

Review

Irrigation-Water Management and Productivity of Cotton: A Review

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Abstract: A decrease in water resources, as well as changing environmental conditions, calls for efficient irrigation-water management in cotton-production systems. Cotton (*Gossypium* sp.) is an important cash crop in many countries, and it is used more than any other fiber in the world. With water shortages occurring more frequently nowadays, researchers have developed many approaches for irrigation-water management to optimize yield and water-use efficiency. This review covers different irrigation methods and their effects on cotton yield. The review first considers the cotton crop coefficient (Kc) and shows that the FAO-56 values are not appropriate for all regions, hence local Kc values need to be determined. Second, cotton water use and evapotranspiration are reviewed. Cotton is sensitive to limited water, especially during the flowering stage, and irrigation scheduling should match the crop evapotranspiration. Water use depends upon location, climatic conditions, and irrigation methods and regimes. Third, cotton water-use efficiency is reviewed, and it varies widely depending upon location, irrigation method, and cotton variety. Fourth, the effect of different irrigation methods on cotton yield and yield components is reviewed. Although yields and physiological measurements, such as photosynthetic rate, usually decrease with water stress for most crops, cotton has proven to be drought resistant and deficit irrigation can serve as an effective management practice. Fifth, the effect of plant density on cotton yield and yield components is reviewed. Yield is decreased at high and low plant populations, and an optimum population must be determined for each location. Finally, the timing of irrigation termination (IT) is reviewed. Early IT can conserve water but may not result in maximum yields, while late IT can induce yield losses due to increased damage from pests. Extra water applied with late IT may adversely affect the yield and its quality and eventually compromise the profitability of the cotton production system. The optimum time for IT needs to be determined for each geographic location. The review compiles water-management studies dealing with cotton production in different parts of the world, and it provides information for sustainable cotton production.

Keywords: cotton; water management; yield; water productivity



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1. Introduction

The global production of cotton fiber is estimated to be 24.65 million tons [1]. In 2018, the production was estimated to be 6.71 million tons in the Americas; 0.38 million tons in Europe; 1.56 million tons in Africa; 0.95 million tons in Oceania; and 15.06 million tons in Asia [1]. In 2020, across the United States, the production of cotton was estimated to be 3.26 million tons, and cotton was grown on about 3.52 million hectares [2]. The United States is the world's leading cotton exporter, supplying about 35% of global cotton exports in recent years [3]. Cotton is a valuable, natural-textile fiber and the purest source of cellulose [4]. Aside from the fibers, cotton also is produced as a source of seeds that provide

edible oil, seed by-products, and other products to industries. Its residues provide organic matter to the soil. Zhang and Dong [5] estimated that cotton fiber contributes to half of the world's clothes.

Recent studies found significant impact of drought and water stress on cotton production have resulted in a reduction in yield and yield components [6–10]. Therefore, different irrigation systems have been developed and used for cotton production across the world with various results. In southwestern Georgia, USA, Sorensen et al. [11] found sprinkler and shallow subsurface drip-irrigation methods to have a better lint yield than a subsurface drip system at full irrigation and the lint yield was the lowest in a rainfed treatment. In India, drip irrigation at the 75% level was found to have a better yield than sprinkler irrigation at full irrigation [12]. Colaizzi et al. [13] and Segarra et al. [14] reported that subsurface drip irrigation (SDI) tended to perform more efficiently than other irrigation systems such as mid-elevation spray application (MESA), low-elevation spray application (LESA), and low-energy precision application (LEPA). However, Bordovsky et al. [15] found that yields from LEPA irrigation were equal to those from drip irrigation. Recent studies also have revealed a decline in production resources [16,17] and changes in the environment [18,19]. Therefore, improved irrigation-water management practices that optimize the lint and seed yield of cotton and promote water-use efficiency, while maintaining maximum quality, are critical for the future sustainability of cotton production. In this review, we look at study outcomes related to irrigation-water practices under full and deficit irrigation, as well as rainfed conditions, using different irrigation methods. The effects on yield and yield components and water-use efficiency are considered. Although, the results from different studies are affected by specific management practices, this review mainly focuses on irrigation-water management and its impact on cotton.

2. Cotton Crop Coefficient

The crop coefficient (K_c) is the ratio of actual crop evapotranspiration to the reference crop evapotranspiration. The Food and Agricultural Organization (FAO) of the United Nations has established a crop coefficient for cotton at different stages (Figure 1) of growth that can be applied across the globe and presented it in the FAO-56 paper [20] (Table 1). Nonetheless, various studies determining local K_c values obtained for various developmental stages have been different from those listed in the FAO-56 paper [21–24]. Therefore, the use of the FAO K_c values has resulted in an important difference between estimated and actual crop evapotranspiration (E_{Tc}) [23,25].



Figure 1. Pictures of cotton at initial, mid-season, and end-season stages at K-State Southwest Research and Extension Center (SWREC), Garden City, Kansas, USA.

According to FAO, the crop coefficients 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 stage [20]. Similar trends have been found by Kumar et al. [26], who reported a gradual increase in K_c from the initial stage, peaking at mid-season, which was approximately 60 to 105 days after planting, and steadily decreasing toward the end of the season. The authors reported 1.44 as the

mid-season daily Kc in 2010 and 1.06 in 2011. They further pointed out that the difference in Kc values was due to excessive precipitation obtained in 2010. Consequently, cotton water use was affected by precipitation, which resulted in an increase in Kc values. In Louisiana, USA, Kumar et al. [26] reported the average Kc in 2010 and 2011 of 0.42, 1.25, and 0.70 for initial, mid-season, and late season stages, respectively. When compared to the FAO-adjusted Kc, the authors found that the local initial Kc value was 26% lower, the Kc at mid-season was 6% higher, and the end season Kc was 11% higher. In the same line, Ko et al. [27] reported that cotton Kc at Uvalde, Texas, USA, increased from 0.40 at the initial stage to 1.25, where it peaked at mid-season. It decreased later to 0.60 at the late season stage. Similar results were found in other semiarid areas in the USA [21,22] and in India [28]. In the Sacramento and San Joaquin valleys, California, USA, the local Kc values of cotton were found to be 0.35 from 0 to 30 days after planting; 1.15 from 90 to 150 days; and 0.87 from 150 to 180 days [22]. The initial and mid-season stage values in California were lower than the cotton Kc values in Texas. However, the end season Kc found in California was different from the coefficient reported in Texas. These differences can be explained by the length of the cotton growing season.

Apart from rainfall, cotton Kc is also influenced by the crop duration. In Syria, Farahani et al. [23] carried out a study on crop coefficients for drip-irrigated cotton and reported that the locally developed Kc curves differed in the 3 years of their study, as well as the adjusted FAO Kc values. The difference between the adjusted FAO and the locally developed Kc values ranged from −47 to 103%. The initial season stage (ranging from −47 to 1%) and the late season stage (ranging from −25 to 103%) had the largest variations. The locally developed Kc values for the mid-season stage were similar (1.05 in 2004 and 2005 and 1.04 in 2006), however, they were about 24% smaller than the adjusted mid-season FAO Kc value of 1.30. Cotton water use is overestimated when it is calculated using higher adjusted FAO Kc values than the locally developed Kc values, and irrigation scheduling built on the high adjusted Kc values augments the cost of production. Over-irrigation contributes to yield losses, because, with more water, the plant roots lack oxygen for respiration to take place. In the semiarid lands of Brazil, Bezerra et al. [24] reported that average, local Kc values were 0.75, 1.09, and 0.80 for the initial, middle, and end of the growing season, respectively. They pointed out that these locally developed Kc values were smaller than the FAO-adjusted Kc values. Therefore, water use computed from FAO-adjusted Kc values was overestimated by 12%. Kc values from initial and end stages obtained by Bazerra et al. [24] were greater than those reported by Ko et al. [27] in Texas, USA. However, the Kc values reported by Ko et al. [27] were higher than the results reported by Hribal [29]. These differences are attributed to the sensitivity of Kc values to irrigation management and the systems used.

The mid-season local Kc value of 1.09 found by Bezerra et al. [24] was similar to the results reported by Farahani et al. [23]. Various studies [21,22,25,27,29] have reported higher mid-season Kc values, ranging from 10–24% higher, in other cotton-production areas in the USA such as Texas, California, Arizona, and Louisiana, than the one reported in Brazil by Bezerra et al. [24]. The difference in Kc among the regions may be explained by the change in environmental conditions induced by higher insolation, lower humidity, and higher temperatures, as well as different cultivars and irrigation management. The end-season Kc value of 0.80 [24] was 10% higher than the FAO end-season Kc value. A similar end-stage Kc value was found by Kumar et al. [26] in Louisiana, USA, while Ko et al. [27] reported a lower value of 0.60 for the Uvalde region, Texas, USA. Hunsaker [21] developed Kc values for short-season cotton in Arizona, USA and found higher Kc values than those reported by FAO. The above review highlights the spatiotemporal variation of the crop coefficient values. Therefore, for efficient irrigation planning, it is important to develop a local Kc experimentally that characterizes local climate, water requirement, and cotton management practices.

Table 1. Cotton crop coefficient values at different stages (Kcb—basal crop coefficient, Kc Local—locally developed Kc, FAO Adj. Kc—FAO adjusted Kc, FAO Adj. Kcb—FAO adjusted basal crop coefficient).

Location	Kc	Climate	Soil Type	Year	Stage			References
					Initial	Mid-Season	End-Season	
USA								
Louisiana	FAO Kc	Subhumid climates			0.35	1.15–1.20	0.70–0.50	Allen et al. [20]
	Kc Local			2010	0.42	1.44	0.62	
		Humid	Sharkey clay	2011	0.42	1.06	0.78	Kumar et al. [26]
	FAO Adj. Kc			2010	0.55	1.18	0.64	
				2011	0.58	1.18	0.62	
Uvalde, Texas	Kc Local	Humid subtropical climate	Silty clay soil	2006–2007	0.40	1.25	0.6–0.1	Ko et al. [27]
California	Kc Local				0.35	1.15	0.87	Grismer [22]
Louisiana	Kc Local	Semitropical climate	Bare soil	2007	0.15	0.64–1.39		Hribal [29]
India					0.46	0.7–1.01	0.23	Mohan and Arumugam, [28]
Arizona	K _{cb}	Semiarid	Sandy loam soil	1993–1994	0.23	1.30	0.4	Hunsaker, [21]
				2002	0.15	1.2	0.52	Hunsaker et al. [30]
				1991	0.15	1.1–1.3	0.7–0.6	Hunsaker et al. [25]
1990	0.2	1.1–1.3	0.7–0.5					
Georgia	Kc Local	Humid subtropical environment		2005	1.12–0.99	1.15–1.2	0.7–0.5	Suleiman et al. [31]
Bushland, Texas	K _{cb}	Subtropical climate	Pullman clay loam	2000	0.08	1.10	0.15	Howell et al. [32]
Bushland, Texas	FAO Adj. K _{cb}	Subtropical climate	Pullman clay loam	2000	0.15	1.23	0.20	
Other countries								
Syria	Kc Local	Mediterranean climate	Fine clay	2004–2006	0.29	1.05	0.66	Farahani et al. [23]
	FAO Adj. Kc				0.20	1.30	0.71	
Brazil	Kc Local	Semiarid	Sandy-clay loam	2008–2009	0.75	1.09	0.80	Bezerra et al. [24]
	FAO Adj. Kc				0.84	1.20	0.70	

3. Cotton Water Use and Evapotranspiration

Knowledge of water use and crop evapotranspiration (ET_c) is crucial for a reliable irrigation scheduling. Many studies have examined the water requirement of cotton in different parts of the world [21,23,26,33] (Table 2). Results have shown that the water requirements vary from 700 to 1200 mm during the growing season, depending on the season length, climate, cultivar, irrigation method, and production goals [34]. Cotton water use gradually increases from the initial stage, reaches maximum at the mid-season stage, and then steadily declines until the end of the season. Following Bezerra et al. [35], water use by cotton differed according to its phenological growth. They found that cotton used 3.8 mm of water per day at emergence, 5.0 mm of water per day during vegetative growth, 5.9 mm of water per day during the reproductive stage, and 5.4 mm of water per day at maturation. The maximum water use corresponds, therefore, to full canopy and maximum boll load of the cotton plant. In southcentral USA, Kumar et al. [26] found the daily average ET_c values of cotton during the mid-season were approximately 7.1 mm d⁻¹ in 2010, and 5.9 mm d⁻¹ in 2011. In Brazil's semiarid climate, Bezerra et al. [24] found daily cotton ET_c values varied from 3.7 to 9.3 mm d⁻¹ in 2008 and from 3.7 to 9.6 mm d⁻¹ in 2009. They further reported that, in both years, the minimum ET_c values were observed in the initial stage, while maximum ET_c values were obtained in mid-season.

The water use of cotton differs around the globe and depends on local climate, soil characteristics, genotypes, irrigation methods, and irrigation regimes. Evett et al. [34] reported that water use ranged from 410 to 780 mm per season depending on the irrigation methods. Cotton water use was found to be lower for SDI and LEPA than for furrow irrigation. Furthermore, water use varies with deficit-irrigation strategies, but similar ranges have been observed for different climates. Under deficit irrigation, cotton water use varied from 432 to 739 mm in Uzbekistan [36], from 594 to 778 mm in California, USA [37], from 397 to 775 in 2000 and from 386 to 739 in Bushland, Texas, USA [32,38]. Under fully irrigated furrow plots, Rajak et al. [39] stated that cotton water consumption varied from 735 to 915 mm in India, while Anac et al. [40] found it varied from 659 to 899 mm in the coastal part of the Aegean region of Turkey.

In Turkey, Dagdelen et al. [41] found that variations of cotton water use, from 272 to 882 mm in 2003 and from 242 to 855 mm in 2004, were related to the changes in climatic factors. In California, USA, Howell et al. [7] measured cotton evapotranspiration using a water balance model and reported that it varied with irrigation regimes. The authors further stipulated that evapotranspiration of narrow row cotton was 778 and 594 mm under full irrigation and limited irrigation, respectively. In Texas, USA, Ko et al. [27] reported smaller cotton water use values than those obtained by Kumar et al. [26]. At Lubbock in Texas, USA, Baker et al. [42] found cotton seasonal water use varying from 353 to 625 mm. Bezerra et al. [24] carried out a study on cotton crop evapotranspiration under sprinkler irrigation in the Apodi Plateau semiarid lands of Brazil and found that accumulated cotton ET_c was 716 and 754 mm in 2008 and 2009, respectively. They further mentioned that the higher value in 2009 was due to the length of the crop growing season being 7 days longer.

Many studies on cotton water use carried out in western Turkey [43], in central Arizona, USA [25], and in northern Syria [23] found a higher accumulated water use of cotton than those reported by Bezerra et al. [24] in Brazil. The higher values in those areas can be explained by the length of the growing season. However, Liu et al. [44] reported lower annual cotton water requirements compared to Bezerra et al. [24]. Liu et al. [44] found 619.1, 673.6, and 651.4 mm for the cotton seasonal water requirement for the Eastern Hebei Plain, the Heilonggang region, and the Piedmont Plain of Taihangshan, China, respectively. Moreover, in the northern High Plains of Texas, the measured total water use was found to be 622 mm and 397 mm under deficit irrigation and dry land in 2000, respectively [32]. In Uvalde, Texas, Ko et al. [27] reported a maximum daily ET_c of 13 mm per day in 2006, and 10 mm per day in 2007 for a total cumulative evapotranspiration of 830 mm and 689 mm in the two respective years. According to the authors, the variation of ET_c in both years was caused by lower air temperatures and recurrent precipitation events

in 2007. Similar results were reported by Grismer [22], who found ET_c values of 710 mm in 1998 and 845 mm in 1999 using the Parlier lysimeters in the San Joaquin Valley, California, USA. In the Mediterranean environment of Syria, Farahani et al. [23] reported cotton mean seasonal ET_c values of 895, 927, and 813 mm in 2004, 2005, and 2006, respectively. These values were higher than the water use reported by Howell et al. [32] in the northern High Plains of Texas.

In summary, cotton water use depends on local climate, the agronomic characteristics of the cotton varieties, crop management practices, and irrigation methods and regimes.

Table 2. Cotton water requirement, evapotranspiration, and seasonal ET_c under different irrigation methods (DI—drip irrigation, SI—sprinkler irrigation, FI—furrow irrigation).

Location	Year	Seasonal Precipitation (mm)	Irrigation Amount (mm)	Seasonal Water Use (mm)	Irrigation Method	Seasonal ET _c (mm)	Cotton Variety	References
USA								
La Paz, Arizona	1988–1999			1304		1362	Upland cotton	Grismer [22]
				1304		1362	Pima cotton	
Northern Texas	2000	470	201	775	SI	770		Howell et al. [32]
St. Joseph, Texas	2006	75	764		SI	830	DP555	Ko et al. [27]
	2009	581	114		SI	689	DP555	
California	1998			710	DI			Soppe [45], Ayars and Soppe [46]
	1999			845	DI			
	1998			561	SI			
	1999			561	SI			
Other countries								
Turkey	1993			834	FI			Preito and Angueira [47]
	1994			899	FI			
Syria	2004		800	895	DI			Farahani et al. [23]
	2005		810	927	DI			
	2006		760	813	DI			
Northeastern Brazil	2008		892	716	SI		CNPA 187 8H	Bezerra et al. [24]
	2009		884	754	SI		CNPA 187 8H	

4. Cotton Water-Use Efficiency

The concept of water-use efficiency (WUE) was introduced more than 100 years ago by Briggs and Shantz [48] indicating a relationship between plant productivity and water use. Cotton lint yield is found to rise with increasing crop water use [42]. Hatfield and Dold [49] defined WUE as the quantity of assimilated carbon in terms of biomass or grain per unit of water used by the crop. In plant breeding, it has been proposed to use WUE to select water-use-efficient genotypes under changing environments, heat and water stress, and the interactions between them. Research results have revealed variations between genotypes for WUE in upland cotton and pima cotton [50–52]. Snowden et al. [53] carried out a study on WUE and irrigation response of cotton cultivars under subsurface drip irrigation in West Texas, USA. They reported that WUE differed among the six cultivars and the deficit strategies used. In 2010, the cotton variety FM9160 had the greatest WUE of 0.20 kg m⁻³ under severe deficit irrigation; DP1044 had the greatest WUE of 0.32 kg m⁻³ under mild deficit irrigation; and DP0912 had the greatest WUE of 0.33 kg m⁻³ under full irrigation (Table 3). Among the irrigation regimes, full irrigation provided the highest WUE while severe deficit gave the lowest WUE in 2010. Moreover, a study conducted in Australia found that the water-use efficiency increased by 40% over a ten-year period along

with developments in plant breeding, the utilization of genetically modified varieties, and improved water management practices, and they resulted in yield increases [54]. These results are in line with the findings of Hatfield and Dold [49] who reported that WUE is dependent upon genotype and management practices. Evett et al. [34] reported that evapotranspiration water-use efficiency (ETWUE) ranged from 0.15 kg/m³ to 0.33 kg/m³. The improvement in ETWUE is most probably attributable to increased yield as well as to reduced soil evaporation and transpiration. It was deduced that management practices that lessen soil water evaporation and move the water for crop water use (more transpiration) reduce crop exposure to water stress and maintain water-use efficiency at the maximum level possible. For instance, Hatfield and Dold [49] reported that the adoption of drip irrigation reduced by 23% wheat water use, but, at the same time, it improved yield by 37%. In cotton, this practice reduced water use by 37% and diminished yield by 21%. Therefore, the use by farmers of micro-irrigation systems, such as drip-irrigation, lessens not only the soil water evaporation from between plant rows early in the season but also prevents almost all the evaporation component from the canopy. These management practices have a positive effect on WUE in areas where crops are micro-irrigated and show that WUE can be improved by water management practices.

Similarly, Evett et al. [34] revealed in several experimental studies at different locations of Texas and California in USA that water productivity (lint/evapotranspiration) and lint yield were improved by adopting drip-irrigation systems instead of furrow irrigation. In the same line, Fan et al. [55] found from a metadata analysis the highest cotton evapotranspiration water-use efficiency of 0.88 kg/m³, and this can be achieved by lessening by 5.5% the crop water use. Moreover, subsurface drip irrigation at the 40 cm depth induced maximum cotton irrigation water productivity (WP_{irr}) of 0.84 kg m⁻³. Increasing the irrigation amount decreased the WP_{irr} [56].

In recent years, the water-use efficiencies of cotton have been studied by many researchers to obtain optimum cotton yield by using less water. For example, Grismer [22] conducted a study on crop water productivity (CWP) for irrigated cotton in Arizona and California, USA. He found that, in Arizona counties, upland cotton actual evapotranspiration (ET_c) water-use efficiency varied from 1.27 to 1.38 kg/ha-mm while, for pima cotton, it varied from 0.9 to 1.09 kg/ha-mm. In California counties, ET_c water-use efficiency varied from 1.34 to 2.10 kg/ha-mm and 1.51–1.77 kg/ha-mm for upland and pima varieties, respectively. In western Turkey, Dagdelen et al. [41] reported WUE values varied from 1.59 to 2.30 kg m⁻³ for corn and from 0.61 to 0.72 kg m⁻³ for cotton in two years. WUE values of 0.38–0.46 kg m⁻³ were obtained by Anac et al. [40] in the coastal part of the Aegean region, Turkey.

It is important to highlight that WUE varies also according to the irrigation technology used. Some irrigation devices are found to limit water to the root zone, while others provide water to all the soil surface. Hodgson et al. [57] compared furrow and drip-irrigation methods for cotton and found that the WUEs were 2.23 and 1.89 kg m⁻³ for drip and furrow irrigation methods, respectively. Under drip, furrow, and sprinkler irrigation, Cetin and Bidgel [58] found water-use efficiencies of 4.87, 3.87, and 2.36 kg/ha-mm, respectively, proving that drip irrigation provides a greater yield per unit drop. Yazar et al. [59] reported that WUE values of cotton irrigated by LEPA and the drip method were, respectively, 0.55–0.67 kg m⁻³ and 0.50–0.74 kg m⁻³ in the Harran Plain in Turkey. Moreover, Kanber et al. [60] determined WUE values of 1.9–5.9 kg ha⁻¹ mm⁻¹ under furrow irrigation in the Cukurova Plain in southern Turkey and found irrigation water-use efficiency (IWUE) values for furrow irrigated cotton ranged from 1.5 to 5.1 kg m⁻³. According to Anac et al. [40], IWUE values were 0.48–0.65 kg m⁻³. In addition, IWUE values for LEPA and drip-irrigated cotton were 0.58–0.77 kg m⁻³ and 0.60–0.81 kg m⁻³, respectively, in the Harran Plain of Turkey [59]. Ertek and Kanber [61] determined IWUE values for drip-irrigated cotton of 0.75–0.94 kg m⁻³ in the Cukurova Plain in Turkey. In Queensland, Australia, furrow irrigation has been optimized and tested in the field for cotton. Results showed an increase in WUE and a decline in labor requirement [62]. The water-use efficiency fluctuates between farming fields and across regions due to many factors. Therefore, site-specific measurements are crucial for decision making and improvements in WUE.

Table 3. Irrigation regimes, yield, and water-use efficiency (WUE) (SE—severe deficit, MD—mild deficit, F.irr—full irrigation, DI—drip irrigation, SDI—subsurface drip irrigation, CEF—closed-end furrow).

Location	Year	Watering Regime	Yield (kg ha ⁻¹)		Water-Use Efficiency (kg m ⁻³)			Cotton Variety	References	
			Lint	Seed	WUE	IWUE	ETWUE			
West Texas, USA	2010	SE	712		0.20			FM9160	Snowden et al. [53]	
		MD	1436		0.32			DP1044		
		F.irr	1743		0.33			DP0912		
	2011	SE	596		0.15			DP0935		
		MD	1268		0.23			DP1044		
		F.irr	1537		0.22			DP0935		
Texas, California and Uzbekistan		DI					0.15–0.33	Evet et al. [34]		
Turkey	2016–2017	SDI		4082	0.83	0.84		Cetin and Kara, [56]		
Arizona, USA	1988–1999	N/A ¹	1280–1420 910–120				0.127–0.138 0.09–0.109	upland cotton pima cotton	Grismer [22]	
California, USA	1988–1999	N/A	1110–1440 1170–1340				0.134–0.210 0.151–0.177	upland cotton pima cotton		
Bushland, Texas, USA	2003	MESA 100%	1229		0.164	0.492			Paymaster2280 BG RR	Colaizzi et al. [38]
		MESA 75%	1001		0.142	0.491				
		MESA 50%	536		0.089	0.288				
		MESA 25%	213		0.045	0.024				
		LESA 100%	1208		0.160	0.482				
		LESA 75%	984		0.143	0.480				
		LESA 50%	575		0.098	0.321				
		LESA 25%	288		0.058	0.130				
		LEPA 100%	1153		0.158	0.456				
		LEPA 75%	1149		0.164	0.581				
		LEPA 50%	685		0.109	0.415				
		LEPA 25%	362		0.072	0.234				
		SDI 100%	1150		0.159	0.454				
		SDI 75%	1082		0.152	0.540				
SDI 50%	844		0.135	0.549						
SDI 25%	491		0.092	0.416						

Table 3. Cont.

Location	Year	Watering Regime	Yield (kg ha ⁻¹)		Water-Use Efficiency (kg m ⁻³)			Cotton Variety	References
			Lint	Seed	WUE	IWUE	ETWUE		
Turkey	2013	CEF 100%		5640	0.64	0.81			
		CEF 70%		4460	0.63	0.91			
		CEF 50%		3720	0.64	1.06			
		CEF 30%		3210	0.71	1.52			
		CEF(0%		1820	0.67	-			
	2014	CEF 100%		5340	0.62	0.74		Nazilli-84	Dagdelen et al. [41]
		CEF 70%		3990	0.62	0.79			
		CEF 50%		3590	0.73	0.99			
		CEF 30%		2800	0.74	1.29			
		CEF 0%		1740	0.72	-			
Bornova-Izmir, Turkey	1992–1994	Furrow			0.38–0.46	0.48–0.65	N84	Anac et al. [40]	
Australia		Drip			2.23				
		Furrow			1.89			Hodgson et al. [57]	
Anatolia, Turkey	1991–1994	Drip			0.487				
		Furrow			0.387		Sayar-314	Cetin and Bidgel [58]	
		Sprinkler			0.236				
Harran plain, Turkey		LEPA			0.55–0.67	0.58–0.77			
		Drip			0.50–0.74	0.60–0.81		Yazar et al. [59]	
Cukurova, Turkey		Furrow			1.9–5.9	1.5–5.1		Kanber et al. [60]	

¹ None available.

5. Cotton Yield and Yield Components under Different Irrigation Techniques

Cotton can be cultivated under rainfed conditions only in a limited number of regions, and usually an optimum yield cannot be achieved without irrigation [58]. Therefore, irrigation is necessary for cotton production. For instance, in the Mississippi Delta region, USA, Pinnamaneni et al. [63] reported that irrigation is a crucial factor in achieving both high fiber yield and seed quality, while Sui et al. [64] found out that irrigation augmented cotton yield and improved fiber length. Different irrigation technologies are widely used to produce cotton, with most common being:

- low-energy precision application (LEPA),
- low-elevation spray application (LESA),
- mid-elevation spray application (MESA),
- mobile drip irrigation (MDI),
- surface irrigation (SI),
- subsurface drip irrigation (SDI), and
- furrow irrigation (FI).

Various results have been obtained under different irrigation practices depending on local climates, soil conditions, genotypes, and management practices. In northern Texas and southwestern Kansas, USA, Colaizzi et al. [38] carried out a study in 2003 on cotton production with surface drip irrigation (SDI), LEPA, and spray irrigation, and found that the highest lint yield and water-use efficiency were achieved with SDI at low irrigation rates. Similar results were found by Colaizzi et al. [13] and Segarra et al. [14], who reported that SDI performed better than any other spray irrigation system (MESA, LESA, and LEPA). Moreover, the same study in 2004 revealed that lint yield and gross returns were improved with SDI at any irrigation rate. Bordovsky [65] found that under irrigation treatments with less than 50% of full irrigation, LEPA induced a 16% yield increase over sprinkler irrigation, but SDI resulted in a 14% higher yield over LEPA. At irrigation levels greater than 50% of full irrigation, yield was slightly smaller in sprinkler compared to LEPA, and SDI was found to provide a 7% greater yield than LEPA. However, Bordovsky et al. [15] carried out a study where soil matric potential was used to schedule irrigation and found that LEPA and drip irrigation provided the same yields for cotton, corn, and soybeans.

In Turkey, Cetin and Bidgel [58] carried out a study with three different irrigation methods on seed cotton yield and yield components and reported that maximum seed yield was 4380, 3630, and 3380 kg/ha under drip, furrow, and sprinkler irrigation, respectively. Drip irrigation generated 21% more yield than furrow irrigation and 30% more yield than sprinkler irrigation. In southeastern Turkey, Cetin et al. [66] did a similar study and compared different irrigation methods for effective water use on cotton. The highest seed cotton yield was found in drip-irrigated plots, and it was 4650 kg ha⁻¹. It was followed by furrow irrigation, which had a yield of 3120 kg ha⁻¹. In terms of lint yield, lint quality, and water-use efficiency, SDI has been found to slightly surpass LEPA and spray irrigation [14,67]. In India, Choudhary et al. [68] found that drip irrigation increased plant height, number of bolls per plant, boll weight, and number of monopods and sympods per plant. Further, water-use efficiency was greatest under drip irrigation as compared to other irrigation systems in all four cotton cultivars that Choudhary et al. [68] studied. According to Sezan et al. [69], for cotton production drip irrigation was more advantageous compared to conventional practices of irrigation. In China, Wang et al. [70] compared traditional flood irrigation and mulched drip irrigation and found that mulched drip irrigation promoted the root growth of cotton and improved the production of fine roots after the full-boll stage. The boll number per plant and yield were increased with mulched drip irrigation.

Drip irrigation has been found to be the most effective water-saving system. It can conserve soil, aggregate structure, successfully prevent deep water loss and surface water loss, and therefore, decrease exposure of the soil to degradation and salinization [71–74]. Fereres et al. [75] reported that an early and increased cotton yield could be achieved by drip irrigation. Mateos et al. [76] stated that drip irrigation was more beneficial than furrow irrigation. In the same line, Ibragimov et al. [36] in Uzbekistan reported that, with

drip irrigation used for cotton production, 18–42% of the irrigation water was saved in contrast to furrow irrigation. According to Ward and Pulido-Velazquez [77], compared to flood irrigation, drip irrigation increased cotton yields by about 25% and helped to save water by 40–50%. In the Harran Plain in Turkey, Cetin and Bilgel [58] found that drip irrigation improved seed cotton yield by 21 and 30% over furrow and sprinkler irrigation, respectively. Similarly, in the Texas High Plain, Colaizzi et al. [78] showed that SDI had the best cotton productivity and gross returns, followed by LEPA and spray irrigation. However, Cetin and Kara [56] reported that the use of SDI is limited, because it has adverse effects on cotton seed germination, if during sowing there is no moisture in the soil. For this reason, an alternative irrigation technology, such as sprinkler irrigation, is advised for better cotton germination.

Many studies have shown the importance of other irrigation methods, aside from drip irrigation, to achieve the best cotton yield. For instance, Yavuz et al. [79] found no statistically significant difference between the yields of cotton grown with drip, sprinkler, or furrow methods. Moreover, Howell et al. [80] tested drip and furrow methods for cotton irrigation and found no yield differences between the two methods. In the southeastern part of the U.S.A., Whitaker et al. [81] compared overhead sprinkler, subsurface drip irrigation (SSDI), and rainfed conditions and found no differences in cotton yield. Further, Yazar et al. [59] compared LEPA and trickle irrigation of cotton in southeast Anatolia and reported that both LEPA and trickle-irrigated plots enhanced the yield of cotton. According to the authors, both trickle and LEPA irrigation technologies could successfully be used to produce cotton under arid climatic environments. Similarly, Lyle and Bordovsky [82] found that LEPA performed better than furrow and sprinkler delivery systems. With LEPA, there was better water distribution and water-use efficiency, and energy was saved. Yuksek and Taskin [83] found no differences in the yield of cotton grown under sprinkler and furrow irrigation systems.

Based on the above studies, it is seen that irrigation technologies have diverse results under different climatic conditions. Field-based studies are critical to identify a technology that can provide an optimum yield and quality of cotton, and, at the same time, maximize water-use efficiency.

6. Response of Cotton Physiological Traits, Yield, and Yield Components to Irrigation Regimes

Among biotic and abiotic stresses, drought is the most harmful for plant growth and productivity. Across the globe, different irrigation regimes have various effects on cotton physiological traits, yield, and yield components. Various studies have been done under different irrigation regimes to measure stomatal conductance, the assimilation level of carbon dioxide, and canopy temperature. A significant decline in stomatal conductance occurs due to water stress [6]. Inamullah and Isoda [84] found that, under water stress, the flow rate of stem sap, stomatal conductance, and transpiration rate decreased more in soybean than in cotton and, therefore, cotton adapted better to limited water by maintaining a higher transpiration rate, compared with soybean. Azhar and Rehman [6] measured photosynthetic rates of cotton under normal and water-stressed circumstances and showed that water stress adversely affected the photosynthetic rate. Water-limited conditions affect the transpiration and the photosynthetic rates of cotton, which then limit the yields. Water stress decreases the leaf area of cotton. For instance, Rehman et al. [85] studied parents and F1 hybrids grown under three different irrigation regimes (none, deficit, and normal irrigation) and observed a reduction in leaf area under water-limited conditions. Moreover, cotton grown under drought has a lower relative water content (RWC). In the same line, Akbar and Hussain [86] carried out a study concerning the identification of water-limited, tolerant cotton genotypes based on the relative water content at different moisture levels. The authors reported that the RWC of cotton leaves declined as drought conditions increased. Furthermore, Siddiqui et al. [87] conducted a study on three cotton cultivars under three irrigation conditions (3-, 5-, and 7-time irrigation events) and found that the highest plant height (105.6 cm) was obtained when the cotton was irrigated seven

times. Moreover, the authors found that cotton irrigated five times during the growing season gave the highest seed cotton yield of 3323.52 kg per ha compared to 3- and 7-time irrigation events.

The effect of water stress on cotton seed yield and yield components has been examined by various researchers and has shown a decrease in yield due to water stress. Water stress reduces the transpiration rate, leaf area, and photosynthetic activities in the cotton plant and indirectly reduces yield and its components. For instance, in California, USA, Howell et al. [7] measured the average lint yield of cotton planted in narrow rows and irrigated under full, limited, and no post-planting irrigation and found that it was 1583, 1423, and 601 kg/ha, respectively. Regarding the dry matter, the authors further stated that the full irrigation regime produced roughly 16 t/ha of dry matter while the limited and no post-planting irrigation regimes provided, respectively, 11 t/ha and 7 t/ha of dry matter. In addition, Pettigrew [88,89] reported a decrease of 25% in lint yield due to water stress by analyzing cotton genotypes under drought stress and normal water conditions. Belaloui et al. [8] revealed that, under limited irrigation in the Mississippi Delta, the growth of cotton plants slowed to some extent, and this impacted the fiber and seed composition. More bolls were found in controlled environments than the stressed environments, and this indicated the negative effects of water stress on the number of bolls [90]. The flowering stage of cotton is found to be more sensitive to water stress than the vegetative one. For instance, under field conditions, Kar et al. [91] examined cotton response to limited water and found that water stress at the flowering stage reduced the yields.

Fiber quality is a key element in the profitability of cotton, and many researchers have studied the effect of water stress on the quality of the cotton fiber. For instance, Mert [9] examined different genotypes of cotton to evaluate the impact of water stress on the length, fineness, and strength of the fiber under normal and water-limited circumstances. The results revealed that water-limited conditions induced the production of fibers that were shorter and weaker with small micronaire values. Similarly, Lokhande and Reddy [10] explored the impact of drought on cotton during its developmental stages and discovered that, during the period of boll formation, the fineness of the fiber was negatively affected by drought.

Germination is also affected by the irrigation regime. Burke and O'mahony [92] indicated that water-limited conditions adversely affected the shoots of cotton varieties more than their roots. Likewise, all measures of shoot growth, comprising height, leaf area, nodes, and the dry weights of stem and leaves, were less in a cotton crop under drought stress compared to the controlled conditions [6]. Alcidu et al. [93] revealed that water stress during vegetative growth of cowpea led to a lower leaf water potential that negatively influenced the yield. With alternating periods of water stress during the vegetative period, Mohamed et al. [94] found that Roselle (a species of *Hibiscus*) exhibited a higher tolerance to water stress than with constant water stress; therefore, alternating wet and dry periods is an appropriate water management for Roselle production.

However, some other studies have demonstrated that cotton has drought resistance. In fact, Mitchell-McCallister et al. [95] revealed that deficit or reduced irrigation (RI) is an adaptive management practice that can increase water productivity and result in water conservation. In Turkey, Onder et al. [96] carried out a study concerning the effects of different water levels on yield and yield components using drip-irrigated cotton and observed an increase of boll weight and opened boll numbers under 25, 50, and 75% of full irrigation. The increase of boll numbers per plant under water-limited conditions indicated that cotton had a great potential in adapting to water stress. However, in west-central Oklahoma, USA, Masasi et al. [97] found that lint and seed yields under full and reduced irrigation did not differ significantly. The authors moreover reported no significant differences in fiber quality among the irrigation treatments, such as full irrigation, reduced irrigation (75%), and no irrigation. Zhan et al. [98] stipulated that limited irrigation can contribute to the adjustment of the shape of the canopy and the distribution of the light in the canopy. Chen et al. [99] concluded that in arid areas deficit-irrigated cotton, given

425-mm water and grown under a plant density of 36 plants per m², had advantages in terms of saving water and energy without yield penalties.

In summary, studies have found mixed results concerning the response of the physiological traits of cotton and its yield and yield components to different irrigation regimes. This is in line with Feng et al. [100] who reported an influence of location on the response of cotton yield and fiber quality to irrigation, which indicates the need to conduct local field studies. Similarly, many reports have emphasized the need to conduct field studies to evaluate crop response to different levels of water stress [101,102]. The findings of the effects of deficit irrigation on cotton performance can assist producers to make better decisions on the suitable levels of deficit irrigation that will produce their yield objectives [103]. There is a critical need to identify and test approaches that optimize water use for cotton production systems.

7. Cotton Yield and Yield Components in Response to Plant Density

Plant density is an important abiotic factor affecting cotton production [104] and has been evaluated in a number of studies [105–108]. According to Ajayakumar et al. [109], an appropriate spacing between plants is an essential agronomic factor that influences optimal use of resources for increased crop productivity. In Venezuela, Guzman et al. [105] assessed four sowing densities (62,500; 83,333; 100,000; and 142,857 plants per ha) on yield and its components of two cotton varieties and discovered high lint yield for “SN-2900” (4216.2 kg ha⁻¹) at 100,000 plants per ha and for “Delta Pine 160” (3917.3 kg ha⁻¹) at 83,333 plant per ha. The highest sowing density (142,857 plants per ha) reduced lint yield and yield components for both varieties. Furthermore, the authors showed that optimum lint yields could be achieved with sowing densities between 83,333 and 100,000 plants per ha in the tropical dry climate of Venezuela. Similarly, various studies of cotton production have indicated an increase in yield and a variation in the quality of the fiber resulting from changes in plant densities [106,107,110]. Many studies have reported the adverse effect of using high planting densities in cotton production systems. The use of high planting densities enhances the emergence of diseases, the appearance of smaller bolls, the shading of immature flowers, lateness in maturation, and a decline in plant size [107,111]. Similarly, Kerby et al. [108] reported that the increase in plant density from 10 to 15 plants per m² delayed cotton boll maturity. Further, Zhang et al. [112] stated that increasing planting density above 22 plants per m² induced shade and yield reduction in the middle and lower parts of the cotton plant. In the USA, the plant arrangement used differs considerably between regions in order to maximize yields. For instance, the plant density is 12.6 plants per m² in Georgia [113], 15.3 plants per m² in Louisiana [114], 6.6 plants per m² in Mississippi [115], and 10.0 plants per m² in Arizona [116]. In China, Khan et al. [117] carried out a study using six different densities and stated that taller plants and a higher number of leaves per plant were obtained with cotton cultivated at a lower plant density, while, under a high plant density, a higher number of branches and fruiting nodes and a greater number of bolls per unit of soil area were observed. The authors further revealed that the highest seed cotton yield (4546 kg ha⁻¹) and lint yield (1682 kg ha⁻¹) were produced by “D5” (87,000 plant ha⁻¹).

Globally, the use of high planting density has become popular in cotton production systems, but it has created problems. Khan et al. [117] stipulated that a high plant density produces more leaf shedding late in the season, along with lower boll weight, and, consequently, a high plant density negatively affects the yield, resulting in lower productivity. Similarly, Yang et al. [111] and Bednarz et al. [107] reported that a high plant density (>10 plants per m²) and the resulting shading may lead to an increase of disease infestation, fruit shedding, lowered boll size, delayed maturity, and reduced individual plant growth and light interception. In the same line, Khan et al. [118] stated that high cotton plant density resulted in fruit shedding, poor boll filling, late maturity, and disease propagation, which induced a decrease in cotton yield. Increasing plant density is found to lower plant height, reduce the number of the main-stem nodes per plant, the number of bolls per plant,

and the weight of individual cotton bolls [119,120]. Moreover, Ali et al. [121] mentioned that cotton yield rises with plant density to a certain density, called the optimum density, while low yield is obtained with very high and very low plant populations. Yang et al. [122] concluded that a dense population makes shade and increases the moisture of the canopy, making the canopy environment appropriate for pest damage. It is desirable not to use applications of insecticides or pesticide, which dense vegetation may require. Similarly, Yang et al. [111] found that a too high and a too low plant density reduced biomass accumulation of the reproductive organs. Khan et al. [117] reported that too high or too low plant densities led to a drop in cotton yields. Siebert et al. [114] also stipulated that a low plant density reduced yields with needless vegetative growth that resulted in fruit shedding and boll rotting.

Several studies have found the importance of high cotton plant densities. Khan et al. [123] revealed that dense plants enhanced plant total biomass, but the individual biomass of a cotton plant was reduced. Still, high plant density expands the cotton population size and stimulates canopy apparent photosynthetic rate (CAP) before the appearance of flowers [124]. Studies also have reported that dense plant populations can cut off water loss from evaporation and increase crop water use [124–126]. Moreover, a normal, but high population, can induce early maturation and a maximum use of optimal temperatures by cotton plants [127,128]. According to Chen et al. [99], a high planting density could be a way for a better combination of temperature, light, and water for optimum yield.

Based on the above research results, plant density has a direct relationship with cotton yield and yield components. Optimum yield, through better management practices, is the goal of cotton agronomists. Optimum plant density is found to vary with various conditions, such as the climate, the genotype and irrigation method used, and soil characteristics. Therefore, it is important to carry out studies in each geographic area to identify the optimal sowing density for maximum yields.

8. Irrigation Termination in Cotton Production

While cotton yield and fiber quality are affected by rainfall and irrigation events [53,129–132], irrigation termination remains a critical decision in cotton production. Many studies across the globe have linked irrigation termination (IT) to cotton yield, yield components, and resource-use efficiency. Results have varied according to the local environment, soil characteristics, water availability, irrigation strategies, and genotypes used.

Studies have pointed out the benefits of early IT without affecting yield. In the Texas High Plains, Lascano et al. [133] found that terminating cotton irrigation at 1000 °C Growing Degree Days (GDD) induced 25 and 50 mm water savings for 2.5 and 5.1 mm d⁻¹ irrigation levels, respectively, without a yield penalty. Therefore, GDD can be used to monitor water management in cotton cultivation. Moreover, the authors found that terminating at 890 °C GDD with 7.6 mm d⁻¹ of irrigation saved 100 to 115 mm of water. Similarly, Reba et al. [134] reported that water conservation could be achieved through implementing early IT based on weather conditions and crop developmental stages without adversely affecting cotton lint yield. According to Karam et al. [135], terminating irrigation at first-boll opening induced maximum yields compared to terminating at a later time.

Other studies have found controversial results on the contribution of early IT by presenting the importance of late irrigation to maintain yield and its components. In southwest Oklahoma, USA, during three growing seasons, Masasi et al. [136] carried out a study concerning the effects of three IT timings on yield and fiber quality. They concluded that cotton yield increased with later IT dates. However, this result depended on late-season rainfall quantity and timing. The authors further revealed that, from the earliest to the latest IT, the average lint yield increased by 347 kg per ha over the study period. In addition, early IT recorded the smallest seed yield and micronaire compared to the latest IT treatment. Moreover, Buttar et al. [137] indicated an increase in cotton yield with later IT. Vories and Glover [138] found similar results. An increase of micronaire due to later IT and its sensitivity to climatic parameters, such as precipitation and temperature,

have been reported in many studies [133,139]. Likewise, in a hot and dry mid-season environment in Arkansas, USA, Teague [140] noticed that a further irrigation after cutout (cutout indicates the end of the boll-loading period) resulted in an increase in micronaire. Silvertooth et al. [141] found an increase of lint yield and micronaire with later IT dates. However, a study carried out by Reeves [142] in Texas using subsurface drip irrigation in 2010 and 2011 highlighted the fact that opposite results can be obtained. He used IT treatments from two to six weeks after physiological cutout and found that the quality of the fiber improved with later IT in one year and with early IT in the other year.

Because irrigation termination has temporal and spatial contradictory effects under different environmental conditions, one approach is to optimize the IT timing, which could be a key factor in cotton-irrigation water management. The timing of IT has a direct positive relationship with maturity through hastening boll opening, decreasing boll rotting, and enabling defoliation by preventing vegetative overgrowth [135,142,143]. For instance, in the Texas High Plains, Ale et al. [144] carried out a study on optimum IT for cotton production. The authors found that the first week of September (about 118 days after planting, DAP) was the optimum time for IT for the full irrigation treatment, which had 6.4 mm per day at the vegetative, reproductive, and maturation developmental stages, and it was based on the simulated mean seed cotton yield and IWUE using the CROPGRO-Cotton model. Further, the authors revealed that, for limited irrigation with 3.2 mm per day at the reproductive and maturation stages, the optimum IT was found to be the second week of September (125 DAP) in normal years. Silvertooth et al. [141] carried out a study concerning the impact of five irrigation termination (IT1, IT2, IT3, IT4, and IT5) times on yield and fiber micronaire and found that the optimum lint yield and micronaire were reached with the IT4 date, which meant that 12 to 18 in (30 to 46 cm) less water was used, compared to IT5.

Studies have linked optimum IT to GDD. For instance, Monge [145] and Vories et al. [146] found that the optimal IT time was roughly 200 growing degree days (15.6 °C base temperature) after physiological cutout. They mentioned that irrigation after this point is inefficient because it resulted neither in increased yield nor profit. Moreover, Hogan [147] determined 306 growing degree days as an optimal IT after cutout.

Cotton irrigation termination is also dependent on soil characteristics. In the San Joaquin Valley, Grimes and Dickens [143] compared the IT of cotton grown on two soils with different water retention capacities and found that optimum IT was 28 days earlier for the higher water-keeping soil than the lower one. It has been found that IT is genotype dependent. To confirm this, Silvertooth and Terry [148] observed no yield differences between early or late IT with the cotton upland genotype “DPL 20”. However, considerable differences were found between it and pima cotton. Similarly, Silvertooth et al. [141] stated that cotton lint yield and fiber micronaire are dependent on IT treatment and the genotype used.

While early IT could induce yield losses, late IT also could waste valuable irrigation water without any extra yield, delay harvest, and increase the costs of management of insects and disease pests [149–151]. The decision to terminate cotton irrigation depends on many variables, such as projected lint yield and quality, market price, and irrigation water costs [133]. The decision should be field-based by considering plant growth stages, soil characteristics and moisture status, genotypes, boll numbers, geographic location, and crop health [152]. An appropriate date for final irrigation, which may save water and accelerate boll maturity without yield penalty [143], must be determined by the producers. Divergent results in different zones call for further studies concerning the effects of IT on cotton yield. As suggested by Lascano et al. [133] and Vories et al. [146], the optimum IT for cotton could improve farmers’ management practices and, more importantly, support water saving endeavors in arid and semiarid areas.

9. Conclusions

This review explored irrigation-water management practices for cotton production. The review first considered the cotton crop coefficient (Kc) and showed that the FAO-56 values are not appropriate for all regions, and local Kc values need to be determined. Second, cotton water use and evapotranspiration were reviewed. Cotton is sensitive to limited water, especially during the flowering stage, and irrigation scheduling should match the crop evapotranspiration. Water use depends upon location, climatic conditions, and the irrigation method and regimes. Third, cotton water-use efficiency was reviewed, and it varies widely depending upon location, irrigation method, and cotton variety. Fourth, the effect of different irrigation methods on cotton yield and yield components was reviewed. Usually yields and physiological measurements, such as photosynthetic rate, decrease with water stress, but studies have shown that cotton has drought resistance and deficit irrigation can be used as an effective management practice. Fifth, the effect of plant density on cotton yield and yield components was reviewed. Yield is decreased at high and low plant populations, and an optimum population must be determined for each location. Finally, the timing of irrigation termination (IT) was reviewed. Early IT can conserve water but may not result in maximum yields, while late IT can induce yield losses due to increased damage from pests. Extra water applied with late IT may adversely affect the yield and its quality and eventually compromise the profitability of cotton production systems. The optimum time for IT needs to be determined for each geographic location. More studies should be conducted to find an integrated approach for sustainable cotton production in the different climatic regions.

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