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REVIEW ARTICLE

Advancing irrigation practices for sustainable cotton production: A comprehensive review of methods, models and water use efficiency

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Abstract

Water management plays a vital role in the sustainable cultivation of cotton (*Gossypium hirsutum* L.), a globally significant cash crop. Effective irrigation practices are essential to enhance water use efficiency (WUE), optimize yield and maintain fiber quality amid challenges like declining water resources and changing climatic conditions. This review critically examines various irrigation methods, including surface irrigation, drip irrigation (surface and subsurface) and advanced systems like Low-Energy Precision Application (LEPA), Low-Elevation Spray Application (LESA) and Mobile Drip Irrigation (MDI). Modernized methods, particularly subsurface drip irrigation, have proven the most efficient in conserving water and increasing yields by minimizing soil evaporation and ensuring precise water delivery to the root zone. Additionally, the role of irrigation models such as AquaCrop, EPIC, Cotton2K and CROPGRO-Cotton, is discussed in relation to their ability to simulate crop growth and optimize irrigation schedules based on local conditions. The review highlights the importance of understanding crop coefficients (Kc), evapotranspiration and region-specific water requirements in tailoring irrigation strategies. Future outlooks emphasize the integration of advanced irrigation technologies with precision farming to enhance WUE and promote sustainable cotton production. By focusing on localized solutions and fostering the adoption of modern irrigation systems, farmers can address water scarcity challenges while achieving better yields and fiber quality, ensuring long-term economic and environmental sustainability.

Keywords: cotton; irrigation methods; Kc; water use efficiency; yield

Introduction

Given declining water supplies and shifting environmental circumstances, it is imperative to optimize the management of irrigation water in cotton farming systems. Cotton (*Gossypium hirsutum* L.) is an important fiber crop, often referred to as "White gold". Globally, cotton is vital to the textile industry and contributes significantly to the Gross Domestic Product (GDP) of many countries. This cash crop provides livelihood for many of agricultural labours in India. In India, Cotton is cultivated on approximately 125.55 lakh hectares, with a production of about 316.57 lakh bales (1). Cotton is a deep-rooted crop; irrigation plays a key role for cotton boll development and fiber quality. Cotton requires between 700 and 1300 mm of water every growing season, depending on the environment and duration of the growing season (ETm) (FAO, 2023). Crop water requirements are minimal during the early vegetative stage, making up only around 10 % of the total. Water requirements peak during the flowering phase, accounting for 50-60 % of the total water demand, as the leaf area reaches its maximum. The requirements decrease as the growth phase progresses (2).

Nowadays trends have changed to modernized irrigation methods like surface drip irrigation and subsurface irrigation systems. This calls for the implementation of enhanced and effective methods for applying water, aiming to boost crop yields through improved irrigation practices (3, 4). In cotton cultivation, the use of drip irrigation led to water savings ranging from 18 % to 42 % compared to furrow irrigation (5). Additionally, it achieved water savings of up to 62.1 % compared to the surface flood method, as shown earlier (6). Subsurface drip irrigation holds significant potential for enhancing water management in arid and semi-arid areas by delivering water and nutrients to the field with greater precision in terms of both location and amount. This precision leads to increased efficiency in water and nutrient utilization (7), as water and nutrients are applied directly beneath the soil surface where evaporation is minimized, particularly in the predominantly dry topsoil layer. Sub-surface drip irrigation system effectively mitigates soil surface evaporation in comparison to both surface drip irrigation and surface flood methods. This is achieved by directly delivering water to the roots through laterals located within the root zone, thereby reducing water loss. In regions like northwestern India, characterized by arid and semi-arid conditions and scarce irrigation water resources, both surface drip and sub-surface drip irrigation present promising opportunities for widespread adoption. Additionally, the presence of brackish groundwater, unsuitable for irrigation, further highlights the suitability of drip irrigation methods in this region (8).

Nowadays, modernized irrigation techniques such as LEPA, LESA, Mid-Elevation Spray Application (MESA) and MDI have been developed for the precise application of water to crops and to improve WUE. These methods of irrigation effectively apply the water to the crop plants and avoid overuse of water and water losses. Hence, improved irrigation-water management techniques that enhance both lint and seed yields of cotton, optimize WUE and uphold quality standards are indispensable for the long-term sustainability of cotton production. This review examines research findings concerning irrigation practices across full and deficit irrigation, as well as rainfed conditions, employing various irrigation methods and irrigation models. It analyzes their effects on yield, yield components and WUE. While specific management practices may influence the outcomes of individual studies, this review primarily focuses on irrigation-water management and its implications for cotton cultivation.

Cotton crop co-efficient (Kc)

Kc values are indicators of crop water use and are influenced by crop development stages and crop type. During the germination and establishment stages, most water loss occurs through soil surface evaporation, especially when the surface is frequently moistened by irrigation or rainfall. As the crop canopy develops, evaporation decreases while transpiration through foliage becomes the dominant pathway for water loss (9). Crop co-efficient of cotton at various stages was illustrated in Fig. 1.

Kc is the ratio of actual crop evapotranspiration to reference crop evapotranspiration. Crop traits and the average impacts of soil evaporation are considered by the Kc coefficient. Average crop coefficients are generally more relevant and practical than daily time-step Kc values using separate crop and soil coefficients. This is especially true for hydrologic water balance studies, routine irrigation planning and the development of basic irrigation schedules (FAO - 56 paper). Kc values are determined in various crops in various location was illustrated in FAO - 56 papers. Kc value was determined in three stages like initial stage, mid-season stage and late season stage. According to FAO - 56 papers, the Kc value of cotton are 0.35 for the initial stage, 1.15-1.20 for the mid-season stage and 0.70-0.50 for the late season. A similar trend has been found in early studies (11). The Kc values determined for the initial, intermediate and final stages were 0.75, 1.09 and 0.80, respectively (12). The Kc for cotton remains constant at 0.9 during the early stages, increases to 1.17 at flowering and then declines to 0.46 in the later stages (13). This pattern indicates a minimal water requirement initially, a peak in the middle of the season and a gradual decline toward the end.

Environmental factors such as precipitation play a crucial role in determining the Kc value of cotton. During the early growth stages, rainfall can reduce the crop's reliance on evapotranspiration by maintaining high soil moisture, leading to lower observed Kc values compared to irrigated conditions. In the early stages, the Kc value significantly increases, followed by a gradual decline in the later stages (14). The reported Kc values for the initial, mid-season and late stages were 0.42, 1.25 and 0.70, respectively. These findings were compared with FAO -56 paper Kc value was 26 % lower at the initial stage and 6 % higher at mid-season stage and 11 % higher in the late season. The crop coefficient value increased from 0.4 to the initial stage, 1.2 at the midseason stage and decreased 0.6 at the later stage (15). The Kc value for cotton was reported as 0.35 at 30 days after planting (DAP), 1.15 at 150 DAP and 0.87 at 180 DAP (16). Photographs of cotton at the a. initial, b. mid-season and c. end-season were given in Fig. 2.

The duration of cotton also affected the Kc value. During a three-year study, the corrected FAO Kc values and locally developed Kc curves fluctuated, showing discrepancies ranging from -47 % to 103 % between the modified FAO and

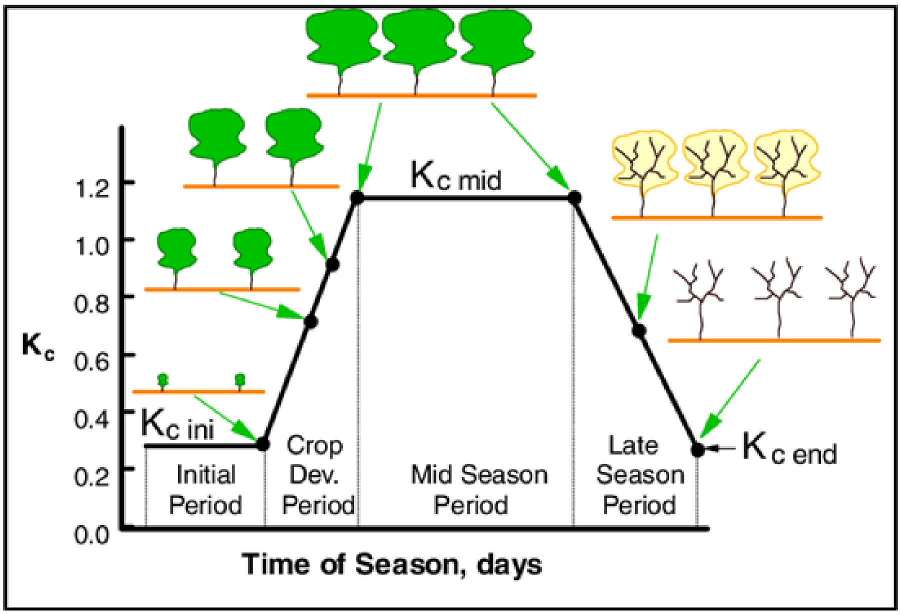

Fig. 1. Crop co-efficient of cotton at various stages (10).

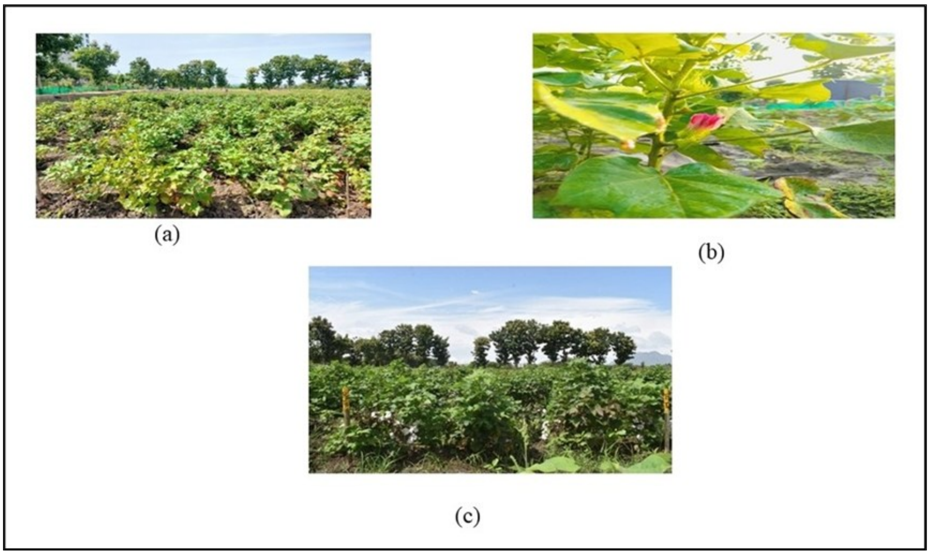

Fig. 2. Photographs of cotton at the a. initial, b. mid-season and c. end-season.

locally derived Kc values (17). The most significant variations occurred in the early season (-47 % to 1 %) and late season (-25 % to 103 %). Estimating cotton water usage based on higher adjusted FAO Kc values tends to overestimate requirements compared to locally developed values. Additionally, irrigation scheduling using these elevated Kc values increases production costs. Over-irrigation can lead to yield losses, as excessive water reduces oxygen availability for root respiration. This review highlights the spatial and temporal variability of Kc values, emphasizing the need for locally validated Kc values that account for regional climate, water requirements and cotton cultivation practices to ensure effective irrigation planning. Table 1 gives the cotton Kc values at different stages.

Water use and evapotranspiration in cotton

Water is essential to cotton's growth and development since it controls the plant's metabolism, nutrition absorption and transformation. When irrigation is used effectively, cotton yield and fiber quality are improved. Evapotranspiration (ET), the combined loss of water through evaporation and plant transpiration is one of the factors that determines how much water crops require to production.

Many studies have demonstrated the relationship between water use and ET. Water requirements of cotton vary from 700 to 1200 mm during the growing season (21). Cotton water use usually increases in the initial stage and it continues at mid-season; at the final stage it will steadily decline. Cotton's water consumption varies according to its phenological growth, with water use recorded at 3.8 mm per day during emergence, 5 mm during vegetative growth, 5.9 mm at the reproductive stage and 5.4 mm at maturity (22).

Globally, cotton uses varying amounts of water depending on factors such as soil properties, genotypes, irrigation techniques and irrigation schedules. Cotton water usage ranged from 410 to 780 mm, depending on the irrigation techniques used (21). Under deficit irrigation strategies cotton water use differs in various locations across the globe Uzbekistan, it ranges from 432 to 739 mm (5); in USA California from 397 to 775; and in Texas, USA from 389 to 739 (23, 24). Under fully irrigated conditions, cotton water use ranges from 735 to 915 mm in India (25). In the coastal part of the Aegean region of Turkey, water consumption varied from 659 to 899 mm (26).

The impact of the growing season length on cotton crop ET in the Apodi Plateau semiarid lands of Brazil was evident, with accumulated evapotranspiration (ETc) recorded at 716 mm in 2008 and increasing to 754 mm in 2009. Climatic changes, such as rising temperatures, altered rainfall patterns and extended dry spells, may further influence ETc by increasing atmospheric demand and shifting the crop's growth cycle, potentially leading to higher water requirements in future seasons (22). The longer growing season in 2009, extended by seven days compared to 2008, likely contributed to this higher ETc value. This suggests that the duration of the growing season can significantly influence the water requirements of cotton crops under sprinkler

Table 1. Cotton crop coefficient values at different stages

S. No.	Kc	Location	Stage			References
			Initial	Mid - season	End - season	
1.	FAO Kc		0.35	1.20	0.50	(11)
2.	Kc Local	Louisiana	0.42	1.44	0.62	(14)
3.	FAO Adj. Kc		0.42	1.06	0.78	
4.	Kc Local	Texas	0.40	1.25	0.6	(15)
5.	Kc Local	California	0.35	1.15	0.87	(16)
6.	Kc Local	Lousiana	0.15	1.39	-	(18)
7.	Kcb	Arizona	0.15	1.2	0.52	(19)
8.	Kc Local	India	0.46	1.01	0.23	(20)

(Kcb- basal crop coefficient, Kc Local locally developed Kc, FAO Adjusted Kc - FAO adjusted Kc, FAO Adjusted Kcb - FAO adjusted basal crop coefficient) irrigation in semiarid regions like the Apodi Plateau. At Lubbock in Texas, USA, cotton's seasonal water use varied from 353 to 625 mm (27). In the Mediterranean environment of Syria, mean seasonal ETc values were recorded at 895 mm in 2004, 927 mm in 2005 and 813 mm in 2006 (17). These values were higher than the water use in the northern high plains of Texas (28). Cotton water use (mm) under different methods of irrigation at different locations was given on Fig. 3.

Water-use efficiency of cotton under different irrigation methods

The photosynthetic carbon fixation and transpirational water loss provide the basis for an instantaneous measurement of WUE at the leaf level (WUEi). Plant WUEi is impacted by stomatal behavior modulation on transpiration and photosynthesis in response to altered water availability (29).

The variety of irrigation systems, such as center pivots, drip irrigation, surface irrigation and lateral-move machines, makes evaluating water-use efficiency more difficult. Comparisons are difficult since each system has unique requirements for management, runoff potential and water application rates. Furthermore, climatic factors like weather extremes and rainfall unpredictability make accurate assessments further complicate accurate assessments. Agronomic parameters like soil type, slope and field conditions can also have a substantial impact on water infiltration and distribution (30).

The concept of WUE was introduced over a century ago, highlighting a correlation between plant productivity and water utilization (31). Cotton lint yield is found to rise with increasing crop water use (27). WUE was described as the amount of carbon assimilated, either in biomass or grain, relative to the amount of water utilized by the crop (32). Research results have revealed variations between genotypes for WUE in upland cotton and pima cotton (33-35). Research on WUE and irrigation response of various cotton cultivars in West Texas, USA, using subsurface drip irrigation, revealed differences in WUE among six cultivars and the irrigation deficit strategies applied (36). In 2010, the cotton cultivar FM9160 exhibited the highest WUE of 0.20 kg m^{-3} under severe deficit irrigation, while DP1044 recorded the highest WUE of 0.32 kg m^{-3} under mild deficit irrigation and DP0912 achieved the highest WUE of 0.33 kg m^{-3} under full irrigation. Among the irrigation regimes, full irrigation resulted in the highest WUE, whereas severe deficit irrigation led to the lowest WUE in 2010.

Furthermore, research conducted in Australia revealed a 40 % increase in water-use efficiency over a decade, attributed to advancements in plant breeding, the adoption of genetically modified varieties and enhancements in water management practices. These improvements corresponded with yield increases (30). Evapotranspiration water-use efficiency (ETWUE) was estimated to range from 0.15 kg m^{-3} to 0.33 kg m^{-3}(21). The increase in ETWUE is likely due to reduced evaporation and improved yield. According to their findings, crop sensitivity to water stress is decreased when management strategies that increase transpiration and minimize soil water evaporation are used. This helps maintain high WUE levels.

The implementation of drip irrigation resulted in a 23 % reduction in wheat water usage while simultaneously increasing yield by 37 % (32). Conversely, in cotton, this irrigation method decreased water usage by 37 % but reduced yield by 21 %. Thus, the adoption of micro-irrigation systems like drip irrigation by farmers not only reduces soil water evaporation between plant rows early in the season but also minimizes canopy evaporation. These management strategies positively impact WUE in regions where micro-irrigation is employed, demonstrating that WUE can be enhanced through effective water management practices. Likewise, using a variety of experimental studies carried out at several locations in Texas and California, USA. Previous studies showed that switching from furrow irrigation to drip irrigation increased both lint yield and water productivity (measured as lint produced per unit of evapotranspiration) (21). Through a meta-analysis, it identified that the highest evapotranspiration water-use efficiency for cotton was 0.88 kg m^{-3}, achievable by reducing crop water use by 5.5 % (37). Additionally, they found that subsurface drip irrigation at a depth of 40 cm resulted in maximum cotton irrigation water

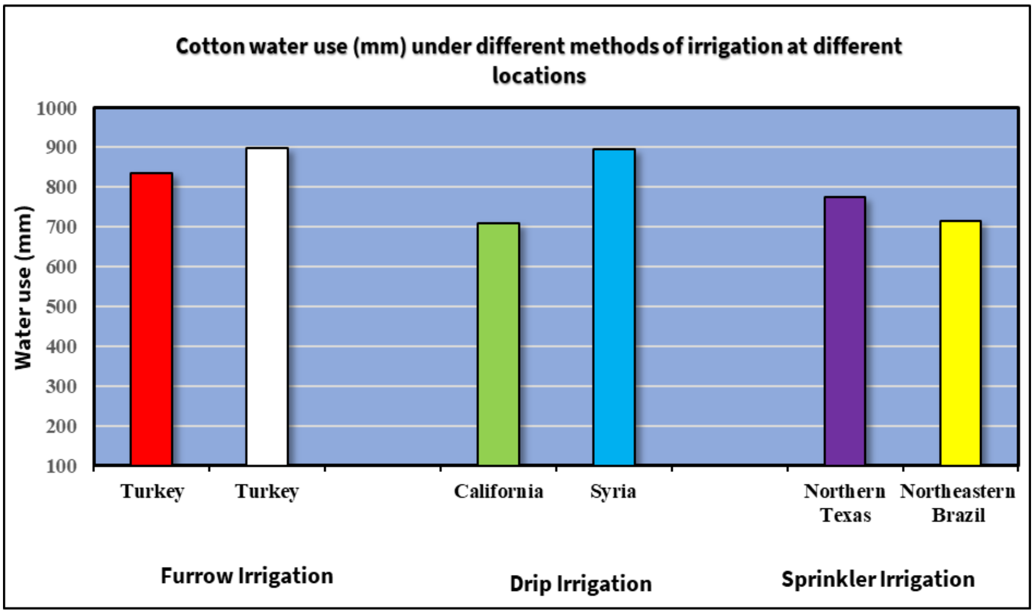

Fig. 3. Cotton water use (mm) under different methods of irrigation at different locations.

productivity of 0.84 kg m^{-3}. Moreover, they observed that increasing the irrigation amount led to a decrease in water productivity (38). In recent years, numerous researchers have investigated the WUE of cotton with the aim of achieving optimal cotton yield while conserving water.

An analysis of Crop Water Productivity (CWP) in irrigated cotton fields across Arizona and California, USA, evaluated real ETc water-use efficiency for different cotton types (16). In Arizona counties, ETc water-use efficiency for pima cotton ranged from 0.9 to 1.09 kg/ha-mm, while for upland cotton, it varied from 1.27 to 1.38 kg/ha-mm. In California counties, the ETc water-use efficiency ranged from 1.34 to 2.10 kg/ha-mm for upland varieties and from 1.51 to 1.77 kg/ha-mm for pima types. In western Turkey, WUE values were recorded between 1.59 and 2.30 kg m^{-3} for corn and between 0.61 and 0.72 kg m^{-3} for cotton over a two-year period (39). Additionally, in the coastline region of Turkey's Aegean region measured WUE values ranging from 0.38 to 0.46 kg m^{-3} (26). In their comparison of drip and furrow irrigation systems for cotton, the WUEs of the two approaches were recorded as 1.89 kg m^{-3} and 2.23 kg m^{-3}, respectively (40).

A comparison of drip irrigation with the traditional check basin method under normal sowing conditions showed an increase in WUE from 17.6 to 22.1 kg/ha cm, representing a 26 % improvement (41). Based on their investigation, it found that the WUE under sprinkler, drip and furrow irrigation were 4.87, 3.87 and 2.36 kg/ha-mm, respectively (42). Drip irrigation provides a better yield per unit of water applied, as these results show. WUE values ranging from 1.9 to 5.9 kg/ ha mm of water under furrow irrigation in the southern Turkish Cukurova Plain were established by Kanber, Onder (43). They also calculated Irrigation Water-Use Efficiency (IWUE) values, which ranged from 1.5 to 5.1 kg m^{-3}, for cotton that was furrow-irrigated. This wide range can be attributed to variations in irrigation scheduling, soil properties, climatic conditions and crop management practices, all of which influence how efficiently the applied water is converted into yield. IWUE values were recorded between 0.48 and 0.65 kg m^{-3} (26). IWUE values of 0.75-0.94 kg m^{-3} for drip-irrigated cotton on the Turkish Cukurova plain (44).

In Queensland, Australia, furrow irrigation has undergone optimization and field testing specifically for cotton cultivation. The outcomes revealed an enhancement in WUE alongside a reduction in labor demands (45). With 50 % of the available water capacity (AWC), WUE increased in all genotypes. There may be less water lost from the field, especially evaporation losses, which would explain this greater WUE under 50 % AWC. When 50 % AWC was applied in 2018 and 2019, CIM-678 showed the highest WUE, measuring 0.54 and 0.64 Kg m^{-3} ha^{-1}, respectively. By contrast, CIM-343 had the lowest WUE in 2018 and 2019 under 50 % and 100 % AWC circumstances, respectively (46). WUE varies due to multiple environmental and management factors across locations. For this reason, taking measurements specific to a certain place is essential for making well-informed decisions and advancing WUE.

Variations in cotton yield and its components across various irrigation methods

Cotton cultivation under rainfed conditions is feasible only in select regions and typically, achieving optimal yields without irrigation is challenging (42). Hence, irrigation plays a vital role in cotton production. Irrigation increased cotton productivity while also enhancing fiber length (47).

An evaluation of cotton cultivation using different irrigation methods-Surface Drip Irrigation (SDI), LEPA and spray irrigation showed that SDI, particularly at lower irrigation rates, resulted in the highest lint yield and water-use efficiency compared to the other methods (24). The study conducted in 2004 also demonstrated that both lint yield and gross returns improved when using SDI at various irrigation rates. Drip irrigation at 75 % capacity for cotton cultivation provided significant benefits by conserving water without reducing yield, while the high WUE highlighted the advantages of deficit irrigation, particularly in water-limited conditions (48).

When plants received less than 50 % of full irrigation, LEPA improved output by 16 % compared to sprinkler irrigation, while SDI demonstrated even higher efficiency, exceeding LEPA by 14 % (49). At irrigation levels above 50 % of full irrigation, sprinkler output was slightly lower than LEPA, whereas SDI produced 7 % more than LEPA.

A comparison of three irrigation techniques demonstrated that the highest seed cotton yield was 4380 kg ha^{-1} with drip irrigation, followed by 3630 kg ha^{-1} with furrow irrigation and 3380 kg ha^{-1} with sprinkler irrigation (42). Notably, drip irrigation led to a 21 % increase in yield compared to furrow irrigation and a 30 % increase compared to sprinkler irrigation.

In southeastern Turkey, an evaluation of different irrigation approaches for improving WUE in cotton cultivation showed that drip irrigation achieved the highest seed cotton yield at 4650 kg ha^{-1}, followed by furrow irrigation with 3120 kg ha^{-1} (42). Furthermore, studies (50, 51) have shown that SDI slightly outperforms spray irrigation and LEPA in terms of lint yield, lint quality and WUE. In India, improvements in several growth indices of cotton plants under drip irrigation, including plant height, the number of bolls per plant, the weight of the bolls and the number of monopods and sympods per plant was documented. It was also observed that, out of all the four cotton cultivars they looked at for their study, drip irrigation had the best WUE.

Over the two study years, there was a statistically significant effect observed for irrigation interval and deficit irrigation on seed cotton production, seed cotton weight and ginning outturn (53). The treatment with the highest seed cotton production, boll weight and lint yield used a 4-day irrigation interval with an irrigation level of 150 % of crop ETc. This indicates that water was applied at 1.5 times the estimated ETc, likely to ensure ample soil moisture and reduce water stress throughout the growing period. On the other hand, the treatments with a 90 % irrigation water level and a 12-day irrigation interval produced the lowest values for these characteristics. It was shown that deficiency irrigation significantly affected the production of seed cotton after a thorough four-year study. Under conditions of severe water stress, evapotranspiration ranged from 376 to 398 mm, but under full irrigation, it fluctuated between 477 and 671 mm. The 100 % irrigation treatment received an average of 382 mm of irrigation water, resulting in the most substantial seed cotton yield of 3397 kg ha^{-1} (54).

In China, a comparison between traditional flood irrigation and mulched drip irrigation revealed that mulched drip irrigation promoted better root growth in cotton plants (55). Additionally, this method increased both the number of bolls per plant and overall yield compared to traditional flood irrigation. Research has consistently demonstrated that drip irrigation is the most efficient water-saving technique, as it preserves soil integrity and aggregate structure while minimizing water loss both deep within the soil and on the surface, thereby reducing the risk of soil degradation and salinization (56, 57). An early and increased cotton yield could be achieved by drip irrigation (58). In comparison to furrow irrigation, Previous works claimed that drip irrigation supplied more advantages (59). A comparison of drip irrigation and flood irrigation demonstrated that drip irrigation increases cotton yields by approximately 25 % while also contributing to water conservation by reducing water usage by an estimated 40-50 % (60).

A 21% increase in seed cotton yield with drip irrigation compared to furrow irrigation and a 30 % increase compared to sprinkler irrigation was documented (42). Likewise, an assessment of various irrigation methods identified SDI as the most effective for cotton productivity and gross returns, followed by LEPA and spray irrigation (61).

Numerous studies have underscored the significance of exploring alternative irrigation methods beyond drip irrigation to optimize cotton yield. No statistically significant difference was found in cotton yields among furrows, sprinklers, or drip systems (62). The drip and furrow irrigation techniques for cotton were compared, no differences were discovered in yield. A comparison of overhead sprinkler irrigation, subsurface drip irrigation (SSDI) and rainfed conditions found no significant differences in cotton yield among the irrigation methods (63). An evaluation of LEPA and trickle irrigation techniques for cotton farming in southeast Anatolia demonstrated that both methods enhanced cotton yields (64). These findings suggest that such methods are viable options for cotton cultivation in arid regions.

The variability in results across studies highlights the influence of climatic conditions on irrigation effectiveness. Field-based investigations are essential to determine the most suitable technologies capable of achieving optimal cotton yield and quality while maximizing WUE.

Impact of irrigation Regime on physiological characteristics, yield and yield components of cotton

The biggest danger to plant development and productivity among biotic and abiotic stressors is drought. Different irrigation techniques worldwide vary in contrast to cotton's physiological traits, yield and yield components. .

Numerous investigations have been conducted across various irrigation methods to assess parameters such as stomatal conductance, carbon dioxide assimilation rates and canopy temperature. A more pronounced reduction was identified in transpiration rate, stomatal conductance and stem sap flow rate in soybeans under water stress compared to cotton (65). As a result, cotton demonstrated greater adaptability to water limitation by maintaining a higher transpiration rate than soybean.

Previous studies observed that water stress negatively affected the photosynthetic rates of cotton compared to normal conditions (66). Water scarcity reduces both transpiration and photosynthesis, ultimately lowering cotton yield. Furthermore, water stress causes cotton plants to have fewer leaves. The study focused on parents and F1 hybrids cultivated under three distinct irrigation regimes: no irrigation, deficit irrigation and normal irrigation (67). They noticed that the leaf area decreased as the amount of water decreased. Additionally, the relative water content of cotton cultivated during a drought was lower. Drought-tolerant cotton genotypes by assessing RWC at various moisture levels was identified and their findings revealed a decline in the RWC of cotton leaves with increasing severity of drought conditions. An evaluation of three cotton cultivars under different irrigation frequencies (3, 5 and 7 times) revealed that the tallest plants, reaching 105.6 cm, were achieved with seven irrigation events (68). Additionally, the highest seed cotton yield, 3323.52 kg ha^{-1}, was recorded with five irrigations throughout the growing season, exceeding the yields from both three and seven irrigation events.

The effects of water stress on cotton seed output and its constituents have been studied in detail by researchers, who have repeatedly shown a drop in yield in these circumstances. Water stress causes cotton plants to lose photosynthetic activity, transpiration rate and leaf area, which lowers yield and its constituent parts. To determine the average lint yield of cotton planted in narrow rows with full, limited and no post-planting irrigation, these irrigation regimes, the average lint output was 1583 kg ha^{-1}, 1423 kg ha^{-1} and 601 kg ha^{-1}, respectively (23). Furthermore, the complete irrigation regime produced around 16 t ha^{-1} of dry matter, but the limited and no post-planting irrigation regimes produced about 11 t ha^{-1} and 7 t ha^{-1} of dry matter, respectively. By comparing cotton genotypes under drought stress and normal water circumstances. The water stress during the flowering stage under field conditions led to a 25 % decrease in lint production (69). In the Mississippi Delta region, limited irrigation moderately inhibited cotton plant growth and led to changes in fiber and seed composition specifically, reductions in fiber length and strength, as well as decreased seed oil and protein content (70). They noted a higher number of bolls in controlled environments compared to stressed conditions, highlighting the adverse impact of water stress on boll quantity (71). Field experiments demonstrated that water stress during the flowering stage led to lower cotton yields, highlighting the greater sensitivity of this stage compared to the vegetative phase (72).

The profitability of cotton is highly dependent on the quality of its fiber, which has led many studies to investigate the effects of water stress on cotton fiber quality. To find out how water stress affected fiber strength, fineness and length under both normal and water-limited conditions, early works noticed at several cotton genotypes (73). When there was water scarcity, the data indicated that fibers tended to be weaker, shorter and had lower micronaire values. Similarly, the effects of drought on cotton at different phases of development were examined earlier (74). They noticed that the fineness of the fiber was negatively impacted by drought during the boll development stage.

However, other research indicates cotton may be resistant to drought. Reduced irrigation, or deficit irrigation, is an adaptive management method that promotes water conservation and increases water productivity (75). An analysis of the effects of different water levels on drip-irrigated cotton revealed that after receiving 25 %, 50 % and 75 % of full irrigation, there was an increase in both boll weight and the number of opened bolls (76). The findings indicated that cotton exhibited strong adaptability to water stress, as evidenced by the increased number of bolls per plant in low-water conditions. However, Masasi, Taghvaeian (77) found that there were no appreciable variations in lint and seed yields between full and decreased irrigation regimes in west-central Oklahoma, USA. Modifying the structure and distribution of light inside the canopy may be facilitated using restricted watering techniques (78). With a water allocation of 425 mm and a plant density of 36 plants m^{-2}, research indicated that deficit irrigation in cotton contributed to water and energy conservation without reducing yield (79).

The physiological characteristics, yield and yield components of cotton have been found to respond differently to varying irrigation techniques. Such variability is consistent with previous findings (80), who emphasized the location impact on cotton yield and fiber quality responses to irrigation, highlighting the need for fieldwork that is specific to a given area. According to many reports, field research is crucial in determining how crops react to different degrees of water stress (54, 81). To meet their yield targets, farmers can choose the appropriate degrees of deficit irrigation with the help of knowledge of how deficit irrigation affects cotton performance (82). There's a crucial requirement to identify and test strategies that optimize water usage within cotton production systems.

Various cotton models used for irrigation management

To improve agricultural water, use in crop production, irrigation management systems must be evaluated using crop simulation models. In Australia, the OZCOT cotton model was shown to provide realistic yield predictions for cotton under both irrigated and rainfed conditions (83). Based on the evapotranspiration (error value <13 %), AquaCrop model predicted seed cotton yield and simulated the entire soil water contents in the soil layer (17). The EPIC cotton model's predicted values were effectively utilized for long-term irrigation management in both fully and deficit-irrigated cotton fields in the southern cotton-growing regions of Texas (15). In the drip irrigation system, AquaCrop model was evaluated in hot, arid climate and its performance was good in the eastern Mediterranean region. With lowest input data AquaCrop model predicted the consequences of evapotranspiration, total dry matter, seed cotton production and soil moisture contents (84). Under various irrigation regimes Cotton2K model performed very well and recorded the seed cotton yield which was not significantly different from each other (85). In America, researchers observed that the relationship between average seed cotton production and evapotranspiration replacement showed that irrigation at 112 % evapotranspiration maximizes seed cotton production at 1406 kg ha^{-1} (86). The volumetric soil water contents, leaf area indices, aboveground total dry matter and seed cotton yield simulated, according to the SWAT model, were all in good agreement with the data that was observed. Furthermore, the results of the model simulation demonstrated that cotton relies heavily on subsurface water as a source of water. Capillary rise contributed 23 % of transpiration. This led to 20 % higher seed cotton yield (87).

In China, the EPIC model performed well, with errors ranging from 2.6 % to 22.6 % for soil moisture content, 6.3 % to 14.1 % for Leaf Area Index (LAI), 4.9 % to 7.2 % for dry matter and 2.5 % to 8.2 % for seed cotton production (88). Under irrigated conditions in America, the CROPGRO-Cotton model was evaluated and validated and it was well capable of seed cotton yield besides seasonal evapotranspiration from 1924 to 2012 historic period (89). According to well-calibrated and evaluated AquaCrop model results (90), applying one irrigation (at seedling), two irrigation events (at seedling plus squaring) and three irrigation events (at seedling, squaring plus flowering) during wet, normal and dry years, in China, respectively, could achieve the highest water productivity. The AquaCrop model can simulate cotton growth response to water under film-mulched drip irrigation. The anticipated results indicated that the appropriate irrigation volumes for silty loam and sandy loam soils in China were 358-457 mm and 406-462 mm, respectively, based on the principle of high productivity aside from WUE (91). Various cotton models are used for irrigation management worldwide are given in Table 2.

Table 2. Various cotton models are used for irrigation management worldwide

Country	Name of the cotton models	Parameters studied	Reference
America	SALUS	LAI, biomass, SCY	(92)
America	EPIC	WUE, lint yield	(15)
America	Cotton2K	Lint yield	(85)
America	CROPGRO	Soil moisture contents, evapotranspiration	(89)
Australia	OZCOT	WUE	(93)
China	SWAT	Soil water contents, biomass, lint yield	(87)
China	AquaCrop	SCY	(90)
China	EPIC	Soil water contents, LAI, biomass, SCY	(88)
Greece	AquaCrop	SCY	(94)
Greece	AquaCrop	Soil water contents, canopy cover, biomass, SCY	(95)

Conclusion

Efficient water management is essential for sustainable cotton cultivation, especially amid declining water availability and the growing demand for resource optimization. This review underscores the critical role of irrigation methods, crop coefficients, WUE and evapotranspiration in maximizing cotton yield and quality. Cotton's sensitivity to water availability throughout its growth stages necessitates precise and informed irrigation strategies. The findings reviewed demonstrate how modern irrigation techniques, such as drip irrigation (surface and subsurface) and advanced systems like LEPA, LESA, MESA and MDI, significantly enhance water use efficiency and yield outcomes compared to traditional methods like furrow and surface flood irrigation. Drip irrigation has emerged as the most effective method for reducing water wastage and improving yield, owing to its ability to deliver water directly to the root zone. Subsurface drip irrigation further minimizes soil evaporation, making it ideal for arid and semi-arid regions. Meanwhile, advanced irrigation models such as AquaCrop, EPIC, Cotton2K and CROPGRO-Cotton have demonstrated their utility in simulating crop growth and optimizing water application under different irrigation regimes. These models account for local climatic conditions, soil properties and crop requirements, offering a data-driven approach to irrigation management.

The review also highlights the variability in water use efficiency and yield responses across different geographical regions, irrigation methods and cotton cultivars. Factors such as climatic conditions, soil characteristics and irrigation schedules heavily influence outcomes. Deficit irrigation strategies often balance water conservation with productivity. In contrast, over-irrigation may reduce yield and increase costs due to oxygen deficiency in the root zone.

Future research should focus on developing localized irrigation strategies that integrate advanced models with precision farming technologies. This approach can further enhance water productivity, particularly in regions facing acute water scarcity. Additionally, promoting the adoption of modernized irrigation systems among farmers through education, incentives and infrastructure development is critical for long-term sustainability. In conclusion, advancing irrigation techniques and adopting region-specific water management practices are indispensable for achieving sustainable cotton production. By leveraging technology, enhancing water use efficiency and addressing local challenges, it is possible to simultaneously ensure higher yields, better quality and reduced environmental impact in cotton cultivation.

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SM wrote the manuscript draft and SS revised it. Authors RM, AP, BRS and RT contributed to the discussion. All authors read, edited and approved the final manuscript.

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