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Study On the Influence of Irrigation Strategies On Cotton Growth and Yield

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Abstract Cotton is an important fiber and cash crop in the world, but major producing areas generally face the challenge of water shortage. This study reviews the water demand characteristics of cotton at various growth stages, as well as the effects of water shortage and excessive irrigation on cotton physiology, growth and yield, and evaluates the effects of traditional irrigation and advanced irrigation technologies (such as drip irrigation, sprinkler irrigation, and underground infiltration irrigation) and precision irrigation strategies (such as deficit irrigation). The analysis shows that different irrigation methods significantly affect the root development, plant height, leaf area index, and flowering and boll setting process of cotton, thereby affecting seed cotton yield and fiber quality. A reasonable irrigation system can improve water use efficiency while ensuring yield and fiber quality. As a field case, the large-scale drip irrigation practice under plastic film in Xinjiang cotton fields has demonstrated significant yield-increasing and water-saving effects, but it also faces problems such as secondary salinization of the soil and residual film pollution. Looking forward to the future, intelligent irrigation integrating remote sensing and the Internet of Things, breeding of drought-resistant cotton varieties, and policy and training support will be the key directions for optimizing cotton irrigation and achieving sustainable production. This study summarizes the research progress on the impact of irrigation strategies on cotton growth and yield in recent years, aiming to provide a scientific reference for efficient water use and stable yield of cotton in arid areas.

Keywords Cotton; Water requirement; Irrigation strategy; Growth and development; Yield and quality

1 Introduction

Cotton (*Gossypium hirsutum* L.) is one of the most important natural fiber crops in the world and a major source of income for farmers in many countries. The global cotton planting area is about 31.92 million hectares, with an annual turnover of about US $5.68 billion, and it occupies a key position in the textile industry (Koudahe et al., 2021). As an economic crop, cotton production is related to the livelihoods of farmers in many developing countries and the development of related industries. China, India, and the United States are major cotton producers, among which Xinjiang, China, accounts for more than 73% of the country's cotton production and plays a strategic role in the country's textile raw material supply (He et al., 2023). However, cotton cultivation is usually concentrated in arid and semi-arid areas with limited precipitation, and irrigation is required to meet its water needs for growth, making water resources one of the decisive factors in cotton production.

Drought and water scarcity are severe challenges faced by cotton-producing areas around the world. In major cotton-producing areas such as northwest China, the South Asian subcontinent, and southwestern America, precipitation is low and varies greatly from year to year, and competition for irrigation water is fierce. Especially in Xinjiang, China, extremely dry climate conditions and unreasonable use of water and soil resources have led to secondary salinization of cotton fields, exacerbating the agricultural water crisis (Yang et al., 2024). Water stress will limit the growth and development of cotton, reduce photosynthesis and nutrient absorption, and ultimately lead to reduced yields. On the other hand, unreasonable excessive irrigation not only wastes water resources, but may also cause problems such as poor soil aeration, nutrient leaching and increased diseases. Therefore, achieving a balance between water supply and demand and improving irrigation water utilization efficiency in cotton-producing areas are crucial to ensuring cotton yield and quality (Hussain et al., 2020). The current challenge is how to formulate scientific irrigation strategies to cope with water shortages based on the water demand characteristics of cotton in each growth period and regional water resource conditions.

This study aims to systematically review the research progress on the effects of cotton irrigation strategies on its growth, yield and fiber quality in the past five years. The focus was on the water demand of cotton at different growth stages, the effects of water stress and over-irrigation on cotton physiology and ecology; the classification and comparison of traditional and advanced irrigation technologies, especially the application of sub-film drip irrigation and other technologies in arid areas; the mechanism of the influence of irrigation system on cotton growth parameters (root system, plant height, canopy development, flowering and boll formation); the influence of different irrigation methods on cotton final yield and fiber quality; water use efficiency and sustainability issues of water-saving irrigation; and the results and experience of large-scale application of sub-film drip irrigation in Xinjiang, China. This study summarizes the key experience of efficient cotton irrigation and proposes future research and practice innovation directions, in order to provide a reference for sustainable cotton production in arid areas.

2 Overview of Cotton Water Requirements

2.1 Cotton growth stages and their specific water requirements

The entire growth cycle of cotton includes the seedling stage, vegetative growth stage (before budding), reproductive growth stage (flowering and boll formation stage) and boll opening and maturity stage, and the water requirements in different stages vary significantly. In the seedling and bud stages, cotton water requirements are relatively low, and excessive water may lead to shallow root development and leggy growth; in the mid-summer when flowering and boll formation occurs, cotton plants reach the maximum leaf area and heavy boll load, and evapotranspiration rises rapidly at this time, reaching 542 mm, accounting for 88% of the total transpiration water loss, which is the peak water requirement throughout the year (Figure 1) (Zhao et al., 2023). Hussain et al. (2020) showed that under sufficient irrigation conditions, the total water requirement of cotton during the entire growth period is approximately between 500-800 mm depending on the regional climate. For example, in the cooler climate of the eastern cotton region of the North China Plain, the seasonal water requirement is about 620-670 mm, while in the hot Mediterranean climate the seasonal water requirement is higher (Yang et al., 2021). Usually, cotton is most sensitive to water and has the greatest demand for water from budding to flowering and in full bloom and boll formation, requiring timely and sufficient water supply; while the requirements for water are relatively low during the sowing and seedling stage and the end of boll opening. Based on this water demand law, phased water supply is often adopted in irrigation practice, with irrigation strengthened during the critical growth period and water control appropriately in the late growth period to ensure both yield and improve water use efficiency (Shen et al., 2012). The water consumption characteristics of cotton at each stage lay the scientific foundation for formulating a phased irrigation system.

2.2 Effects of water shortage and overwatering on cotton physiology

Water stress directly affects the physiological process and growth vitality of cotton. When the available soil water is lower than the cotton water requirement, the plant's stomatal conductance decreases, the photosynthesis rate decreases, the relative water content and chlorophyll content of the leaves decrease, and the plant growth is hindered (Luo et al., 2016). Mild to moderate drought stress first inhibits the growth of cotton stems and leaves and the development of flower buds. Severe drought will lead to increased shedding of young buds and flowers. Shareef et al. (2018) showed that drought stress reduced plant height and leaf area, and caused a decrease in photosynthesis rate under increased water deficit. Under moderate drought, photosynthesis decreased by about 30%, growth traits decreased by more than 20%, and significantly increased the content of osmotic regulating substances such as proline and abscisic acid to help plants resist water deficit. On the other hand, excessive water (such as long-term soil overwetting or excessive irrigation) can also have an adverse effect on cotton. Excessive irrigation can cause soil hypoxia, inhibit root respiration and deep rooting, and cause "waterlogging" symptoms. Cotton is manifested as yellowing leaves, root rot, and increased bud and boll shedding rates (Yan et al., 2009). An overly humid environment can also easily induce the occurrence of soil-borne diseases such as cotton wilt, reducing the number of bolls per plant and the yield of cotton. In general, whether it is water shortage or overwatering, it will disrupt the normal physiological metabolic balance of cotton and affect dry matter accumulation and reproductive growth. Therefore, extreme water stress and long-term overhumidity should be avoided in cotton planting, and soil moisture should be controlled in an appropriate range through reasonable irrigation to maintain the healthy growth of cotton (Pchelkin et al., 2023).

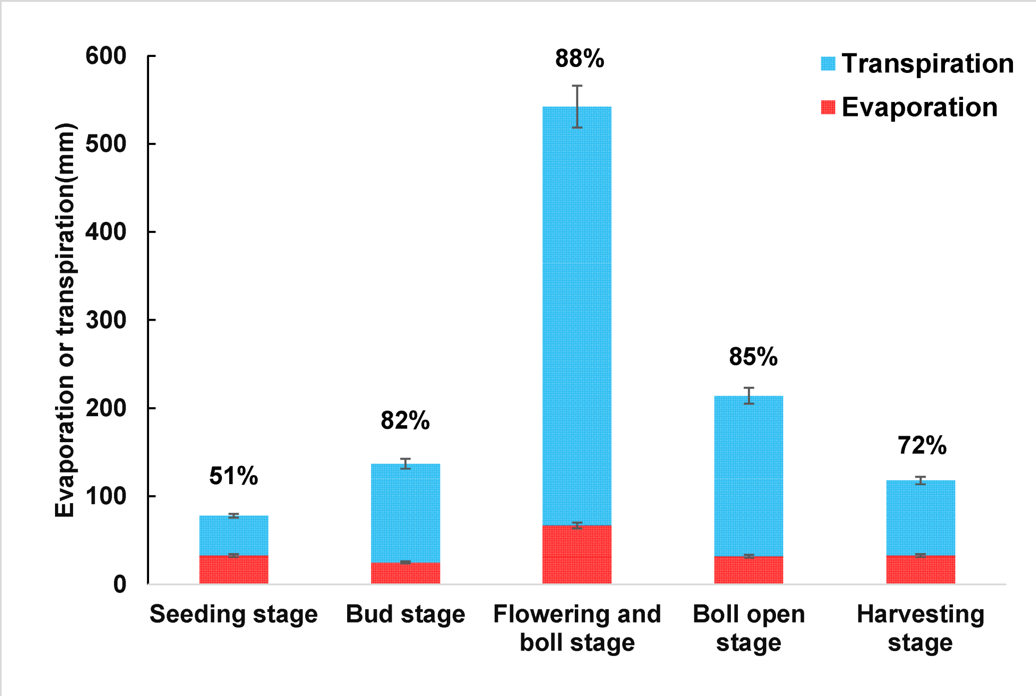

Figure 1 Changes in the evapotranspiration components and the proportion of transpiration to evapotranspiration at different growth stages of cotton (Adopted from Zhao et al., 2023)

2.3 Effect of climate and soil conditions on water use efficiency

The water use efficiency (WUE, dry matter or yield obtained per unit of water consumption) of cotton is significantly affected by the climate and soil conditions of the planting area. In an environment of high temperature, low humidity and strong radiation, the transpiration rate and evaporation loss of cotton are increased, and WUE is often lower under the same irrigation conditions; on the contrary, in a milder climate, cotton can convert more dry matter per unit of water. For example, improper irrigation in arid and hot areas such as Xinjiang and Texas will cause a large amount of water evaporation or deep seepage, resulting in low water use efficiency (Li et al., 2016; Evett et al., 2019). Soil texture and water storage capacity also affect cotton's use of water. Sandy soil has poor water storage capacity and requires more frequent irrigation, but the amount of water each time should be small, otherwise it is easy to leak and waste; clay soil has poor aeration, and excessive irrigation is prone to waterlogging (Wang et al., 2021). The degree of soil salinization is also a key factor: in saline soil, cotton needs to maintain a high irrigation leaching rate to suppress the increase in salt, but excessive irrigation will reduce WUE. Studies have shown that by optimizing irrigation scheduling, controlling soil salinity while ensuring cotton growth, efficient water use can be achieved that takes into account both water and salt. Zhang et al. (2021) found that under saline-alkali water irrigation conditions, when soil salinity is controlled within a certain threshold, cotton yield is equivalent to freshwater irrigation, thus achieving a relatively high water productivity. Therefore, when formulating a cotton irrigation system, it is necessary to consider the local climate evaporation requirements and soil characteristics, and determine the irrigation intensity and frequency according to local conditions to maximize the efficiency of cotton's use of every drop of water.

3 Classification of Cotton Irrigation Strategies

3.1 Conventional irrigation methods

Before the popularization of modern water-saving technologies, conventional ground irrigation methods dominated cotton cultivation. The most traditional of these is flood irrigation (sometimes called flood irrigation), which is to flood the field at one time on flat land. This method is simple and easy to implement, but it uses a large amount of water and has uneven water distribution, which can lead to local overwetting and deep leakage. Another common method is furrow irrigation, which is to dig ditches to divert water along the ridges to flood and infiltrate the cotton rows. This method has better water flow control than flood irrigation, relatively uniform irrigation in the field, and reduces surface runoff losses. Therefore, traditional cotton fields mostly use furrow irrigation. However, conventional ground irrigation is inefficient, with the water use efficiency of SF irrigation being only 57%. Other studies report that the efficiency of flood irrigation is even between 35% and 44% (Singh et al., 2022). Ground irrigation was widely used in cotton fields when water resources were abundant or water prices were low in the past. However, in the current context of water shortage, its disadvantages of high water consumption and low efficiency are prominent. Excessive surface irrigation can also cause the movement and accumulation of soil salts and nutrient loss, which is not conducive to the long-term health of the soil environment. Despite this, in some areas where farmland infrastructure is poor or pressurized water delivery equipment cannot be used, conventional flooding and furrow irrigation are still the irrigation methods followed by cotton farmers, and field engineering improvements and scientific guidance are needed to improve their water use efficiency (Sajid et al., 2020).

3.2 Advanced irrigation technology

In order to improve the efficiency of cotton irrigation water use, various efficient and water-saving irrigation technologies have been developed and applied. Among them, drip irrigation is one of the fastest-growing technologies in cotton in recent years. Drip irrigation uses drip irrigation pipes laid on the surface or underground to directly provide water to the vicinity of the cotton root zone in a low-flow, frequent and small-dose manner. In Xinjiang and other places, sub-film drip irrigation is widely used, that is, drip irrigation belts are buried under the ridges covered with plastic film to achieve the dual effects of reducing surface evaporation and precise water and fertilizer supply. Drip irrigation technology can increase the efficiency of irrigation water use to about 90% and significantly increase cotton yield. Studies have shown that compared with traditional furrow irrigation, drip irrigation can save 30%-50% of water and increase seed cotton yield by 10%-20% (Ayer et al., 1984). Another advanced technology is sprinkler irrigation, which uses sprinklers to simulate rainfall for irrigation. It is widely used in cotton-growing areas such as the United States and Australia. Sprinkler irrigation can moisten the soil more evenly and is suitable for large-scale mechanization, but evaporation losses are relatively high in windy and dry areas. In recent years, a new type of subsurface drip irrigation has also begun to be used for cotton, that is, burying drip irrigation pipes deeper underground to further reduce evaporation losses and promote root penetration. Some innovations, such as introducing air into the drip irrigation system to form oxygenated drip irrigation to improve oxygen supply in the root zone (Pendergast et al., 2013), or integrated water and fertilizer irrigation combined with nutrient delivery, are also being tested in cotton fields (Nie et al., 2021). Overall, advanced irrigation technology has achieved a higher output-input ratio for cotton by more accurately distributing water. For example, in an IoT-controlled smart drip irrigation experiment, cotton yield increased by nearly 67% and water consumption decreased by about 12% compared with manual empirical irrigation (Guo and Chen, 2024). The promotion of these technologies provides important support for the development of cotton production towards high yield, high efficiency, water conservation and environmental protection.

3.3 Deficit and precision irrigation methods

Under conditions of limited water resources, deficit irrigation strategies are often adopted, that is, planned reduction of irrigation water supply within the crop tolerance range to save water. For cotton, moderate deficit irrigation can reduce irrigation volume without significantly reducing yield, thereby improving water production efficiency (Xu et al., 2024). Guirguis et al. (2015) showed that reducing irrigation volume by 10% during the entire growth period of cotton has little effect on yield, but can save about 15.2% of water and increase water use efficiency by 7%. In particular, if water deficit occurs in a growth stage where cotton has strong tolerance (such as the end of the vegetative growth period), the plant can minimize the impact through physiological adaptation (Ullah et al., 2017). In field trials, a mild deficit treatment of 90% full irrigation not only met the water needs of cotton but also avoided over-irrigation, showing a yield equivalent to full irrigation and significant water-saving effect (Xu et al., 2024). In order to achieve more sophisticated water management, the concept of precision irrigation came into being. Precision irrigation relies on modern sensing, control and information technology to monitor soil moisture and crop status in real time and automatically irrigate on demand. Through soil moisture sensors, crop water stress detection (such as leaf temperature, canopy images) and remote control systems, cotton fields can achieve precise water control at different locations and times. A two-year field study by O'Shaughnessy et al. (2023) proved that the automatic control irrigation system based on sensor feedback can maintain a yield equivalent to full irrigation at a cotton water replenishment level of 75%, while saving 16%-20% water, and the automatic control effect is equivalent to manual monitoring. The introduction of internet of things (IoT) technology has made precision irrigation of cotton fields a reality. Through wireless sensor networks and intelligent algorithms, irrigation time and dosage can be dynamically determined to achieve "water supply on demand" (Faruk and Debnath, 2021). Precision irrigation upgrades traditional experience management to digital precision management, and is one of the future development directions of cotton irrigation.

4 Effects of Irrigation Strategies on Cotton Growth Parameters

4.1 Root development and plant height

Irrigation level directly affects cotton root morphology and aboveground growth. Appropriate water supply promotes the growth of cotton roots to the deep layer, thereby expanding the volume of water and nutrient absorption; on the contrary, excessive drought will force the root growth to be restricted or even cause root dehydration and necrosis, and excessive moisture will reduce root activity due to soil hypoxia (Luo et al., 2016). Under deficit irrigation conditions, cotton plants often adapt to water shortage by increasing the root-to-crown ratio, that is, the root system allocates more biomass to explore water sources, while the aboveground growth is inhibited to a certain extent. Wang (2008) found that moderate water deficit (50%-60% of field water holding capacity) at all growth stages can stimulate cotton roots to go deeper and better absorb deep residual water, while inhibiting excessive stem and leaf growth and achieving root-crown coordination. Li et al. (2020) found that severe water shortage at any growth stage significantly inhibited plant height and stem diameter. However, mild deficit (irrigation volume of 90% of full water) has no significant effect on plant height. At the same time, the root system shows higher root length density and root hair volume under moderate drought (Guo et al., 2023). On the contrary, under excessive irrigation conditions, due to the long-term wetness of the surface soil, the cotton root system tends to be shallowly distributed, and the shallow rooting reduces the plant's stress resistance. In addition, excessive moisture will reduce the number of root fibrous roots and reduce the root absorption efficiency. Wang et al. (2007) compared the cotton root systems of different irrigation strategies and found that strictly controlling the lower limit of irrigation under drip irrigation under film can significantly affect the root morphology: the average root diameter of the root system increased and the total root length decreased in the treatment of lower irrigation limit (more drought), while the root system was finer and denser but shallowly distributed in the treatment of higher lower limit (wet). In summary, the irrigation strategy regulates the distribution of cotton roots and the aboveground part through the soil water environment: reasonable water stress is conducive to creating "deep roots and strong plants", while excessive water supply is easy to lead to "shallow roots and vigorous growth", which in turn affects the stress resistance and stable yield of cotton.

4.2 Leaf area index and canopy development

Leaf Area Index (LAI) is an important indicator for measuring cotton canopy growth, reflecting the total leaf area per unit land area. When irrigation is sufficient, cotton can maintain a high LAI and form a dense canopy, thereby intercepting more light energy for photosynthesis; when water is insufficient, leaf growth is inhibited, LAI decreases, and plants may shed leaves to reduce transpiration during severe drought. Studies have shown that cotton LAI varies significantly under different irrigation regimes (Table 1). Field trial data from Papastylianou and Argyrokastritis (2014) showed that compared with full irrigation of two cotton varieties ("Julia" and "Zoi"), LAI under deficit irrigation decreased by 23% and 38%, respectively. The LAI of cotton treated with mild water deficit (irrigation lower limit 75% field capacity) was only slightly lower than that of full irrigation, while severe water deficit (lower limit 50%) resulted in significantly smaller leaves and fewer leaves (Wu et al., 2023). The reduction of LAI caused by water deficit is also accompanied by changes in leaf function, such as decreased stomatal conductance and reduced net photosynthetic rate (Pettigrew, 2004). On the other hand, excessive irrigation may lead to an overly dense cotton canopy and an increase in ineffective leaves. When there is too much water, cotton plants grow vigorously and easily form a closed canopy structure. The internal leaves will prematurely age and turn yellow due to limited light, and the photosynthetic efficiency of the whole plant will decrease. Therefore, appropriate irrigation should ensure a high LAI while preventing the canopy from being overly closed. Practical experience shows that moderate water regulation (such as a small water deficit during the flowering and boll stage) can control the growth of ineffective cotton leaves, improve canopy ventilation and light transmission conditions, and increase the distribution of photosynthetic products to cotton bolls (Zhan et al., 2015). For example, in the drip irrigation cotton field experiment in southern Xinjiang, high-frequency and small-volume irrigation kept the cotton LAI growing steadily without large fluctuations, while the low-frequency irrigation treatment caused the LAI to rise sharply after irrigation and then drop rapidly between irrigations, showing an unbalanced canopy development rhythm (Han et al., 2011). It can be seen that by adjusting the irrigation frequency and lower limit, the growth dynamics of the cotton canopy can be regulated, the appropriate LAI level can be maintained, and a good foundation for yield formation can be laid.

Table 1 Effect of irrigation systems and irrigation durations on theaverage number ofbranches per plant (branch .plant $^{-1}$) (Adopted from Jabr et al., 2020)

Irrigation systems	Irrigation duration		Irrigation systems average
	Two days	Four days	
Subsurface irrigation	7.33	6.67	6.50
Drip irrigation	4.33	5.00	4.67
LSD= 0.05	0.814		0.717
Irrigation duration average	5.33	5.83	
LSD= 0.05	NS		

4.3 Flowering and boll formation time

The flowering and boll formation process of cotton is also significantly affected by irrigation strategies. Water conditions will change the growth period of cotton: when there is sufficient water, cotton usually blooms and bolls at a normal rhythm; while drought stress may delay or shorten certain growth stages. For example, drought often delays the flowering time because the plant prioritizes survival and delays reproductive transformation when vegetative growth is inhibited and assimilation products are insufficient (Pilon, 2015). When there is severe water shortage, some flower buds will fall off prematurely due to insufficient water and nutrient supply, resulting in a decrease in the number of effective flowers and delayed boll formation. In contrast, appropriate water supply can ensure that cotton blooms on time, the boll formation period is fully extended, and it is conducive to the maturation of seed cotton. Similarly, excessive water supply may also affect the flowering and boll formation dynamics of cotton. Excessive water supply can easily cause excessive vegetative growth of cotton, resulting in delayed flowering and "long and late flowering" phenomena (Wang et al., 2020). This will cause the growth period of cotton fields to be prolonged, the maturity of bolls and fruits in the later period to be inconsistent, and increase the difficulty of harvesting and the risk of reduced yield. Therefore, in order to achieve a reasonable arrangement of cotton flowering and bolling period, it is necessary to regulate it through irrigation. Deficit irrigation has been proven in practice to adjust the growth process: for example, in the Xinjiang experiment, the implementation of mild water control during the flowering period of cotton can slightly shorten the flowering period, make cotton concentrate bolls, improve water use efficiency and do not lose yield (Guo et al., 2015). On the other hand, although continuous and sufficient water supply is conducive to increasing the number of bolls per plant, if irrigation is stopped too late, some late bolls may not fully crack due to water shortage in the later period, affecting yield and quality. Determining the appropriate irrigation termination time is also key. Reeves (2012) suggested that irrigation should be stopped in time after the last effective flowering of cotton to facilitate the maturity and opening of cotton bolls in the later period. In summary, different irrigation strategies change the flowering and bolling pattern of cotton by affecting its growth process. Reasonable irrigation scheduling (including irrigation time and termination period) should ensure that cotton blooms on schedule and produces more and earlier bolls, while avoiding growth delays and bud and boll losses due to water imbalance.

5 Effects on Cotton Yield and Fiber Quality

5.1 Yield under different irrigation systems

Irrigation system is one of the important factors that determine the yield of cotton seed cotton. Sufficient and uniform irrigation can meet the water demand of cotton throughout the growth process, thereby realizing the yield potential; on the contrary, unreasonable irrigation (whether insufficient or excessive) will lead to reduced yield. A large number of studies have compared the effects of different irrigation modes and water management on cotton yield. In general, the treatment with efficient irrigation technology and water supply according to the law of crop water demand has the highest yield. For example, in an experiment in Baotai, Shihezi (northern Xinjiang), the seed cotton yield of the treatment with full irrigation under film drip irrigation increased by more than 10% compared with traditional furrow irrigation (Li et al., 2009). The effect of deficit irrigation on cotton yield depends on the degree and period of water deficit. Mild deficit often has no obvious effect on yield; Lin et al. (2024) reported that the yield of mild deficit (90% irrigation) treatment was the same as that of full irrigation, showing the advantage of water saving without reducing yield. However, as the degree of water deficit increases, the number of bolls per cotton plant and the boll weight both decrease, and the yield is significantly reduced. In the study of Rao et al. (2016), severe water deficit treatment (only 50% irrigation) resulted in a 17% reduction in seed cotton yield compared with full irrigation. Irrigation frequency also affects yield performance: high-frequency small-water irrigation is conducive to avoiding drought stress, maintaining stable growth, and often has higher yields; low-frequency large-water irrigation may cause drought stress between two irrigations, and yield is slightly affected (Yu et al., 2011). Jia et al. (2024) found in a three-year experiment in southern Xinjiang that the seed cotton yield of high irrigation volume (420 mm seasonal total) treatment was 2.5%-7.5% higher than that of medium irrigation volume (370 mm), and high frequency (once every 4 days) was slightly better than low frequency (every 12 days). In areas with water shortages, moderately sacrificing a certain yield in exchange for substantial water savings may be a realistic option. For example, a comprehensive analysis by Ouda et al. (2024) showed that compared with full irrigation, implementing an irrigation deficit of about 20% can save 20% of water while only reducing cotton yield by 5%. Therefore, in production, the irrigation system should be selected according to the water resource status and economic trade-offs: if the water source is sufficient and the goal is to maximize the yield, sufficient irrigation combined with drip irrigation and other efficient methods can be adopted; if the water source is limited, the deficit irrigation strategy is adopted to control the yield loss to the minimum through fine management. Regardless of the strategy, it is proved that scientific irrigation plays a decisive role in the high and stable yield of cotton.

5.2 Influence of cotton lint quality and fiber strength

Irrigation not only affects the yield of cotton, but also has an important impact on the quality of cotton fiber. Cotton fiber quality includes indicators such as length, fineness (micronaire value), specific strength, and maturity. These characteristics depend to a large extent on the water and nutrient supply during cotton growth. The study of Nazar et al. (2012) showed that moderately sufficient and balanced water supply can help improve fiber quality; on the contrary, water stress may cause the fiber to become shorter, thicker, and the strength to decrease. In the process of post-flowering development, cotton fiber needs continuous water to support cell elongation and cellulose deposition. If drought occurs during the flowering and boll-setting period, the fiber cell elongation period is shortened, and the final fiber length is reduced. At the same time, the cell wall of the fiber is not fully developed under water stress, and the maturity and strength are also affected. Analysis of irrigation experiments in cotton fields in Xinjiang shows that increasing the amount of irrigation and appropriately increasing the frequency of irrigation are beneficial to improving fiber quality. The specific strength of cotton fibers in high irrigation treatments increased significantly, and the micronaire value (reflecting fineness and maturity) decreased, indicating that the fibers were more slender and matured uniformly; while the fiber strength of low irrigation treatments was low, the micronaire value increased, and the proportion of coarse and short fibers increased. In addition, compared with low-frequency irrigation, high-frequency irrigation increased the average length of cotton fibers by about 0.5 mm, increased the specific strength at break, and improved the quality (Jia et al., 2024). Another study on different irrigation strategies also found that the length and strength of cotton fibers decreased under water shortage conditions, but if the lower limit of irrigation was reasonably controlled (such as the relative soil water content was not less than 60%), the fiber quality could be maintained at a good level (Sheng et al., 2014). In the context of saline-alkali water irrigation, moderate irrigation and leaching are necessary, but if excessive irrigation leads to premature aging in the later stage, it will also make the fibers fragile. Therefore, high-quality and high-yield cotton requires a "double guarantee" of water supply: both to meet the formation of yield and to take into account fiber development. Practical experience shows that keeping the cotton field moderately moist before boll opening can give the fiber ample time to complete its development; and proper water control during the boll opening period to prevent premature aging can also help improve the maturity of the fiber in the later stage. Through such irrigation regulation, high-strength, long-staple, and moderately fine high-quality cotton fibers can be produced, thereby improving the economic value and textile performance of cotton.

5.3 Harvest index and economic return

The harvest index is usually used to express the ratio of crop economic yield (seed cotton) to total biological yield (including cotton stalks and leaves, etc.), which can reflect the efficiency of dry matter allocation to economic yield. Irrigation strategies will change the harvest index by affecting the balance between cotton vegetative growth and reproductive growth. Under sufficient irrigation conditions, cotton vegetative bodies (stems and leaves) and reproductive bodies (cotton bolls) grow well, and the harvest index is generally maintained at around 0.3-0.4; under water stress conditions, cotton often prioritizes the growth of rhizomes to survive, and the decline in economic yield is greater than that of biomass, resulting in a decrease in the harvest index (Buttar et al., 2009). On the contrary, if the irrigation strategy promotes moderate "vigorous control" of cotton and reduces ineffective growth, more dry matter can be used for boll formation and improve the harvest index. Studies have shown that sub-film drip irrigation can increase the cotton harvest index by about 10% compared with flood irrigation due to the reduction of cotton transpiration and ineffective branch and leaf growth, which means that a higher proportion of biomass is converted into cotton lint fiber and seeds (Wang et al., 2021a). From the perspective of economic return, optimizing irrigation strategies can increase the output value of cotton per unit of water use. Although there is an initial investment in the use of advanced water-saving technologies, a higher input-output ratio can usually be achieved through water-saving and increased production. For example, after the large-scale promotion of drip irrigation in southern Shanxi, the economic output value of cotton production per cubic meter of water increased by more than 30% compared with traditional flood irrigation (Wang and Sun, 2013). In addition, precision irrigation and automated control can reduce labor and energy costs and improve economic benefits. However, it is necessary to balance the impact of water fees and equipment costs on income. In areas with high water prices, the cost savings brought about by water saving will significantly increase net profits; while in areas with low water resource costs, farmers are more concerned about increased production and income. In general, reasonable irrigation strategies can bring higher economic returns and risk resistance to cotton farmers by improving cotton harvest index and water productivity. This is also the driving force for the widespread application of water-saving irrigation technology in cotton production: only when irrigation optimization is reflected in real economic benefits, farmers will be motivated to adopt new water use strategies. Therefore, when promoting water-saving irrigation, local governments should analyze input-output and demonstrate the effect of water-saving and yield-increasing according to local economic conditions and water price policies, so as to promote a win-win situation for the economy and environment in cotton production.

6 Water Use Efficiency and Sustainability

6.1 Irrigation water productivity of cotton systems

Water use efficiency is one of the core indicators to measure the effectiveness of irrigation strategies. In cotton production, there are various related concepts, such as irrigation water use efficiency (IWUE, yield per unit of irrigation water) and total water productivity (WUE including precipitation). Improving the irrigation water productivity of cotton means producing more cotton with less water. By optimizing the timing and intensity of irrigation, the water productivity of cotton fields can be significantly improved. For example, in a two-year field trial conducted on the southern edge of the Taklimakan Desert in northwestern China, cotton yield under full irrigation (100% field capacity) reached 4376 kg/ha (about 1458 kg/mu), water consumption (ETc) was 1079 mm, and IWUE was 0.48 kg/m^3. Under 80% irrigation, yield only decreased by 13%, while IWUE increased. Under

60% irrigation, cotton yield remained close (about 1500 kg/mu), but water consumption decreased significantly and IWUE increased to about 0.62 kg/m³ (Shareef et al., 2018). For example, O'Shaughnessy et al. (2023) reported that the use of automated precision irrigation reduced the irrigation water volume of cotton by 20% while maintaining the same yield, which is equivalent to a 20% increase in IWUE. Under the conditions of drip irrigation under film in Xinjiang, due to the small evaporation loss, the total water consumption of cotton fields is relatively reduced, and the water productivity is significantly improved compared with traditional flooding. Review studies in recent years also support this point: the average WUE of drip irrigation cotton fields can reach 1.2-1.4 kg/m³, while that of flood irrigation cotton fields is usually only 0.6-1.0 kg/m³. To further improve the water use efficiency of cotton, the key is to reduce non-productive water consumption (such as soil surface evaporation, deep infiltration and weed transpiration) and optimize productive water consumption (crop transpiration). Covering the ground with film, weeding between rows and improving irrigation methods can all help. At the same time, variety selection and cultivation measures (such as dense planting adjustment) will also affect the transpiration efficiency of the group. The combined use of these measures can enable cotton production to achieve the ideal state of "producing the most cotton with the least water". In general, improving cotton irrigation water productivity not only alleviates water pressure, but also reduces production costs and improves the ability to maintain stable production in drought years. It is one of the important goals of sustainable development of agriculture in cotton-growing areas.

6.2 The role of scheduling and automation in water conservation

Irrigation scheduling refers to determining when and how much to irrigate based on crop water requirements and soil moisture conditions. In traditional agriculture, cotton farmers often irrigate based on experience or fixed schedules, which makes it difficult to respond to the real needs of crops in a timely manner, resulting in either water stress or excessive irrigation waste. Scientific irrigation scheduling is crucial to water saving and efficiency improvement. In recent years, with the development of sensing technology and information technology, irrigation scheduling is shifting from manual experience to automated intelligent decision-making. The automatic soil moisture monitoring system can track the soil moisture content at different depths in the field 24 hours a day, and automatically trigger irrigation when the moisture content is lower than the set lower limit to avoid drought stress on crops (Joji Mitto and Savant, 2022). At the same time, plant sensors (such as stem diameter change and leaf temperature thermal infrared imaging) can directly reflect the moisture status of cotton itself, providing a basis for precise irrigation. O'Shaughnessy et al. (2023) deployed an ISSCADA irrigation automatic control system based on a central pivot sprinkler. Through GIS monitoring of crop water stress index combined with meteorological data, the irrigation plan of the cotton field was dynamically adjusted. As a result, the yield was successfully maintained under deficit irrigation conditions and water was greatly saved. The application of Internet of Things (IoT) technology enables the fusion of data from different types of sensors and realizes remote irrigation control through wireless networks and cloud platforms (Guo and Chen, 2024). Farmers can view the soil moisture, weather and crop conditions of cotton fields in real time through mobile phones or computers, and automatically or manually issue irrigation instructions. This not only improves the accuracy of irrigation decisions, but also reduces the loss of manual field inspections and canal water delivery. In addition to automatic irrigation, data-based irrigation decision support systems (DSS) also play a role in water conservation. Models established through years of experimental data can provide optimal irrigation recommendations for different climate years and different cotton growth stages. In general, advanced scheduling and automation technologies can transform cotton irrigation from empirical extensive management to scientific and fine management, minimizing ineffective water use. These technologies have achieved initial results in arid areas such as Xinjiang, improving the efficiency of irrigation water use and reducing the labor intensity of cotton farmers. With the reduction of technical costs and the increase in promotion efforts, smart irrigation is expected to be applied in a wider range of cotton areas, providing a solid guarantee for water-saving agriculture.

6.3 Environmental factors and soil health protection

The sustainability of cotton irrigation strategies is also reflected in the impact on the environment and soil health. First, long-term and large-scale irrigation may lead to groundwater over-exploitation and water source depletion, which is a macro-environmental problem faced by cotton fields in many arid areas. Implementing scientific irrigation and improving water use efficiency can reduce the adverse impact on the water environment while meeting agricultural needs. Secondly, irrigation methods affect soil salinity dynamics. In arid areas, soil salt is prone to accumulate on the surface due to evaporation and concentration, threatening cotton growth. Reasonable irrigation should not only supplement leaching to prevent salt accumulation, but also prevent excessive leaching from causing water waste. Wu et al. (2020) proposed a soil salinity threshold that cotton can tolerate, and suggested that the root zone salinity be maintained within the acceptable range for crops by controlling the irrigation volume, thereby achieving water-salt balance. For cotton fields that have already been salinized, concentrated irrigation can be used to wash away salt in early spring or during the fallow period, and then the irrigation volume can be finely controlled during the growing period to balance salt suppression and water conservation (Feng et al., 2021). Thirdly, mulch film residue pollution is a new environmental problem brought about by the large-scale application of drip irrigation under film. Traditional PE mulch film is difficult to completely recycle, and some residual film remains in the soil every year. As farming continues year after year, it accumulates and causes the physical and chemical properties of the soil to deteriorate. Residual mulch film will hinder soil water and air permeability, inhibit root growth, and may also adsorb pesticides and fertilizers to cause secondary soil pollution. It is reported that the amount of residual film in the tillage layer of some cotton fields in Xinjiang that have been irrigated with drip irrigation under film for a long time has exceeded 20 kg/mu, affecting both soil bulk density and water holding capacity (Zhang et al., 2019). To this end, it is necessary to strengthen the management of residual film and promote alternatives such as degradable mulch films.

7 Case Study: Irrigation Practices in Xinjiang, China

7.1 Regional overview and importance of cotton planting

Xinjiang Uygur Autonomous Region is the largest cotton producing region in China, ranking first in the country in terms of planting area, total output and yield per unit area. According to the Xinjiang Statistical Yearbook (2023), Xinjiang's cotton planting area is stable at around 37 million mu, accounting for about 80% of the country. Its natural conditions of drought, little rain and abundant sunshine are conducive to cotton growth, but also cause a high degree of dependence on irrigation. In order to achieve high and stable yields, Xinjiang took the lead in promoting sub-film drip irrigation technology on a large scale in the country, becoming one of the largest water-saving irrigation areas in the world (Wang et al., 2008). This technology not only changed the traditional way of water resource utilization, but also reshaped the water use pattern of cotton planting.

7.2 Implementation of drip irrigation under plastic cover

The sub-film drip irrigation system used in Xinjiang cotton fields usually consists of a water supply main, capillary tubes, drip irrigation belts, ground film and control valves. The water source is mostly surface water or groundwater, which is transported to the field through a pressurized system. Mulching with plastic film helps reduce soil evaporation, increase soil temperature, and inhibit weed growth. Drip tapes are buried in the furrows, with one tape per ridge or two rows per tape. Farmers use timers or smart irrigation systems to accurately irrigate according to the cotton growth stage. Under this mode, the cotton yield per unit of water is greatly increased. According to Jia et al. (2024), in the three-year experimental field of drip irrigation under plastic film in southern Xinjiang, the average water saving rate reached 30%, and the seed cotton yield increased by 12%-18% compared with traditional furrow irrigation. Drip irrigation under plastic film can also realize the integrated supply of water and fertilizer, dissolving fertilizer in water and transporting it to the vicinity of the root system, improving fertilizer utilization efficiency and reducing loss (Figure 2) (Yin et al., 2010).

7.3 Results: yield increase, water saving and challenges

Drip irrigation under plastic film has greatly improved the water use efficiency and yield of cotton fields in Xinjiang. Sheng et al. (2014) showed in Shihezi area in northern Xinjiang that the IWUE of cotton fields irrigated with drip irrigation under plastic film was 2.8 kg/m³, which was 47% higher than that of traditional furrow irrigation. In addition, this technology significantly reduces the problem of soil salt accumulation caused by irrigation, which is conducive to maintaining the root zone ecology. However, the system also has some challenges: first, the residual film under the film is seriously polluted, posing a threat to the physical and chemical properties of the soil and the development of the crop root system; second, the investment cost of the drip irrigation system is high, and some small and medium-sized farmers have difficulties in equipment maintenance and use; third, over-reliance on drip irrigation in some areas has led to imbalanced irrigation frequency and redundant water, causing diseases and waste of resources. Therefore, the promotion of mulch substitutes, intelligent upgrades of drip irrigation systems and agricultural technology training should be combined to ensure the long-term sustainable development of drip irrigation.

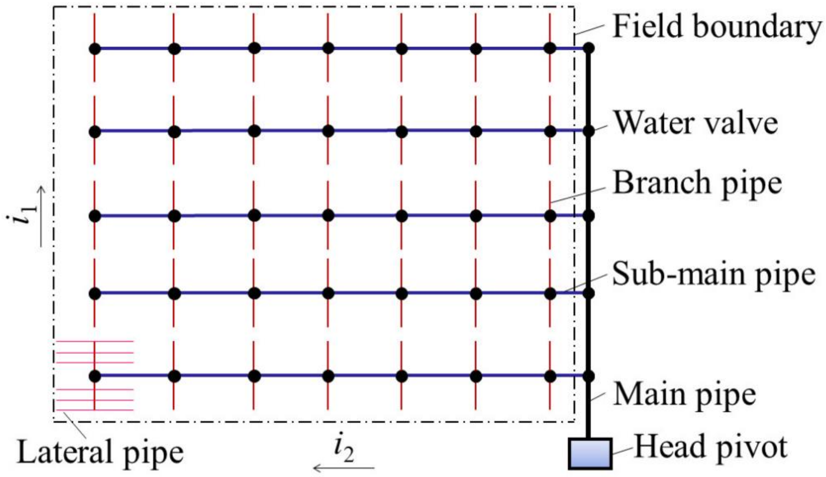

Figure 2 Schematic diagram of the “comb-type” pipe network layout (Adapted from Fan et al., 2024)

8 Future Directions and Innovations

8.1 Integration of remote sensing and IoT for smart irrigation

In recent years, remote sensing and IoT have been increasingly used in agricultural water resource management. UAVs, high-resolution satellite remote sensing images, and ground-based multispectral sensors can monitor cotton field canopy temperature, NDVI index, leaf area index, and other parameters in real time to determine crop moisture conditions (Shanmugapriya et al., 2022). By integrating these data with soil moisture sensors, a dynamic decision support system can be built to achieve precise irrigation control for the entire field, all weather, and the entire process (O'Shaughnessy et al., 2023). For example, the smart drip irrigation system designed by Guo and Chen (2024) is based on IoT control nodes, cloud platforms, and irrigation algorithms. It can automatically adjust irrigation frequency and volume during different cotton growth periods, improving water use efficiency by more than 13%. This "air-sky-ground" integrated perception system will promote irrigation to move towards digital and refined management.

8.2 Breeding of drought-tolerant cotton varieties

In drought-prone areas, it is difficult to fundamentally solve the water resource pressure by improving irrigation technology alone. The breeding and promotion of drought-tolerant and efficient cotton varieties is a key direction to improve the water use efficiency of crops from the source. Through transcriptomics, QTL positioning and other technologies, several key genes related to drought tolerance have been identified (Rasheed et al., 2023). For example, transcription factors such as GhDREB and GhWRKY regulate the stomatal closure and osmotic regulation ability of plants under drought conditions. At present, cotton breeding units at home and abroad are accelerating the integration of conventional breeding and molecular marker-assisted technologies to screen drought-resistant and stable product lines, and combine them with precision irrigation systems for supporting cultivation (Xing and Wang, 2024). The promotion of drought-tolerant and high-yield varieties will significantly reduce cotton's dependence on irrigation water sources and achieve the synergy of biological and engineering water conservation.

8.3 Policy support and farmer training for optimized irrigation

The promotion of technology is inseparable from institutional guarantees and farmer participation. At present, some cotton farmers lack the knowledge of irrigation scheduling and maintenance, and still rely on experience for water management, resulting in inefficient water use and even waste of water resources (Hunsaker et al., 2015). It is recommended that the government formulate more operational irrigation management specifications, such as formulating a guiding irrigation calendar based on regional climate and variety water requirements. At the same time, subsidies for the purchase and operation of irrigation equipment should be increased to promote equipment upgrades and water price reforms for small and medium-sized farmers. In addition, the new professional farmer training program should be combined with systematic field teaching of precision irrigation, water-fertilizer integration and water-saving theory to improve farmers' water management literacy.

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Conflict of Interest Disclosure
The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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