, likely because excess moisture reduced root activity and favored vegetative growth over reproductive development. High humidity and intermittent rainfall further increased evaporative losses and disease incidence, indicating that greater water input did not necessarily guarantee higher yield efficiency without precise irrigation scheduling. Season 3 had 490.4 mm (174.3 mm irrigation + 316.1 mm rainfall), with effective rainfall 231.9 mm; FAO ETc was 386.4 mm compared to 428.1 mm under adjusted values. These results align with reports that cotton generally requires 550-950 mm water depending on climate and management (31, 32). The higher adjusted ETc values emphasize the importance of locally calibrated crop coefficients to capture canopy development and climatic variability (25, 33). Seasonal variation in effective rainfall highlights the need for supplemental irrigation to maintain optimal water status, as both deficit and excess water adversely affect yield and fiber quality (34-36).

Seasonal cotton yields (Table 2) varied across the three crop cycles. Season 1 recorded a seed cotton yield of 2142 kg/ha, lint yield of 710.5 kg/ha and cotton seed yield of 1389.3 kg/ha. Season 2 was slightly lower, with 1997 kg/ha seed cotton, 678.8 kg/ha lint and 1280.3 kg/ha seed yields, indicating that increased water supply did not translate into proportional yield improvement. Although the highest irrigation (336.1 mm) and adjusted ETc (607.2 mm) were recorded in Season 2, lint yield and ET-WUE were lower, likely because excess moisture reduced root activity and promoted vegetative growth over reproductive development. High humidity and intermittent rainfall further increased evaporative losses and disease incidence, indicating that greater water input did not guarantee higher yield efficiency without precise irrigation timing. Season 3 achieved the highest productivity, with 2237 kg/ha seed cotton, 761.7 kg/ha lint and 1456.1 kg/ha seed yields. The improved performance in Season 3 despite lower total water input suggests that optimal irrigation timing and balanced soil moisture favored reproductive growth and boll retention.

This indicates that water use efficiency depends more on irrigation scheduling than on the total volume applied. The results also indicate strong correlations between seed cotton

Table 2. Seasonal variation in seed cotton, lint and cotton seed yields

Season	Seed cotton yield	Lint yield	Cotton seed yield
		(kg/ha)	
1	2142	710.5	1389.3
2	1997	678.8	1280.3
3	2237	761.7	1456.1

Note: Seed cotton yield represents the total harvested cotton, while lint yield is the marketable fiber portion and cotton seed yield is the by-product.

Table 1. Seasonal water input, effective rainfall and ETc-based irrigation estimate for cotton

Season	Irrigation Applied	Rainfall	Total water supply	Effective rainfall	ETc FAO	Irrigation FAO	ETc Adj Kc	Irrigation Adj Kc
				(mm)				
1	170	493.2	663.2	332.1	410.9	130.7	473.6	153.5
2	336.1	240.9	577	187	495.7	309.4	607.2	381.4
3	174.3	316.1	490.4	231.9	386.4	247.6	428.1	277.6

Note: ETc FAO and Irrigation FAO were estimated using FAO-56 method (24). ETc Adj Kc and Irrigation Adj Kc were calculated using locally adjusted crop coefficients.

yield and its components, consistent with cotton physiology and production studies (37, 38). Lint yield, determined by ginning outturn, generally accounts for 30-40 % of seed cotton under favorable agronomic practices (39, 40). The observed lint-to-seed cotton ratios fall within this range, supporting data reliability. Yield variation between seasons reflects differences in effective rainfall and irrigation patterns, highlighting the influence of water supply on cotton productivity. Aligning irrigation with crop evapotranspiration enhances both lint and seed yields (41, 42). Seed cotton yield remains a key indicator of economic returns, with lint contributing to the textile sector and seed serving as a valuable oil and feed resource.

Water use efficiency (WUE) indicators (Table 3) varied notably across the three cotton seasons. Crop WUE ranged from 0.107 to 0.155 kg/m^3, with the highest value in season 3, reflecting better yield per unit of combined irrigation and rainfall. ET-based WUE peaked in season 1 (0.15 kg/m^3) but was lowest in season 2 (0.11 kg/m^3), showing that crop productivity was closely linked to water transpired. Irrigation WUE was highest in season 1 (0.463 kg/m^3), compared to 0.178 and 0.274 in seasons 2 and 3, respectively, indicating more effective use of irrigation water in the first season. Seasonal variations were consistent with earlier studies in semi-arid systems, where WUE is influenced by irrigation scheduling, crop stage and climatic conditions (43, 44). The higher efficiency in season 1 points to balanced water supply and timely irrigation, while the low values in season 2 suggest excess irrigation or evaporative losses. Water productivity (WP) also varied, being lowest in season 1 (0.32 kg/m^3) and highest in season 3 (0.46 kg/m^3). Moderate WP in season 2 (0.35 kg/m^3) reflected better alignment between supply and demand. The contrasting WUE and WP trends indicate that efficient water use was governed more by timing and distribution than total water applied. Season 1's high irrigation WUE reflected precise irrigation matching crop demand, whereas Season 2's low efficiency likely resulted from excess moisture and higher non-productive losses. Season 3 achieved the best overall water productivity, showing that balanced rainfall and irrigation improved conversion of water into yield. These results emphasize that precision irrigation, accurate ETc estimation and effective rainfall use are vital to improving WUE and WP in semi-arid cotton cultivation (45-47).

Table 3. Seasonal water use efficiency (Crop, ET-Based and Irrigation) in cotton

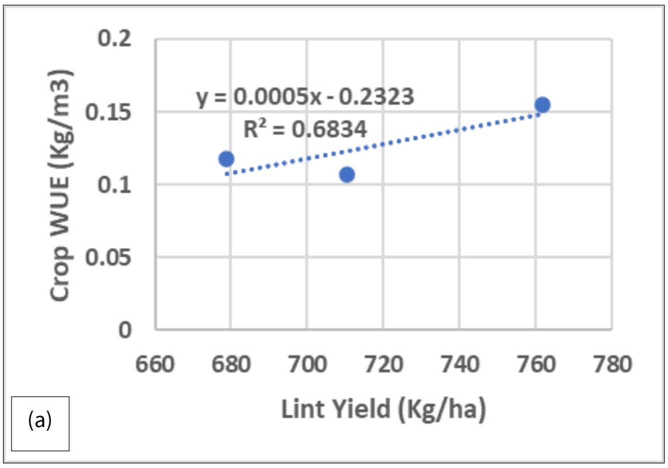
Season	Crop WUE	ET - WUE	Irrigation WUE	Water productivity
			(kg/ha-m³)	
1	0.107	0.15	0.463	0.32
2	0.118	0.11	0.178	0.35
3	0.155	0.18	0.274	0.46

Note: Crop Water Use Efficiency (Crop WUE) = Lint yield / Total water supplied; Evapotranspiration Water Use Efficiency (ET-WUE) = Lint yield / Crop evapotranspiration (ETc); Irrigation Water Use Efficiency (Irrigation WUE) = Lint yield / Irrigation applied; Water productivity represents lint yield per unit water.

Fig. 5a depicts the regression analysis showed a positive relationship between lint yield and crop WUE in cotton (y = 0.0005 x - 0.2323; R^2 = 0.6834), with lint yield explaining 68 % of WUE variation (48). Higher yields were associated with improved WUE, likely due to effective irrigation scheduling, favorable growing conditions and balanced water supply (43, 44, 46, 49). This relationship underscores the reliability of climate-based water requirement estimation models for semi-arid cotton systems and highlights the potential of precision irrigation technologies to apply ETc-derived indices for real-time water management and conservation.

Additionally, Fig. 5b shows regression between ETc adjusted by crop coefficient (ETc Adj Kc) and irrigation applied (y = 0.9476x + 288.04; R^2 = 0.9288) demonstrated a strong linear relationship, with 93 % of irrigation variation explained by ETc. The near-unity slope indicates that each additional mm of ETc corresponds closely to increased irrigation requirements. The adjusted ETc (Adj Kc) proved to be a reliable predictor for irrigation scheduling, consistent with FAO-56 guidelines (25). ET-based irrigation enhanced both water efficiency and yield stability in cotton (33, 46), reinforcing the robustness of climate-based water requirement models for semi-arid systems. This also underscores the potential of precision irrigation technologies to apply ETc-derived indices for real-time irrigation decisions and water-saving management.

Fig. 6a states the regression between lint yield and ET-WUE in cotton showed a strong positive relationship (y = 0.0008x - 0.4083; R^2 = 0.9505), with lint yield explaining over 95 % of ET-WUE variability. Higher lint yields were strongly associated with improved ET-WUE, emphasizing the role of productive cultivars and efficient agronomic practices. Consistent with earlier studies, WUE increased when irrigation matched crop evapotranspiration (43, 44). ET-WUE serves



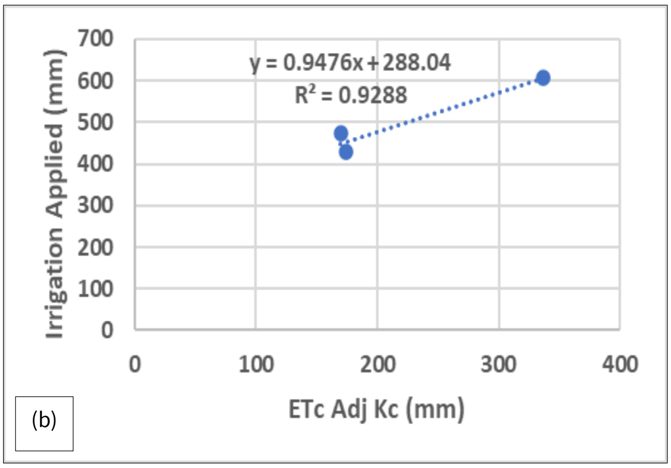


Fig. 5. Relationships in cotton (CO 17) under semi-arid conditions.
(a) Relationship between lint yield and crop water use efficiency.
(b) Relationship between irrigation applied and adjusted crop evapotranspiration (ETc, Kc adjusted).

as a key indicator for maximizing cotton productivity under limited water while ensuring sustainable resource use. The strong correlation between yield and evapotranspiration efficiency suggests minimal non-productive water losses, highlighting that combining genetic improvement with precise water management can greatly enhance water productivity and yield stability.

Conversely, Fig. 6b observes the regression between total water supply and lint yield showed a negative slope ($y = -0.2968x + 888.2$; $R^2 = 0.3756$), explaining 38 % of yield variation. Excess water can lower yield through waterlogging, nutrient loss and improper irrigation timing. The weak correlation suggests that factors such as soil quality, crop management and varietal traits also play major roles, highlighting the need for precise irrigation scheduling and efficient rainfall use rather than maximizing water input (46). This negative trend confirms that higher water application does not always translate to greater yield, as over-irrigation can induce physiological and soil-related stress. Therefore, aligning irrigation with ETc demand ensures optimal water use, minimizes losses and sustains long-term productivity.

Fig. 7a gives the regression between ETc Adj Kc and lint yield in cotton showed a strong negative relationship ($y = -0.412x + 924.21$; $R^2 = 0.8404$), indicating that higher crop evapotranspiration reflecting excess water use or increased evaporative demand, reduces yield. Excess ETc likely caused waterlogging, excessive vegetative growth, or stress from unfavorable conditions, emphasizing that optimal yields occur under moderate, balanced Etc (24). Precision irrigation aligning water supply with crop demand is therefore critical to sustain both lint yield and water productivity. The strong negative trend highlights that beyond a physiological threshold, additional evapotranspiration contributes little to productive biomass formation. This demonstrates the need to identify crop-specific ETc limits where photosynthetic efficiency and reproductive allocation remain maximized without inducing water stress or wastage (33, 46).

Similarly, Fig. 7b provide the regression between irrigation applied and irrigation WUE demonstrated a negative correlation ($y = -0.0012x + 0.5739$; $R^2 = 0.5991$), with WUE declining as irrigation increased. Over-irrigation decreased efficiency through runoff, percolation and evaporation losses, whereas moderate, well-timed irrigation aligned with crop growth stages achieved optimal WUE. These results emphasize the value of ETc-based irrigation scheduling and soil moisture monitoring to sustain cotton yield under limited water availability (36, 44). The decline in WUE with higher irrigation volumes indicates diminishing returns from excessive water use. Incorporating decision-support tools like soil moisture sensors or ET-based controllers can help optimize

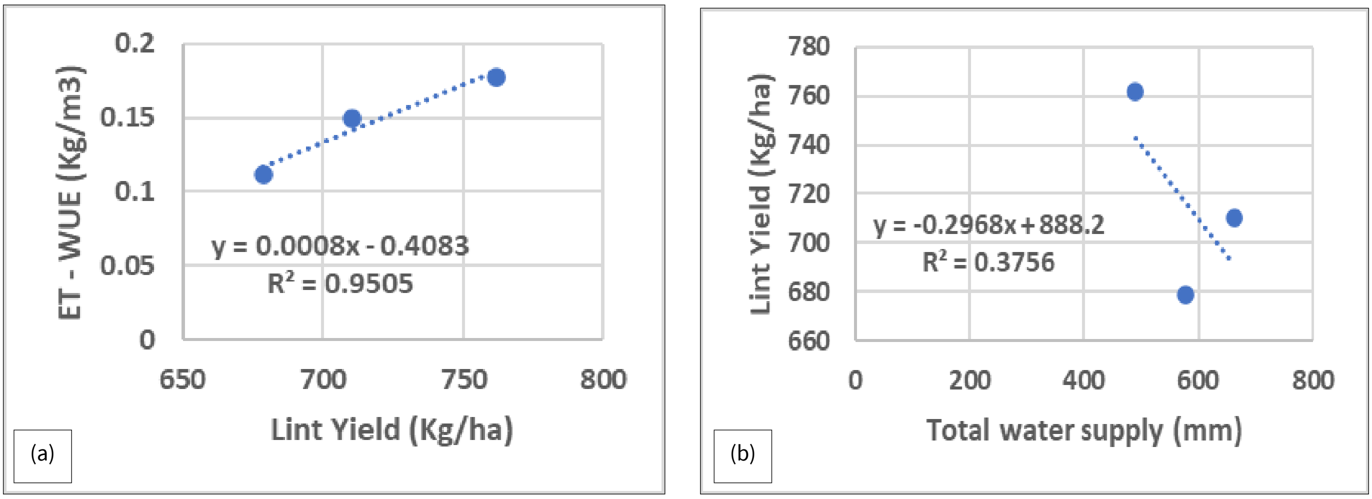


Fig. 6. Relationships in cotton (CO 17) under semi-arid conditions.
(a) Relationship between ET-water use efficiency and lint yield.
(b) Effect of total water supply on lint yield.

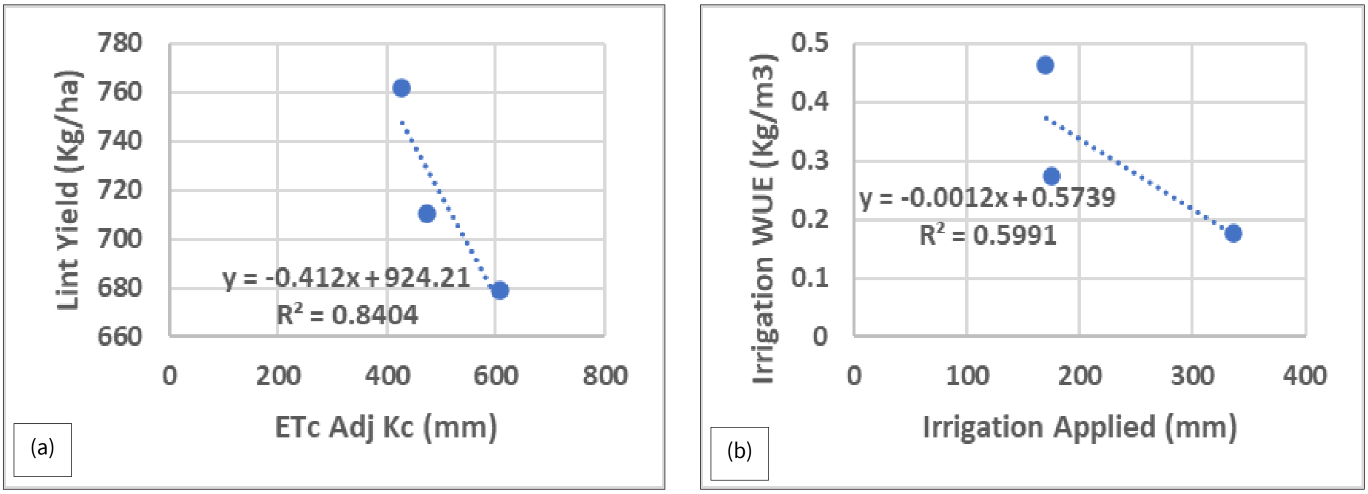


Fig. 7. Relationships in cotton (CO 17) under semi-arid conditions.
(a) Relationship between lint yield and adjusted crop coefficient ETc.
(b) Effect of irrigation applied on irrigation water use efficiency.

irrigation frequency, ensuring each unit of water contributes effectively to yield.

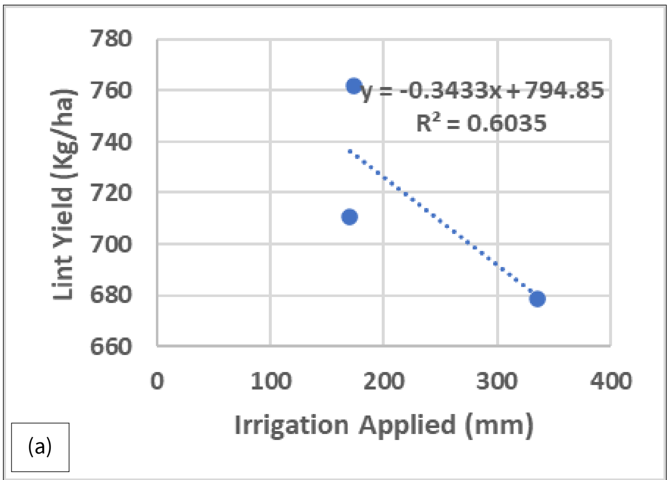
Fig. 8a shows the regression between irrigation applied and lint yield in cotton showed a negative relationship (y = -0.3433x + 794.85; R^2 = 0.6035), indicating that increasing irrigation reduced yield, likely due to waterlogging, nutrient leaching or stress conditions. Irrigation accounted for about 60 % of the yield variation, with additional effects from agronomic and climatic factors. Moderate irrigation was found to maximize cotton yield, while excess water reduced aeration, delayed maturity and increased pest or disease incidence (44). Precision approaches such as ETc (Adj Kc)-based scheduling, deficit irrigation and soil moisture monitoring are therefore crucial for sustaining high yields (33, 43). The inverse relationship indicates that greater irrigation does not always improve productivity, as cotton performs best within a narrow moisture range. Defining crop-specific irrigation thresholds can strengthen system resilience, conserve water and reduce adverse soil-plant interactions under variable climatic conditions (25, 46, 49).

Similarly, Fig. 8b depicts the regression between irrigation applied and ET-WUE showed a strong negative relationship (y = -0.0003x + 0.218; R^2 = 0.8054), with higher irrigation reducing ET-WUE and explaining 81 % of its variability. Declines resulted from inefficiencies such as runoff, deep percolation and non-productive transpiration. Optimal ET-WUE was achieved through well-timed, moderate irrigation synchronized with crop evapotranspiration. Efficient water management improved yield, biomass and nutrient uptake while reducing water losses, supporting sustainable cotton production (50). The strong influence of irrigation on ET-WUE suggests that even minor deviations from optimal water supply can significantly impact efficiency. Incorporating remote-sensing-based ETc estimation and automated irrigation scheduling can further optimize water application, enhancing productivity and long-term sustainability in cotton systems.

Fig. 9a gives the regression between total water supply and crop WUE (kg/m^3) in cotton showed a strong negative relationship (y = -0.0003x + 0.2876; R^2 = 0.9049), indicating that excessive water sharply reduces water productivity through runoff, percolation, nutrient leaching or waterlogging. The high R^2 indicates that water supply largely determines WUE variation. Optimal efficiency is achieved when irrigation matches crop demand, as excess water seldom increases yield proportionally and often promotes vegetative rather than reproductive growth. Accurate scheduling, evapotranspiration-based management and integrated soil-water monitoring are therefore vital to sustain both yield and WUE (43). The strong inverse correlation shows that WUE drops sharply once the optimal water threshold is exceeded, underscoring the importance of fine-tuning irrigation frequency and depth to real-time crop needs for sustainable yield and resource efficiency.

Fig. 9b draws regression between FAO-based irrigation and adjusted crop coefficient irrigation (Adj Kc) showed a near-perfect linear relationship (y = 1.2477x - 15.191; R^2 = 0.9846), with adjusted irrigation consistently exceeding FAO estimates. The slope greater than unity reflects the influence of local climatic and crop-specific factors-particularly higher wind speed, lower relative humidity and the vigorous growth characteristics of the cotton variety CO 17 cultivated under semi-arid conditions. These factors collectively contributed to elevated actual evapotranspiration, thereby resulting in higher locally adjusted Kc values. While FAO-56 coefficients provide a robust global reference, their calibration under sub-humid to humid environments may underestimate ET in semi-arid regions. The locally derived Kc values thus enhanced the precision of irrigation estimation, aligning more closely with field-measured data and improving water productivity. This strong correlation reinforces the validity of the FAO-56 framework while demonstrating that site -specific adjustment of Kc is essential for accurate irrigation scheduling and sustainable water resource management under regional climatic variability.

Fig. 10a observes the regression between irrigation WUE and crop WUE in cotton showed a weak, inverse relationship (y = -0.067x + 0.1471; R^2 = 0.1471), explaining only 15 % of crop WUE variability. The negative slope indicates that higher irrigation WUE does not always enhance overall water efficiency, likely due to the combined effects of rainfall, seasonal crop responses and soil moisture variability (36, 43). This weak association suggests that irrigation efficiency alone cannot fully represent the complex water dynamics affecting crop performance. Therefore, incorporating rainfall use efficiency and soil water storage dynamics is essential for a more comprehensive evaluation of total system water productivity.



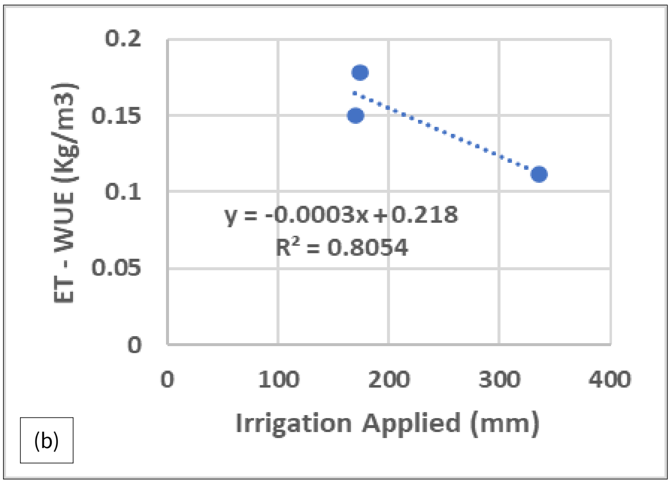


Fig. 8. Relationships in cotton (CO 17) under semi-arid conditions.
(a) Relationship between irrigation applied and lint yield.
(b) Effect of irrigation applied on ET-based water use efficiency.

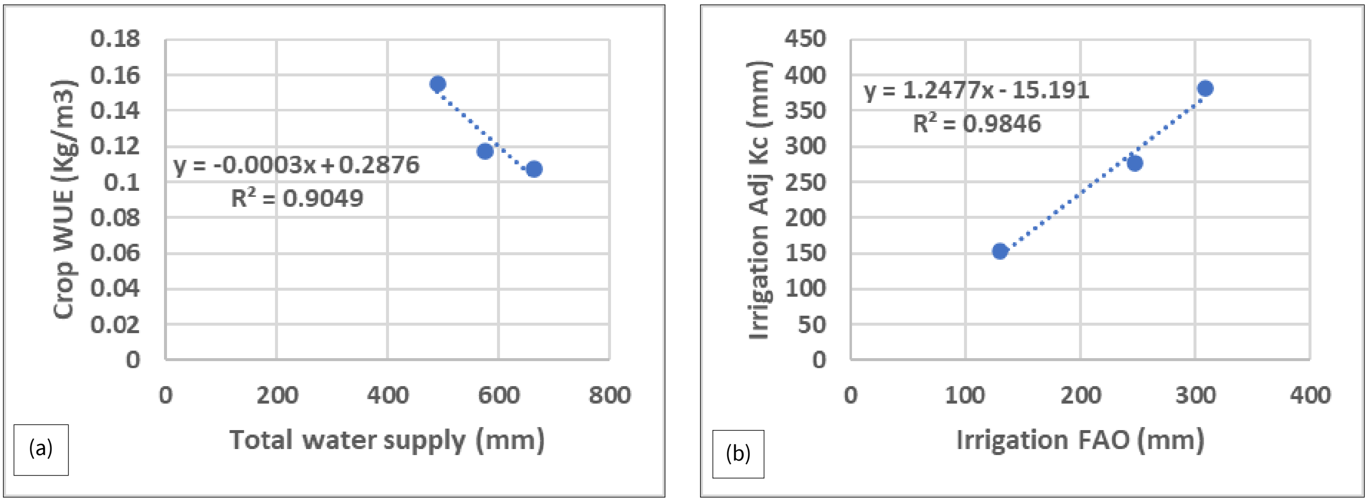


Fig. 9. Relationships in cotton (CO 17) under semi-arid conditions.
(a) Relationship between total water supply and crop water use efficiency.
(b) Comparison of FAO irrigation and adjusted crop coefficient (Kc) irrigation.

Similarly, Fig. 10b gives regression between ET-WUE and irrigation WUE (y = 1.8132x + 0.0393; R^2 = 0.1725) indicated a weak positive correlation, with ET-WUE explaining only 17 % of irrigation WUE variability. The scattered data in both cases reflect the influence of environmental, management and climatic factors. These findings indicate that optimizing ET-WUE or irrigation WUE alone is inadequate to achieve maximum water efficiency. Integrated water management-combining precise irrigation scheduling, effective rainfall uses and improved agronomic practices-is crucial to enhance crop performance and overall water productivity in cotton (14). The low explanatory power also suggests that microclimatic variability, canopy structure and management-induced differences significantly influence efficiency indices. Developing composite WUE metrics that integrate both and irrigation-based components could more accurately represent true system-level efficiency.

Fig. 11 depicts the regression between seed cotton yield and lint yield in cotton showed a strong positive relationship (y = 0.335x + 4.9849; R^2 = 0.9366), with 94 % of variability explained. Higher seed cotton yield was strongly associated with increased lint yield, reflecting efficient ginning outturn. This strong correlation allows reliable prediction of lint yield, aiding agronomic planning, economic assessment and crop management (37). Enhancing seed cotton yield through genetic improvement and optimized management directly boosts lint production, making it a key indicator of cotton productivity. The close relationship also indicates effective assimilate partitioning toward fiber development, confirming that improved crop growth, boll retention and ginning efficiency can collectively enhance lint yield without additional resource inputs.

Evapotranspiration (ET) estimation and irrigation scheduling are complex due to interactions among weather, soil and crop factors. Integrating machine learning and dynamic modeling has enhanced ET and crop coefficient (Kc) estimation, enabling precise irrigation under data-scarce conditions (51, 52). These computational approaches process large climatic datasets, predict Kc variations and support real-time irrigation decisions. Climate-resilient cotton frameworks integrating adaptive irrigation and stress -tolerant cultivars have improved yield stability in semi-arid regions (53). In India, region-specific irrigation management is essential due to spatial productivity variability (54). Dynamic, sensor-based irrigation systems further optimize water allocation, supporting climate-smart and resource-efficient cotton cultivation (55).

Conclusion

This study demonstrated that weather-based estimation of evapotranspiration (ETc) using locally calibrated crop coefficients (Kc) is a reliable method for quantifying cotton water use and irrigation demand under semi-arid conditions. Irrigation aligned with crop water requirements maximized lint yield and

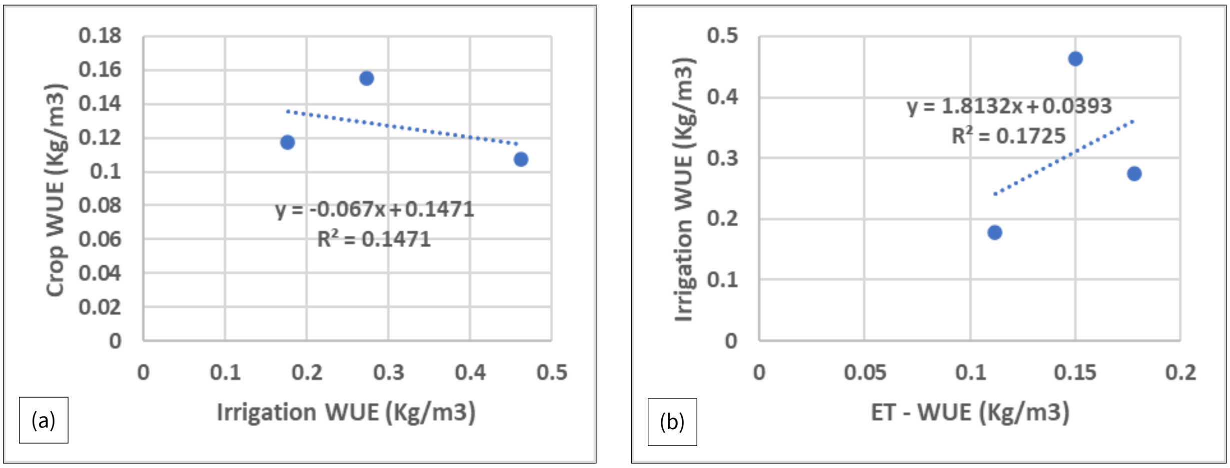


Fig. 10. Relationships in cotton (CO 17) under semi-arid conditions.
(a) Relationship between irrigation water use efficiency and crop WUE.
(b) Relationship between ET-based water use efficiency and irrigation WUE.

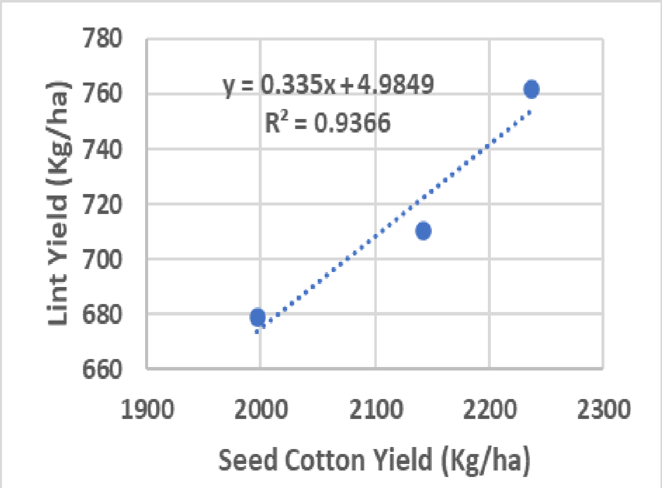


Fig. 11. Relationship between seed cotton yield and lint yield in cotton.

water use efficiency, while excessive irrigation reduced both. For practical use, farmers and irrigation planners are advised to adopt the locally developed Kc equation (Eqn. 3) for irrigation scheduling in semi-arid conditions. Applying irrigation consistent with adjusted ETc ensures optimal water use, higher yield and reduced water loss. The site-specific Kc approach is particularly effective for cotton grown on clay loam soils influenced by local microclimates. Thus, precision irrigation using ETc modeling and local Kc calibration enhances water conservation and yield stability.

Future Thrust

Future research should focus on integrating remote sensing-based ET estimation with ground-truth weather data to refine spatio-temporal variability in cotton water use. Developing dynamic crop coefficient (Kc) models that respond to real-time climatic fluctuations and soil moisture variations can further improve irrigation scheduling. Moreover, incorporating machine learning and decision-support systems will enhance predictive accuracy and enable scalable, climate-smart irrigation strategies for sustainable cotton production under semi-arid ecosystems.

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Authors' contributions

GM Conceptualization, study design, methodology, data collection, formal analysis and writing original draft preparation. SP Supervision, validation of data, review and editing of the manuscript and correspondence. APS Experimental guidance, field management and support in data collection. DM Data analysis, interpretation of results and preparation of figures and tables. SS Literature review, drafting sections of the introduction and discussion and manuscript editing. KR Guidance on experimental design, critical review and final approval of the manuscript. All authors read and approve the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

Ethical issues: This study did not involve human participants or animals; therefore, ethical approval was not required.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors acknowledge the use of AI (ChatGPT) for grammatical corrections and language editing during the preparation of this manuscript. Following its use, the authors thoroughly reviewed and revised the content as necessary, taking full responsibility for the accuracy and integrity of the publication.

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