Effect of irrigation technology and plant density on cotton growth, yield, yield components, and water use efficiency

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Abstract

Limited water resources and insufficiently developed infrastructure provide challenges to sustainable production of cotton (*Gossypium hirsutum* L.) in Western Kansas. This study aimed to (i) assess the effect of irrigation technology and plant density on cotton growth, yield, and yield components, and (ii) determine the actual evapotranspiration, water use efficiency, and grass-reference crop coefficients of cotton under different irrigation technologies and rainfed conditions. Four irrigation technologies, which were Low Energy Precision Application (LEPA), Low Elevation Spray Application (LESA), Mobile Drip Irrigation 1 (MDI1 with 3.79 L/hour), Mobile Drip Irrigation 2 (MDI2 with 7.57 L/hour), and rainfed treatments were evaluated under two crop densities (135,908 and 160,618 plants/ha) in a split plot design with three replications using cotton variety PHY 205 W3FE in 2021. The results indicated that the MDI2 had the highest growth characteristics, such as plant height, leaf area index (LAI), and canopy cover, while the rainfed treatment registered the lowest growth performance. There is a significant positive relationship ($p<0.05$) between the canopy cover and LAI with coefficient of determination (R^2) of 0.98, between NDVI and LAI (R^2 of 0.92), and between the plant height and LAI (R^2 of 0.87). Likewise, the R^2 of the yield and the maximum growth characteristics were high (0.59-0.72) indicating that the variability of the yield could be explained by the variability of the crop growth parameters at flowering and early boll development stage. The cotton lint yield varied and was statistically significant ($p<0.05$) between the irrigation technologies and rainfed condition with the LEPA having the highest cotton lint yield (950.3 kg ha^{-1}). The low-density provided the optimum cotton lint yield. The soil water balance analysis showed that, of all irrigation technologies, cotton under MDI1 had the highest actual evapotranspiration (ETa) of 490.3 mm, while the rainfed treatments had the lowest ETa of 287.1 mm. In terms of the impact of crop density, high-density plots registered a higher ETa of 447.1 mm compared to 441.3 mm of low-density plots. The LEPA irrigation technologies resulted in the highest crop water use efficiency (CWUE), actual evapotranspiration water use efficiency (ETWUE), and irrigation water use efficiency (IWUE), and the values were 0.30 kg m^{-3}, 21 kg m^{-3}, and 0.44 kg m^{-3}, respectively. Irrigated cotton crop coefficients were estimated at 0.35, 0.92 to 1.04, and 0.39 to 0.48 for initial, mid, and late season stages, respectively. Under rainfed conditions, the crop coefficients were 0.18, 0.46 to 0.48, and 0.10 to 0.28 for the respective growth stages. These results indicate that the irrigated initial Kc is similar to the Food and Agriculture Organization of the United Nations (FAO) initial Kc, while mid and late season Kc are lower than the FAO values by 15% and 4%, respectively. On average, the two-step approach (ETa = ETo x Kc.adj.) overestimated cotton ETa by approximately 30% for irrigated fields and 118% for the rainfed condition compared to the water balance approach. This study shows that the development of a site-specific, local cotton Kc is important for better understanding of irrigation management strategies and crop water use in Western Kansas.

Keywords: Actual evapotranspiration, crop coefficient, cotton, irrigation

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I dedicate this thesis to Almighty God who granted me this opportunity and gave me the Grace to successfully complete it.

Chapter 1 - Introduction

1.1 Background

Cotton (*Gossypium* sp.) is one of the most important crops across the United States and its production was estimated to be 3.26 million tons on about 3.52 million hectares in 2020 (USDA, 2021). The United States of America (U.S.A) is the world's leading cotton exporter, supplying about 35% of global cotton exports in recent years (OECD/FAO, 2019). Cotton is a valuable, natural textile fiber and the purest source of cellulose (Hsieh, 2007). Aside from the fibers, cotton is also produced as a source of a seeds that provide edible oil and seed by-products, and other products to industries. Cottonseed oil contains a high number of antioxidants, which are essential for good health, and the seed by-products are used in animal feeding. However, cotton production is affected by different biotic and abiotic factors that limit the expression of crop potential yield. Water stress and plant density are the important target factors for high yield achievement.

Studies have reported that water stress and drought resulted in the growth of shorter cotton plants with a smaller number of nodes on the stem compared to cotton grown under normal water requirements, which, on average, grew taller with a high number of nodes (Moore, 2020; Azhar and Rehman, 2018). Water stress is caused by a poor distribution of irrigation water due to irrigation technology or a state of dry weather that causes hydrological shortage in a specific region. Different irrigations technologies have been used for cotton production for various results. For instance, in Western Kansas, Oker et al. (2020) found that LEPA, LESA, MDI1, and MDI2 applicators have an efficiency of 98.4%, 51.2%, 76.1%, 96.8%, respectively. Haag et al. (2013) also reported on irrigation strategies for corn and cotton cropping systems in Southwest Kansas. In Turkey, Cetin and Bilgel (2012) compared cotton yield performance under furrow, sprinkler, and drip irrigation and found that drip irrigation produced 21% more seed-cotton than the furrow method and 30% more than the sprinkler method. The authors further reported that the shedding ratio was significantly higher under sprinkler irrigation than furrow or drip irrigation, resulting in lower seed-cotton yield for sprinkler irrigation. In southwestern Georgia, Sorensen et al. (2020) found sprinkler and shallow subsurface drip (S3DI) irrigation methods had a better lint yield than the subsurface drip (SSDI) system at full irrigation and the lint yield was the lowest in the rainfed treatment. Nilesh et al. (2005), in India, compared drip with sprinkler irrigation on cotton production and found that drip irrigation at a low level of irrigation (75%) had higher yield than sprinkler irrigation at a high irrigation level (100%). Therefore, drip irrigation is found to contribute to better yield with less water. However, in Southeast U.S., Whitaker et al. (2008) found no cotton yield difference between overhead sprinkler, SSDI, and rainfed plots. Across the United States, diverse results for cotton production have been obtained with various irrigation techniques. Furthermore, irrigation water redistribution is an important factor to consider when selecting irrigation technologies. A poor distribution of water in the soil profile contributes to cotton plant water stress. Oker et al. (2021) reported that soil water redistribution uniformity under mobile drip irrigation (MDI) was less than under Low Elevation Spray Application (LESA) and Low Energy Precision Application (LEPA) in Kansas. Chastain et al. (2014) reported stomatal conductance, transpiration rate, and net photosynthesis decreased under water stressed conditions. Pettigrew (2004) found a reduction of 25% in lint yield due to water stress.

Another critical factor determining cotton yield is the planting density (Bednarz et al. 2000), and its effect has been reported by various studies across the world (Bednarz et al. 2006, 2007; Feng et al. 2010; Xiao-yu et al. 2016). Plant density influences light interception, moisture content, and wind movement, and further impacts plant height, crop maturity, and yield. Zhi et al. (2016) found that an optimal plant density not only improves the cotton yield and its components but also contributes to resource use efficiency. In the US, plant densities vary among the states to optimize the yield and its components. For instance, the plant density of cotton is reported to be 126000 plants ha^{-1} in Georgia (Bednarz et al. 2005), 153000 plants ha^{-1} in Louisiana (Siebert et al. 2006), 66000 plants ha^{-1} in Mississippi (Read et al. 2006), and 100000 plants ha^{-1} in Arizona (Kawakami et al. 2012). Xiao-yu et al. (2016) revealed that, with plant densities of 51000 and 87000 plants ha^{-1}, an increase of lint yield by 61.3 and 65.3% in 2012 and 17.8 and 15.5% in 2013, respectively, compared to the low plant density (15000 plants ha^{-1}) was obtained. They further mentioned that between 51000 and 87000 plants ha^{-1}, there was no significant difference in lint yield. Moreover, Khan et al. (2019) reported that the highest seed cotton yield (4546 kg ha^{-1}) and lint yield (1682 kg ha^{-1}) were obtained with 87000 plants ha^{-1}. In sum, an optimum plant density offered a good canopy micro-environment for better yield.

In Kansas, U.S.A, where, in 2020, cotton yield and production area were each 2.1 % of that in U.S.A (USDA, 2021), an increasing interest has given to cotton production by farmers. The above research results indicate that cotton yield and its components are affected by irrigation technology and plant density. The response is also function of soil type, management practices, climatic conditions, and cotton variety. Hence, it is important to investigate the best irrigation technology and the optimum plant density for high yield and resource use efficiency.

1.2 Objectives

Cotton is a new crop in the High Plains region of Kansas and with the decrease of the Ogallala aquifer, there is need to identify the best irrigation technology and optimum plant density for effective cotton production. The objectives of this study are to: (1) determine the effect of different irrigation technologies and plant densities on cotton growth, yield, and yield components, (2) estimate cotton actual evapotranspiration, total water use efficiency (CWUE), seasonal irrigation water use efficiency (IWUE), evapotranspiration water use efficiency (ETWUE), and estimate the grass-reference crop coefficients of cotton under different irrigation technologies and rainfed conditions.

Chapter 2 - Literature Review

2.1 Generality of cotton crop

Cotton (*Gossypium* Sp.) is from the family of *Malvaceae*. Cotton is native to tropical and subtropical zones. According to Wendel et al. (2009), there are nearly 50 *Gossypium* species, making it the largest genus in the tribe of *Gossypieae*, and new species of cotton crop continue to be discovered. Grown cottons are perennial shrubs, however they are often cultivated as annuals. The perennial nature of the cotton crop permits farmers to manage its growth and development to optimize seed and lint yield.

Three stages characterize the growth of cotton. They are (i) initial development, (ii) mid-development, and (iii) late-season development stages (Figure 2.1). During the initial development, the seed germinated and emerged, followed by the seedling establishment. The mid-development is characterized by the leaf area and canopy development, followed by the flowering and boll development. The late stage of cotton growth encompases boll maturation and plant defoliation. Below are three images illustrating the cotton plant during the three development phases.

Figure 2.1 Pictures of cotton at initial, mid-season, and late-season stages at K-State Southwest Research and Extension Center (SWREC), Garden City, Kansas, USA

2.2 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 (Cetin and Bidgel, 2001). Therefore, irrigation is necessary for cotton production. For instance, Pinnamaneni et al. (2021) reported that irrigation is a crucial factor in achieving high fiber yield and seed quality in the Mississippi Delta region and Sui et al. (2017) found that, in the Mississippi Delta, irrigation augmented cotton yield and improved fiber length. However, different irrigation technologies, such as low energy precision application (LEPA), low elevation spray application (LESA), mid-elevation spray application (MESA), mobile drip irrigation (MDI), surface irrigation, subsurface drip irrigation, and furrow irrigation, are used to produce cotton, and various results have been obtained depending on local climates, soil conditions, genotypes, and management practices. In northern Texas and southwestern Kansas, Colaizzi et al. (2005) carried out a study 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 in 2003. Similar results were found by Colaizzi et al. (2004) and Segarra et al. (1999), who reported that SDI performed better than any other irrigation system such as MESA, LESA, and LEPA. Moreover, in 2004, lint yield and gross returns were improved with SDI at any irrigation rate in 2004. Bordovsky (2019) found that, under irrigation treatments 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% full irrigation, yield was slightly smaller in sprinkler compared to LEPA, and SDI was found to provide 7% greater yield than LEPA. However, Bordovsky et al. (1984) carried out a study where soil matric potential was used to schedule irrigations and found that LEPA and drip irrigation provided the same yield for cotton, corn, and soybeans.

In Turkey, Cetin and Bidgel (2002) carried out a study on the three different irrigation methods (furrow, sprinkler, and drip irrigation) on seed cotton yield and yield components. Maximum seed yields were 4380, 3630, 3380 kg ha^{-1} 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. (1994) 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 (Segarra et al., 1999; Bordovsky and Porter, 2003). In India, Choudhary et al. (2016) 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 (WUE) was greatest under drip irrigation as compared to other irrigation systems in all four cotton cultivars that Choudhary et al. (2016) studied. According to Sezan et al. (2008), for cotton production drip irrigation was more advantageous compared to conventional practices of irrigation. In China, Wang et al. (2020) compared traditional flood irrigation and mulched drip irrigation and found that mulched drip irrigation promoted root growth of cotton and improved production of fine roots after the full-boll stage. 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 the soil, aggregate structure, successfully prevent deep water loss and surface water loss, and, therefore, decrease exposure of the soil to degradation and salinization (Wang et al., 2011; Ayars et al., 1999; Batchelor et al.,1996; Karlberg and Frits, 2004). Fereres et al. (1985) reported that an early and increased cotton yield is achieved by drip irrigation. Mateos et al. (1991) stated that drip irrigation was more beneficial than furrow irrigation. In the same line, Ibragimov et al. (2007) 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 (2008), 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 (2002) found that drip irrigation improved by 21 and 30% seed cotton yield over furrow and sprinkler irrigation, respectively. Similarly, in the Texas High Plains, Colaizzi et al. (2008) showed that subsurface drip irrigation (SSDI) had the best cotton productivity and gross returns followed by LEPA and spray irrigation. However, Cetin and Kara (2019) reported that the use of SSDI 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. (1993) found no statistically significant difference among yields of cotton grown with drip, sprinkler, or furrow methods. Moreover, Howell et al. (1989) 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. (2008) compared overhead sprinkler, SSDI, and rainfed conditions and found no differences in cotton yield. Further, Yazar et al. (2002) compared LEPA and trickle irrigation of cotton in southeast Anatolia and reported that both LEPA and trickle-irrigated plots enhanced 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 (1983) 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 (1974) found no differences in 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 lint cotton, and, at the same time, maximize water used efficiency.

2.3 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 (Azhar and Rehman, 2018). Compared to soybean, Inamullah and Isoda (2005) found that under water stress, the flow rate of stem sap, stomatal conductance, transpiration rate decreased more in soybean than in cotton and, therefore, cotton adapted better to limited water by maintaining higher transpiration compared to soybean. Azhar and Rehman (2018) 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 leaf area of cotton. For instance, Rehman et al. (2017) 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, Mu-XiuLing and Bao-Xiao (2003) carried out a study concerning the effect of various water stress levels (control, light, medium, and heavy drought) on cotton RWC. The authors reported that the RWC of cotton leaves declined as drought conditions increased. Furthermore, Siddiqui et al. (2007) 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 5-times during the growing season gave the highest seed cotton yield of 3323.52 kg ha^{-1} compared to 3- and 7- 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 of 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, Howell et al. (1984) measured the average lint yield of cotton planted in narrow rows and irrigated under full, limited, and no post-plant irrigation and found that it was 1583, 1423, and 601 kg ha^{-1}, respectively. Regarding the dry matter, the authors further stated that the full irrigation regime produced roughly 16 t ha^{-1} of dry matter while the limited and no-post-plant irrigation regimes provided, respectively, 11 t ha^{-1} and 7 t ha^{-1} of dry matter. In addition, Pettigrew (2004a,b) reported a decrease of 25% in lint yield due to water stress by analyzing cotton genotypes under drought stress and normal water conditions. Also, Bellaloui et al. (2015) 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 (Shamim et al. 2013). 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. (2005) 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 cotton fiber. For instance, Mert (2005) examined different genotypes of cotton to evaluate the impacts 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 (2014) 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 (2001) 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 dry weights of stem and leaves, were less in a cotton crop under drought stress compared to the controlled conditions (Azhar and Rehman, 2018). Alcidu et al. (2013) 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. (2015) found that Roselle (*Hibiscus sabdariffa*) exhibited 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. (2020) 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. (2009) 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. In addition, in west-central Oklahoma, Masasi et al. (2020) found that lint and seed yields under full and reduced irrigation did not differ significantly. The authors moreover reported that differences in fiber quality were observed among the irrigation treatments, such as full irrigation, reduced irrigation (75%), and no irrigation. Zhan et al. (2015) 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. (2019) concluded that in arid areas deficit-irrigated cotton, given 425-mm water and grown under a plant density of 36 plants per m^2, had advantages in terms of saving water and energy without yield penalties.

In sum, studies have found mixed results concerning the response of physiological traits of cotton and its yields and yield components to different irrigation regimes. This is in line with Feng et al. (2014) 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 (Unlu et al. 2011; Geerts and Raes 2009). 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 (Chen et al. 2020). There is a critical need to identify and test approaches that optimize water use for cotton production systems.

2.4 Cotton yield and yield components in response to plant density

Plant density is an important abiotic factor affecting cotton production (Bednarz et al. 2000) and has been evaluated in many studies (Guzman et al. 2019; Venugopalan et al. 2013; Bednarz et al. 2006; Kerby et al. 1990). According to Ajayakumar et al. (2018), 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. (2019) assessed four sowing densities (62500; 83333; 100000; and 142857 plants per ha) on yield and its components of two cotton varieties and discovered that high lint yield was in ‘SN-2900’ (4216.2 kg ha^{-1}) at 100000 plants per ha; and in ‘Delta Pine 160’ (3917.3 kg ha^{-1}) at 83333 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 variation of the quality of the fiber resulting from changes in plant densities (Bednarz et al. 2006; Zhi et al. 2016; Venugopalan et al. 2013). 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 (Yang et al. 2014; Bednarz et al. 2006). Similarly, Kerby et al. (1990) reported that the increase in plant density from 10 to 15 plants per m^2 delayed cotton boll maturity. Further, Zhang et al. (2016) stated that increasing planting density above 22 plants per m^2 induced shade and yield reduction in the middle and lower parts of the cotton plant. In the U.S.A., the plant arrangement used differs considerably among regions in order to maximize yields. For instance, the plant density is 12.6 plants per m^2 in Georgia (Bednarz et al. 2005), 15.3 plants per m^2 in Louisiana (Siebert et al. 2006), 6.6 plants per m^2 in Mississippi (Read et al. 2006), and 10.0 plants per m^2 in Arizona (Kawakami et al. 2012). In China, Khan et al. (2020) carried out a study using 6 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. (2020) stipulated that a high plant density produces more leaf shedding late in the season, alongside with lower boll weight, and, consequently, a high plant density negatively affects the yield resulting in lower productivity. Similarly, Yang et al. (2014) and Bednarz et al. (2006) reported that a high plant density (>10 plants per m^2) 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. (2017) 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, number of bolls per plant, and the weight of individual cotton bolls (Gwathmey and Clement 2010; Clawson et al. 2006). Moreover, Ali et al. (2016) mentioned that cotton yield rises with plant density to certain density, called the optimum density, while low yield is obtained with very high and very low plant populations. Yang et al. (2010) 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 pesticides, which dense vegetation may require. Similarly, Yang et al. (2014) found that a too high and a too low plant density reduced biomass accumulation of the reproductive organs. Khan et al. (2020) reported that too high or too low plant densities led to a drop in cotton yields. Siebert et al. (2006) 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. (2019) 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 (Antonietta et al., 2014). Studies also have reported that dense plant populations can cut off water loss from evaporation and increase crop water use (Kaggwa-Asiimwe et al. 2013; Antonietta et al. 2014; Yao et al. 2015). Moreover, a normal, but high population, can induce early maturation and a maximum use of optimal temperatures by cotton plants (Li 2002; Bai et al. 2017). According to Chen et al. (2019), 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.

2.5 Cotton crop coefficients

The crop coefficient (Kc) 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 (Kc) for cotton at different stages of growth that can be applied across the globe and presented it in the FAO-56 paper (Allen et al. 1998) (Table 2.1). Nonetheless, various studies determining local Kc values obtained for various developmental stages have been different from those listed in the FAO-56 paper (Hunsaker 1999; Grismer 2002; Farahani et al. 2008; Bezerra et al. 2012). Therefore, the use of the FAO Kc values has resulted in an important difference between estimated and actual evapotranspiration (ETa) (Hunsaker et al. 2003; Farahani et al. 2008).

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 (Allen et al. 1998). Similar trends have been found by Kumar et al. (2005), who reported a gradual increase in Kc 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, Kumar et al. (2005) 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. (2009) reported that cotton Kc at Uvalde, Texas, 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 (Grismer 2002; Hunsaker 1999) and in India (Mohan and Arumugam 1994). In the Sacramento and San Joaquin valleys, California, 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 (Grismer 2002). 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. (2008) 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 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 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 FAO Kc-mid-season value of 1.30. Cotton water use is overestimated when using adjusted FAO Kc values higher than the locally developed Kc values, and irrigation scheduling built on the high adjusted Kc values augments the cost of production. Also, over-irrigation contributes to yield losses, because, with more water, the plant roots lack oxygen for respiration to take place. In semiarid lands of Brazil, Bezerra et al. (2012) reported that average, local Kc values were 0.75, 1.09, and 0.80 for the initial, middle, and end of growing season, respectively. They pointed that these locally developed Kc values were smaller than the FAO-adjusted Kc values. Therefore, the water use computed from FAO adjusted Kc values was overrated by 12%. The initial and end stage Kc values obtained by Bazerra et al. (2012) were greater than those reported by Ko et al. (2009) in Texas. However, the Kc values reported by Ko et al. (2009) in Texas were higher than the results reported by Hribal (2009). These differences are attributed to the sensitivity of Kc values to irrigation management and systems.

The mid-season, local Kc value of 1.09 found by Bezerra et al. (2012) was similar to the results reported by Farahani et al. (2008). Various studies (Hunsaker 1999; Grismer 2002; Hunsaker et al. 2003; Ko et al. 2009; Hribal 2009) have reported higher mid-season Kc values, ranging from 10-24% higher, in other cotton-production areas such as Texas, California, Arizona, and Louisiana, than the one reported by Bezerra et al. (2012). 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 studied and irrigation management. The end-season Kc value of 0.80 (Bezerra et al. 2012) was 10% higher than the FAO end-season Kc value. A similar end-stage Kc value was found by Kumar et al. (2005) in Louisiana. However, Ko et al. (2009) reported a lower coefficient of 0.6 for the Uvalde region, Texas, USA. Hunsaker (1999) developed Kc values for short-season cotton in Arizona and found higher Kc values than those reported by FAO. The above review highlights the spatio-temporal variation of the crop-coefficient values. Therefore, for efficient irrigation planning, it is important to develop a local Kc experimentally that characterizes the local climate, the water requirement, and cotton management practices.

Table 2.1 Cotton crop coefficient values in different parts of the world

Location	Kc	Climate	Soil type	Year	Initial stage	Mid-season	End-season	References
				U.S.A				
	FAO Kc	Subhumid climates			0.35	1.15-1.20	0.70-0.50	Allen et al. 1998
Louisiana	Kc Local[1]	Humid	Sharkey clay	2010	0.42	1.44	0.62	Kumar et al. (2005)
				2011	0.42	1.06	0.78	
	FAO Adj. Kc[2]			2010	0.55	1.18	0.64	
				2011	0.58	1.18	0.62	
Bushland, Texas	K_{cb}[3]	Subtropical climate	Pullman clay loam	2000	0.08	1.10	0.15	Howell et al. 2004
Bushland, Texas	FAO Adj. K_{cb}[4]	Subtropical climate	Pullman clay loam	2000	0.15	1.23	0.20	
Uvalde, Texas	Kc Local	Humid subtropical climate	Silty clay soil	2006-2007	0.40	1.25	0.6-0.1	Ko et al. (2009)
California	Kc Local				0.35	1.15	0.87	Grismer, 2002
Louisiana	Kc Local	Semitropical climate	Bare soil	2007	0.15	0.64-1.39		Hribal (2009)
Georgia	Kc Local	Humid subtropical environment		2005	1.12-0.99	1.15-1.2	0.7-.5	Suleiman et al., 2007

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[1] locally developed Kc

[2] FAO adjusted Kc

[3] basal crop coefficient

[4] FAO adjusted basal crop coefficient

Arizona	K_{cb}			1993-1994	0.23	1.30	0.4	Hunsaker, 1999
			Sandy loam soil	2002	0.15	1.2	0.52	Hunsaker et al., 2005
			Trix clay loam	1991	0.15	1.1-1.3	0.7-0.6	Hunsaker et al., 2003
				1990	0.2	1.1-1.3	0.7-0.5	
			Other countries					
Syria	Kc Local	Mediterranean climate	Fine clay	2004-2006	0.29	1.05	0.66	Farahani et al. (2008)
	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. (2012)
	FAO Adj. Kc				0.84	1.20	0.70	
India					0.46	0.7-1.01	0.23	Mohan and Arumugam, 1994

2.6 Cotton water use and evapotranspiration

Knowledge of water use and crop evapotranspiration (ETc) is crucial to know when building a reliable irrigation schedule. Many studies have examined the water requirement of cotton in different parts of the world (Kumar et al. 2015; Ayars and Hutmacher 1994; Farahani et al. 2008; Hunsaker 1999) (Table 2.2.). Results have shown that water requirements vary widely depending on growing season length, climate, cultivar, irrigation method, and production goals, but the water requirement may range from 700 to 1200 mm in the growing season (Evett et al. 2012). Cotton water use increases gradually from the initial stage and reaches a maximum at the mid-season stage and steadily declines until the end of the season. According to Bezzera et al. (2010), 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 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, with a full canopy and maximum boll load of the cotton plant. In the mid-south of the United Stated, Kumar et al. (2015) found the daily average evapotranspiration values of cotton during 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. (2012) found daily cotton ETc 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 ETc were observed in the initial stage, while the maximum values were obtained in mid-season.

However, the water use of cotton differs around the globe. It depends on the local climate, soil characteristics, genotypes, and irrigation methods and regimes. Evett et al. (2012) reported water use ranged from 410 to 780 mm per season depending on irrigation methods. Cotton water use is found to be less for drip and low energy precision application (LEPA) than 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 (Ibragimov et al. 2007), from 594 to 778 mm in the California (Howell et al., 1987), from 397 to 775 in 2000, from 386 to 739 in 2001 in Bushland, Texas (Howell et al. 2004), and from 437 to 739 mm in Texas (Colaizzi et al. 2005). Under fully irrigated furrow plots, Rajak et al. (2006) stated that cotton water consumption varied from 735 to 915 mm in India, while Anac et al. (1999) found it varied from 659 to 899 mm in the coastal part of Aegean region of Turkey.

In Turkey, Dagdelen et al. (2006) found that variations in water use, from 272 to 882 mm in 2003 and from 242 to 855 mm in 2004 were related to changes in climatic factors. In California, Howell et al. (1984) 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, Ko et al. (2009) reported smaller cotton water use values than those obtained by Kumar et al. (2015). At Lubbock in Texas, Baker et al. (2015) found cotton seasonal water use varied from 353 to 625 mm. Bezerra et al. (2012) carried out a study on cotton crop evapotranspiration under sprinkler irrigation in the Apodi Plateau semiarid lands of Brazil and found that accumulated cotton ETc 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 crop growing season that was 7 days longer.

Many studies on cotton water use carried out in western Turkey (Allen 2000), in central Arizona, USA (Hunsaker et al., 2003), and in northern Syria (Farahani et al. 2008) found higher accumulated water use of cotton than those reported by Bezerra et al. (2012). The higher values in those areas can be explained by the length of the growing season. However, Liu et al. (2013) reported lower annual cotton water requirements compared to Bezerra et al. (2012). Liu et al.

(2013) found 619.1, 673.6, and 651.4 mm of cotton seasonal water requirement for the Eastern Hebei Plain, the Heilonggang region, and the Piedmont Plain of Taihangshan, respectively. Moreover, in the northern High Plains of Texas, measured total water use was found to be 622 mm and 397 mm under deficit irrigation and dry land in 2000, respectively (Howell et al. 2004). In Uvalde, Texas, Ko et al. (2009) reported a maximum daily ETc 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 the ETc in both years was caused by lower air temperatures and recurrent precipitation events in 2007. Similar results were reported by Grismer (2002), who found ETc values of 710 mm in 1998 and 845 mm in 1999 using the Parlier lysimeters at San Joaquin valley, California. In the Mediterranean environment of Syria, Farahani et al. (2008) reported cotton mean seasonal ETc 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. (2004) in the northern High Plains of Texas.

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

Table 2.2 Cotton water requirement and evapotranspiration under different irrigation methods and rainfed conditions in different locations

Locations	Year	Seasonal Precipitation (mm)	Irrigation Amount (mm)	Seasonal Water Use (mm)	Irrigation Method	Seasonal ETc (mm)	Cotton variety	References
				U.S.A.				
Lapaz, Arizona	1998-1999			1304		1362	Upland cotton	Grismer 2002
				1304		1362	Pimacotton	
Northern Texas	2000	470	201	775	SI[5]	770		Howell et al. (2004)
St. Joseph, Texas	2006	75	764		SI	830	DP555	Ko et al. 2009
	2009	581	114		SI	689	DP555	
California	1998			710	DI[6]			Soppe (2000), Ayars and Soppe (2001)
				845	DI			
				561	SI			
				561	SI			
				Other countries				
Turkey	1993			834	FI[7]			Preito and Angueira (1999)
	1994			899	FI			

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[5] sprinkler irrigation

[6] drip irrigation

[7] furrow irrigation

Syria	2004	800	895	DI		Farahani et al. (2008)
	2005	810	927	DI		
	2006	760	813	DI		
Northeastern Brazil	2008	892	716	SI	CNPA 187 8H	Bezerra et al. (2012)
	2009	884	754	SI	CNPA 187 8H	

2.7 Cotton water use efficiency

The concept of water use efficiency (WUE) was introduced more than 100 years ago by Briggs and Shantz (1913) indicating a relationship between plant productivity and water use. Cotton lint yield is found to rise with increasing crop water use (Baker et al. 2015). Hatfield and Dold (2019) 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 interactions between them. Research results have revealed variation among genotypes for WUE in upland cotton and pima cotton (Quisenberry and McMichael 1991; Fish and Earl 2009; Saranga et al. 2004). Snowden et al. (2013) carried out a study on WUE and irrigation response of cotton cultivars under subsurface drip irrigation in West Texas. They reported that WUE differed among the six cultivars and the deficit strategies used. In 2010, 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 2.3). 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 (Roth et al. 2013). These results are in line with the findings of Hatfield and Dold (2019) who reported that WUE is dependent upon genotype and management practices. Evett et al. (2012) reported that evapotranspiration water use efficiency (ETWUE) ranged from 0.15 kg m^{-3} to 0.33 kg m^{-3}. Improvement in ETWUE is most probably attributable to increased yield as well as to reduced soil evaporation and transpiration. It is 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 (2019) reported that 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 shows that WUE can be improved by water management practices.

Similarly, Evett et al. (2012) revealed in several experimental studies at different locations of Texas and California 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. (2016) found from a metadata analysis the highest cotton evapotranspiration water use efficiency of 0.88 kg m^{-3}, 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 (WPirr) of 0.84 kg m^{-3}. Increasing the irrigation amount decreased the WPirr (Cetin and Kara, 2019).

In recent years, water use efficiencies of cotton have been studied by many researchers to obtain optimum cotton yield by using less water. For example, Grismer (2002) conducted a study on crop water productivity (CWP) for irrigated cotton in Arizona and California. He found that, in Arizona counties, upland cotton actual evapotranspiration (ETc) 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, ETc 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. (2006) 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. (1999) in the coastal part of Aegean region.

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. (1992) compared furrow and drip irrigation methods for cotton and found that water use efficiencies (WUE) 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 (2002) 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. (2002) reported that WUE values of cotton irrigated by low energy precision application (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. (1996) determined WUE values of 1.9-5.9 kg/ha-mm under furrow irrigation in the Cukurova Plain in southern Turkey. According to Anac et al. (1999), irrigation water use efficiency (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 (Yazar et al., 2002). Ertek and Kanber (2001) 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 (Koech et al. 2014). Water use efficiency fluctuates among farming fields and across regions due to many factors. Therefore, site-specific measurements are crucial for decision making and improvements in WUE.

Table 2.3 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).

Locations	Year	Watering Regime	Yield (Kg/ha)		Water Use Efficiency (kg m^{-3})			Cotton variety	References
			Lint	Seed	WUE	IWUE	ETWUE		
West Texas	2010	SE	712		0.20			FM9160	Snowden et al. (2013)
		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		Evett et al. (2012)
Turkey	2016-2017	SDI		4082	0.83	0.84			Cetin and Kara 2019
Arizona	1988-1999	N/A[8]	1280-1420				0.127-0.138	upland cotton	Grismer (2002)
			910-120				0.09-0.109	pima cotton	
California	1988-1999	N/A	1110-1440				0.134-0.210	upland cotton	
			1170-1340				0.151-0.177	pima cotton	

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[8] Non available

Bushland, Texas	2003	MESA 100%	1229		0.164	0.492	Paymaster2280 BG RR	Colaizzi et al. (2005)
		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		
Turkey	2013	CEF 100%		5640	0.64	0.81	Nazilli-84	Dagdelen et al. (2006)
		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		
		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	1992-1994	Furrow		0.38–0.46	0.48–0.65	N84	Anac et al. (1999)
Australia		Drip		2.23			Hodgson et al. (1992)
		Furrow		1.89			
Anatolia, Turkey	1991-1994	Drip		0.487		Sayar-314	Cetin and Bidgel (2002)
		Furrow		0.387			
		Sprinkler		0.236			
Harran plain, Turkey		LEPA		0.55–0.67	0.58–0.77		Yazar et al. (2002)
		Drip		0.50–0.74	0.60–0.81		

Chapter 3 - Effect of Irrigation Technology and Plant Density on Cotton Growth, Yield, and Yield components

3.1 Materials and methods

3.1.1 Site description

This study was conducted at the Southwest Research and Extension Center (SWREC) of Kansas State University (KSU) (latitude 32.024°, longitude -100.826°, elevation of 885 m above mean sea level), Garden City, Kansas, for the 2021 growing season (Figure 3.1).

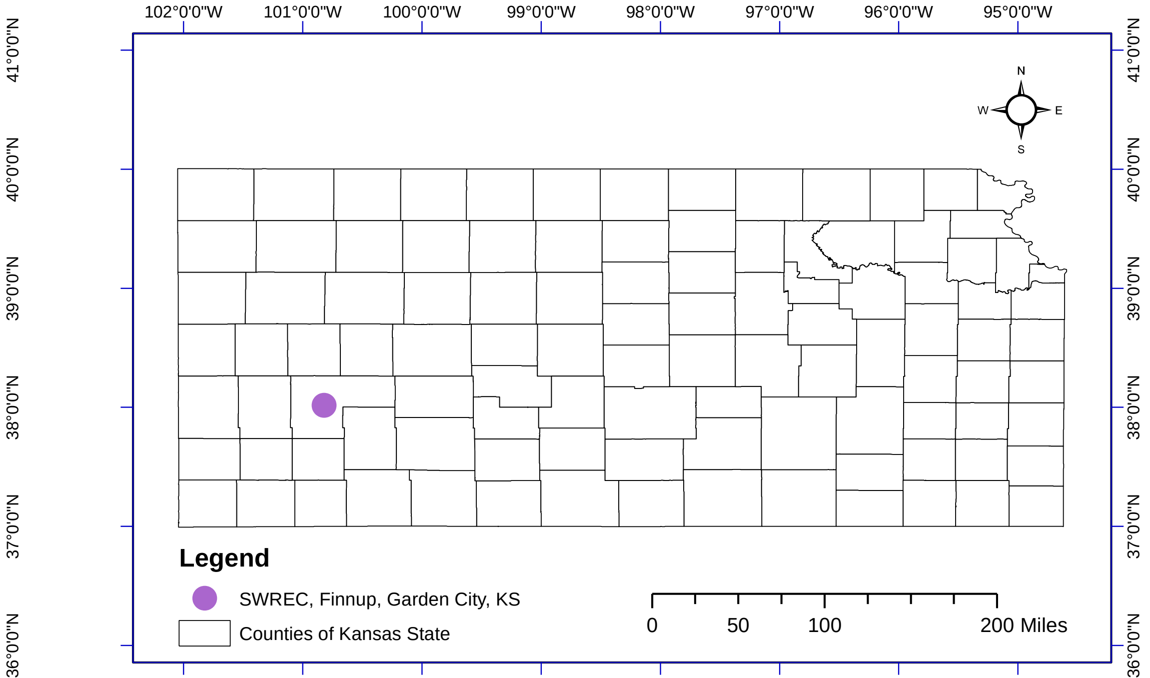


Figure 3.1: Map of the study location, SWREC, Garden City

Minimum temperature (Tmin), maximum temperature (Tmax), average temperature (Tmean), minimum relative humidity (RHmin), maximum relative humidity (RHmax), average relative humidity (RHmean), wind speed (U_2), and solar radiation (Rs) were collected daily from Kansas Mesonet weather station of Garden City. The daily precipitation was collected from the weather station in the experimental location at Finnup, Garden City. The soil at the location is classified as Ulysses silt loam (Stone et al. 2011). The weather conditions for the 2021 growing season are summarized in Table 3.1 and the long-term (2003-2020) average weather conditions are presented in Table 3.2.

Table 3.1 Monthly average weather conditions during the 2021 growing season (from May to November) at the Southwest Research and Extension Center

Month	Tmin (°C)	Tmax (°C)	Tmean (°C)	Precipitation (mm/month)	RHmean (%)	Solar radiation (MJ m^{-2})	Wind speed (m s^{-1})
May	10.2	23.4	16.8	144.1	73.5	20.2	3.8
June	16.5	32.0	24.3	28.6	63.3	24.0	2.9
July	18.0	33.7	25.8	27	62.1	22.4	2.8
August	18.2	35.1	26.6	12.1	55.6	21.8	3.1
September	14.4	31.8	23.1	45.4	54.5	18.7	3.0
October	5.4	23.5	14.4	27.9	57.4	14.0	2.7
November	-0.8	17.5	8.3	5.1	50.4	10.0	2.5

Table 3.2 Long-term (2003-2020) monthly average of the growing season weather conditions in Garden City

Month	Tmin (°C)	Tmax (°C)	Tmean (°C)	Precipitation (mm/month)	RHmean (%)
May	9.3	25.4	17.3	49.8	65.7
June	15.7	31.7	23.7	67.3	63.7
July	18.2	33.5	25.9	77.4	64.4
August	17.0	31.8	24.4	49.7	67.5
September	12.0	27.9	19.9	28.7	64.3
October	4.2	20.5	12.3	36.3	65.3
November	-2.9	13.9	5.2	7.2	65.5

3.1.2 Experimental design and crop management

The experiment was performed at the Southwest Research and Extension Center, Garden City, Kansas in 2021. Two plant densities (135,908 and 160,618 plants per ha) were evaluated under four irrigation technologies (LEPA, LESA, MDI1, and MDI2) and rainfed settings (Figure 3.2). All irrigation technologies provide the same amount of water to the ground. MDI1 has a flow rate of 3.79 L per hour, while MDI2 has 7.57 L per hour. PHY 205 W3FE was the testing cotton variety. Before the planting, the soil was disked and harrowed. The experiment was set up under a split plot design with three replications. The main plots were attributed to the planting densities and the subplots were attributed to the irrigation technologies (Photo 3.1) under center pivot system. The rainfed condition was set up at the corner of the center pivot system. The experimental plot size was 6 m over 12 m. A John Deere 7200 six-row planter with 80-cm row spacing was used for planting on May 24, 2021. Early in the season, all treatments without rainfed received the same depth of water from sprinkler bringing the soil water content to near field capacity for providing adequate and uniform soil moisture for seed germination.

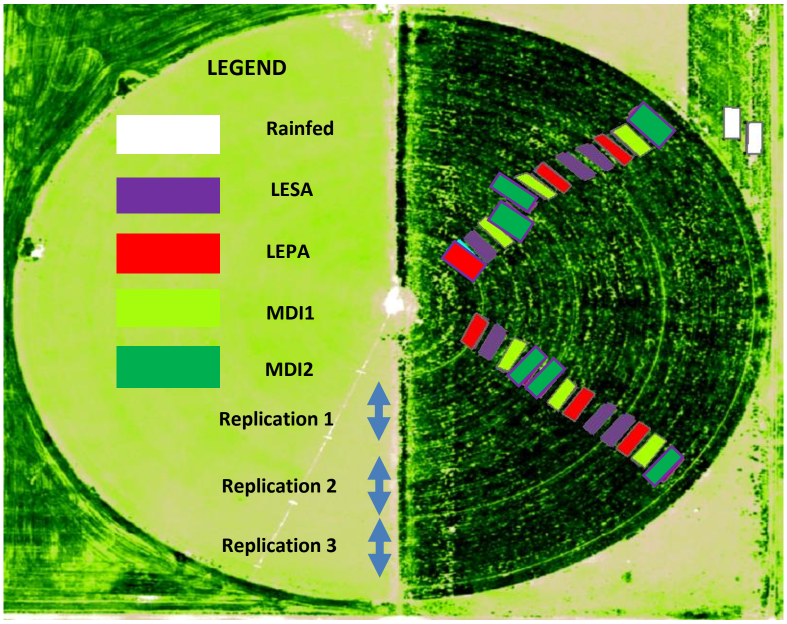


Figure 3.2: Plots of the experiment, Southwest Research and Extension Center (SWREC), Garden City

The irrigation scheduling was later based on neutron probe soil moisture readings. Water to the center pivot was supplied by means of a 74.6 kW three-phase electrical pump, North American Electric Inc, model NAE-VHS-100-4 (North American Electric Inc, 2328, 350 Vaiden Dr, Hernando, Mississippi 38632). Dry fertilizer of urea 46-0-0 was applied on March 10, 2021, at the rate of 67.25 kg per ha. Liquid phosphorus 10-34-0 of N-P-K was also applied on planting date May 24, 2021, at the rate of 93.54 liters per ha. Plots were kept weed-free by herbicide application at the rate of 0.29 liter per ha on June 09, 2021, and at the rate of 5.56 liters per ha on June 30, 2021.

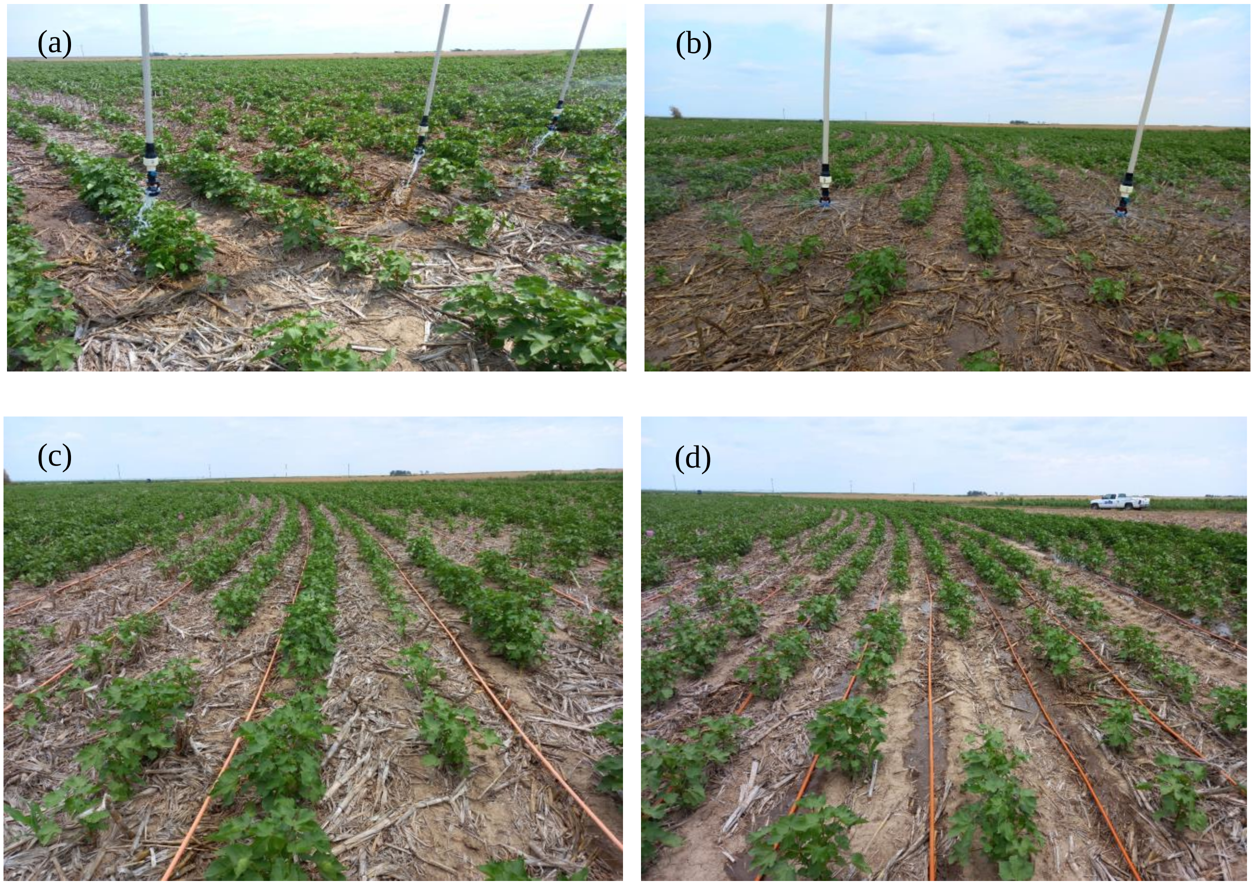


Photo 3-1 Pictures of cotton crop under different irrigation technologies (a) LEPA, (b) LESA, (c) MDI1, (d) MDI2.

3.1.3 Data collected and instruments used

Cotton height was measured on a weekly basis on five plants per unit plot and reported in centimeters. Plant height was measured from the ground level to its top. The leaf stomatal conductance was measured with a porometer (METER Group, Pullman, WA) in each unit plot once a week and reported in mmol/($m^2 \cdot s$) (Photo 3.2 b). Also, the leaf area index (Photo 3.2 a) was measured using LAI-2200C plant canopy analyzer (LI-COR Inc., Lincoln, NE, USA) once a week in each plot. The Unmanned Aerial Vehicle (UAV) (GJI, Shenzhen, China, 518057) (Photo 3.2 c) was flown weekly, and the images were processed using Agisoft Metashape Professional to derive the Normalized Difference Vegetation Index (NDVI) values. The digital Elevation Model and the Orthomosaic were built and the NDVI value were calculated using equation 3.1. Moreover, ArcGIS (version 10.8) was used to retrieve the NDVI data representing each plot.

$$NDVI = \frac{NIR - Red}{NIR + Red} \qquad Equation\ 3.1$$

Where: NDVI= Normalized Difference Vegetation Index, NIR= Near Infrared.

Further, the cotton canopy cover was measured on weekly basis using Canopeo (www.canopeoapp.com) developed by Oklahoma State University. The Canopeo tool was developed using Matlab and is based on color ratios of red to green (R/G) and blue to green (B/G) and an excess green index (2G–R–B) (Patrignani and Ochsner, 2015). At crop maturity, cotton in each plot was machine harvested to determine the fiber yield reported in kg ha^{-1}. The mean number of bolls per plant was obtained by averaging 10 plant bolls in each plot. The average number of seeds per boll was obtained using 10 random bolls per plot. Also, 5 plants were randomly selected, cut, and oven dried to get the above ground biomass in kg ha^{-1}. Moreover, a sample of 100 randomly bolls was collected from each plot to determine the boll weight in kg.

(a) (b) (c)

Photo 3-2 Pictures of devices used to collect data (a) LAI-2200C, (b) Porometer, (c) UAV

3.1.4 Standardized Penman-Monteith reference evapotranspiration model

Daily grass-reference evapotranspiration was computed using the standardized American Society of Civil Engineers (ASCE) form of the Penman–Monteith (PM-ETo) (Equation 3.2):

$$ETo = \frac{0.408\Delta(Rn - G) + (\gamma CnU_2/(T + 273))(es - ea)}{\Delta + \gamma(1 + CdU_2)} \qquad Equation\ 3.2$$

where: ETo is the reference evapotranspiration (mm/day), Δ is the slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1}), Rn = net radiation at the crop surface (MJ m^{-2} d^{-1}) is the difference between the net shortwave radiation (Rns) and the net longwave radiation (Rnl), G = soil heat flux density at the soil surface (MJ m^{-2} d^{-1}) is ignored for daily estimates as the magnitude of the flux is relatively small, T = mean daily air temperature at 1.5-2.5 m height (°C), U_2 = mean daily wind speed at 2 m height (m s^{-1}), es = the saturation vapor pressure at 1.5-2.5 m height (kPa), ea = the actual vapor pressure at 1.5-2.5 m height (kPa), es-ea= saturation vapor pressure deficit (kPa), γ = psychrometric constant (kPa °C^{-1}), Cn = 900 °C mm s^{3} Mg^{-1} d^{-1}, Cd= 0.34 s m^{-1}. All parameters necessary for computing ETo were computed according to the procedure developed in FAO-56 by Allen et al. (1998).

3.1.5 Thermal Unit (TU)

To produce a high-yield and quality cotton crop, a proper understanding of cotton plant growth and development is necessary. Thermal Unit (TU), also known as accumulation of the Growing Degree Day (GDD) factor, is one of the most essential indicators in understanding cotton plant phenology (Equation 3.3). GDDs are used as a phenological and climatic measurement to signify the difference in temperature change related to a cotton crop (Anandhi, 2016) (Equation 3.3). Thermal unit is a cumulative air temperature that contributes to plant growth during the growing season (Equation 3.4).

$$GDD = \frac{{T_{max}}^{*} + {T_{min}}^{*}}{2} - T_{base} \qquad Equation\ 3.3$$

$$TU = \sum_{i=1}^{n} \frac{{T_{max}}^{*} + {T_{min}}^{*}}{2} - T_{base} \qquad Equation\ 3.4$$

$${T_{max}}^{*} = \begin{cases} T_{max} & if \ \ T_{base} < T_{max} < T_{opt} \\ T_{base} & T_{max} \leq T_{base} \\ T_{opt} & T_{max} \geq T_{opt} \end{cases}$$

$${T_{min}}^{*} = \begin{cases} T_{min} & if \ \ T_{base} < T_{min} < T_{opt} \\ T_{base} & T_{min} \leq T_{base} \\ T_{opt} & T_{min} \geq T_{opt} \end{cases}$$

where Tmax = maximum air temperature, Tmin = minimum air temperature, Tbase = base temperature threshold for cotton (15.6 °C), Topt = optimum temperature (32.2 °C), and n = number of days. The base temperature for calculating growing degree days is the minimum threshold air temperature at which plant growth starts (Wright et al. 2005). The optimum temperature is the upper threshold temperature, because at a temperature greater than the optimum temperature, plant roots have difficulty taking in water for growth and development (Wright et al. 2005).

All temperature values exceeding the threshold should be reduced to 32.2 °C, and values below 15.6 °C were taken as 15.6 °C because no growth occurs above or below the threshold air temperature values. If the average daily air temperature was below the base temperature, the TU value was assumed to be zero.

3.1.6 Statistical analysis

The analysis of variance (ANOVA) was performed to analyze cotton lint yield, yield components (above ground biomass, number of bolls per plant, number of open bolls per plant, number of seeds per boll, boll weight, lint weight per boll, and seed weight per boll) under different irrigation technologies and plant densities using CoStat statistical software (Cardinali and Nason, 2013). The data were checked for variance homogeneity before the ANOVA processing. Means were cross-paired and compared using Least Significant Difference (LSD) at 5% significance level. Significant differences were determined among irrigation technologies and plant densities for cotton yield and yield components using the LSD.

Regression analysis was also performed to develop the relationships between weather and cotton growth parameters, and between the cotton lint yield and cotton growth parameters. The coefficient of determination R^2 was used to quantify the fitness of the relationships.

3.2. Results and discussions

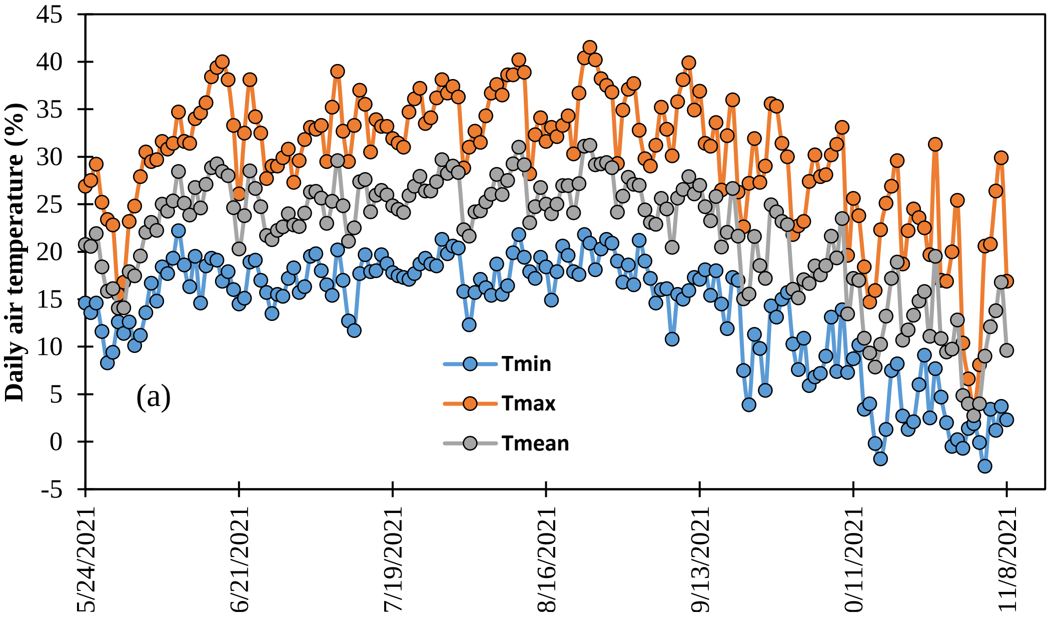
3.2.1 Weather conditions and thermal unit during the growing season

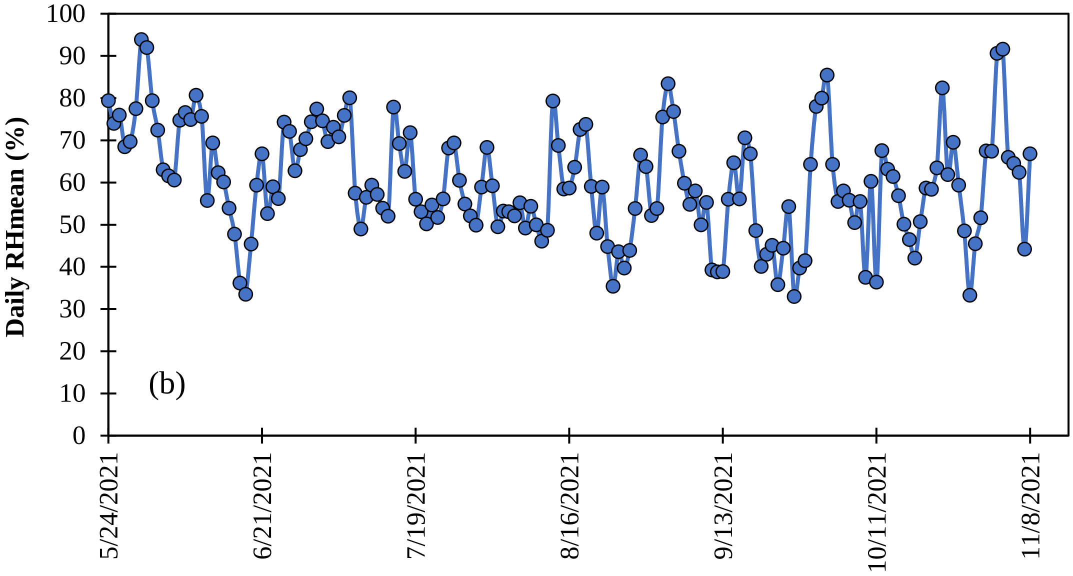
Daily weather conditions during the experiment period in 2021 are presented in Figure 3.3. The maximum, minimum, and mean temperature increased from the planting date to the highest value in late August and decreased thereafter to a minimum value at the end of the season in November. Daily average temperature varied from 18.4 ºC (May 27) to 31.2 ºC (August 24) and decreased to the lowest value 2.8 ºC (November 2). The average maximum, minimum, and mean temperatures during the growing season were 30.1, 13.7, 21.9 ºC, respectively.

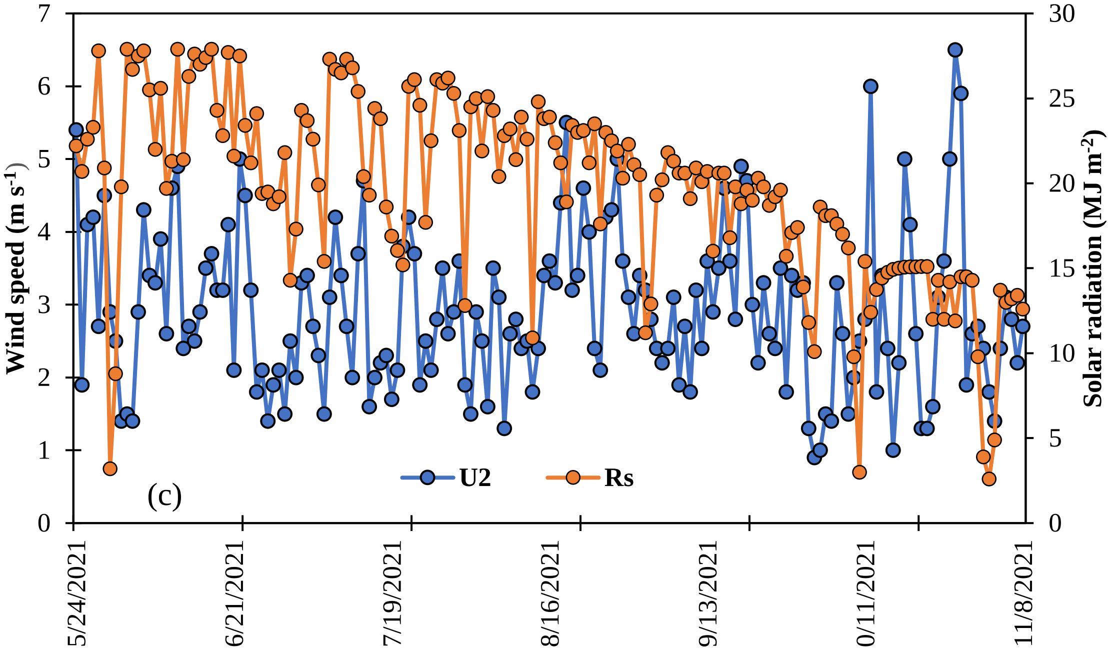
The average relative humidity increased from 79.4% at planting date to a highest value of 93.9 % on May 30 and decreased till the end of the season. During the growing season, the average relative humidity was 60%. The solar radiation decreased from the planting date to the end of the growing season. The highest value of 27.9 MJ m^{-2} was obtained on June 2, while the lowest value of 2.6 MJ m^{-2} was received on November 2. The average solar radiation during the growing season was 19.6 MJ m^{-2}. The wind speed varied during the growing season with the maximum value of 6.9 m s^{-1} obtained on October 27 and the lowest value 0.9 m s^{-1} obtained on October 2. The average wind speed during the growing season was 2.9 m s^{-1}. The total precipitation obtained during the growing season was 171.704 mm and the highest daily precipitation of 20.64 mm was obtained on October 12, 2021.

The growing degree days (GDD) and the thermal unit (TU) during the growing season are presented in Figure 3.4. The growing degree days is related to crop performance and starts with crop emergence until freezing. Baumhardt et al. (2021) reported that it varied with climate as well as elevation and latitude. In the experimental conditions, the thermal unit was found to be 1239.65 ºC day. 2021 TU is higher than the average 2003-2020 TU by 113 °C day. Similarly, Baumhardt et al. (2021) simulated the TU for Garden City from 1961 to 2000 and revealed that the TU varied from a minimum of 753 °C day to a maximum of 1288 °C day. Gowda et al. (2007) reported crop failures when growing season GDD did not exceed 800 °C day. Our results indicate that Garden City weather meets the temperature requirement for cotton growth and development. Thorp et al. (2014) mentioned that many crop models used a GDD concept as function of air temperature to simulate crop growth, and this makes the cumulative GDD an essential factor to crop yield. In the same way, Wanjura et al. (2002) found stronger relationships between maximum lint yields and GDD than total water application. Our study confirmed the work of Baumhardt et al. (2021) who reported that the risk of producing cotton is significantly less in Garden City in southwest Kansas compared with the central western or northwestern Kansas. During the 2000 and 2001 seasons, at the USDA-ARS Laboratory in Bushland, Texas, Howell et al. (2004) reported that the cumulative GDD did not exceed 1130 °C days in either season. However, Peng et al. (1989) noted that in the Southern Texas High Plains, the accumulated GDD approximated 1450°C days. Wanjura et al. (2002) revealed that it varied from 1092 to 1576°C days in Lubbock, Texas.

The variation in the daily grass reference evapotranspiration during 2021 growing season at the experiment station is presented in Figure 3.5. The reference evapotranspiration increased to a maximum value of 10.29 mm on June 17 and decreased thereafter to a minimum of 0.67 mm on November 2. The seasonal total evapotranspiration was 953.4 mm.




Daily RHmean (%)
100
90
80
70
60
50
40
30
20
10
0
(b)
5/24/2021
6/21/2021
7/19/2021
8/16/2021
9/13/2021
10/11/2021
11/8/2021


Wind speed (m s⁻¹)
Solar radiation (MJ m⁻²)
7
6
5
4
3
2
1
0
30
25
20
15
10
5
0
(c)
U2
Rs
5/24/2021
6/21/2021
7/19/2021
8/16/2021
9/13/2021
10/11/2021
11/8/2021

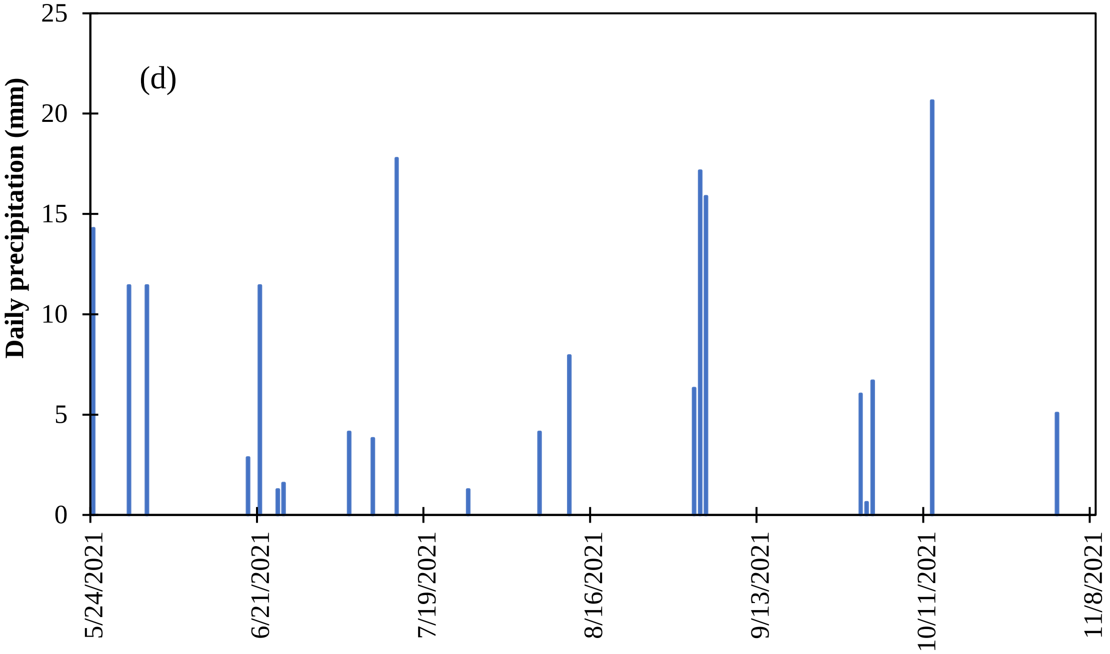


Figure 3.3 Weather conditions during the growing period at Southwest Research and Extension Center: (a) air temperatures, (b) air relative humidity, (c) wind speed and solar radiation, (d) precipitation.

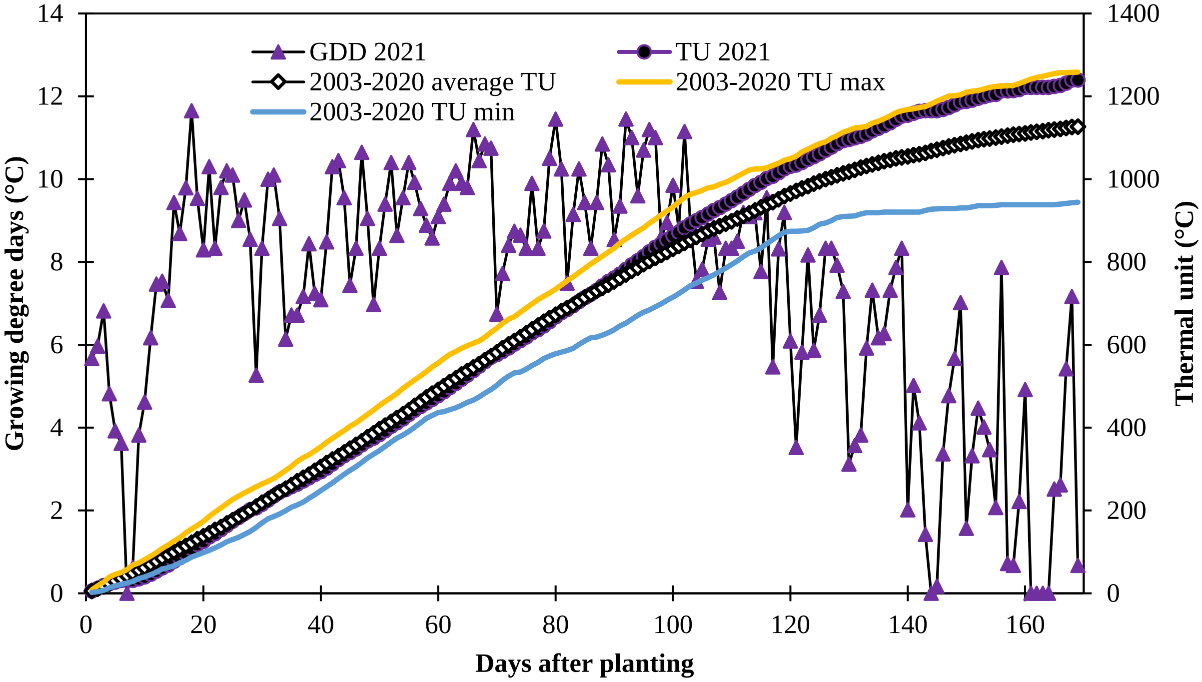


Figure 3.4 Variation in the Growing Degree Days (GDD) and Thermal Unit (TU) during the growing season at the experiment station

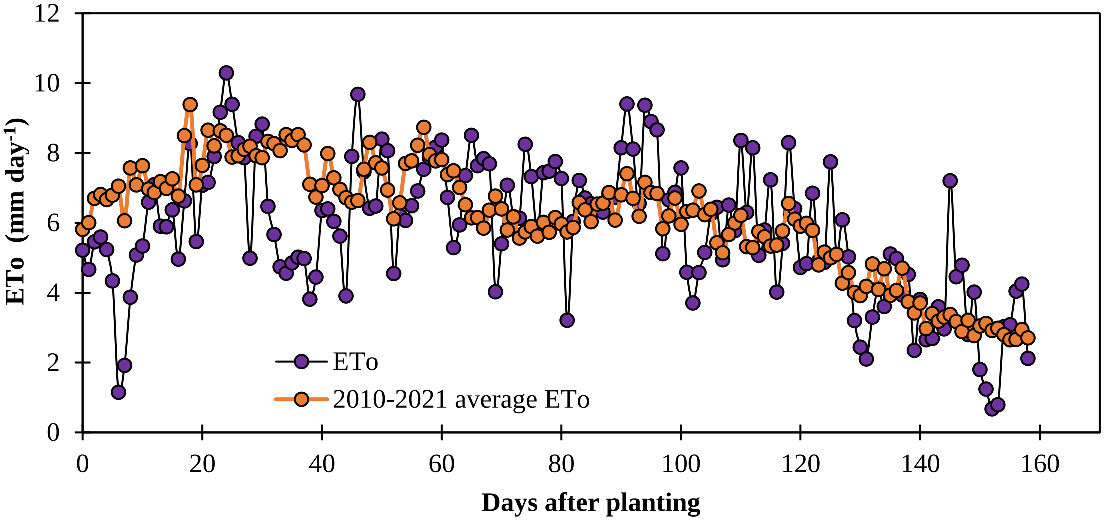


Figure 3.5 Variation in the daily grass reference evapotranspiration during 2021 growing season at the experiment station

3.2.2 Variation of cotton growth parameters under different treatments

3.2.2.1 Variation of plant height under different treatments as function of thermal unit during the growing season

Figure 3.6 presents the variation of the plant height under different irrigation technologies and plant densities as function of thermal unit. Plant height increased in different treatments with the thermal unit. Plant growth depends on temperature and demands a specific amount of heat to develop from seeding to the harvest stage. Parthasarathi et al. (2013) reported that temperature is an important element for the timing of biological processes, growth, and development of plants, as was confirmed by our results. For all the treatments, the maximum cotton height was obtained at 123 days after planting (DAP). Results indicated that at 123 DAP, the plant height varied significantly ($p<0.05$) as function of irrigation technology and rainfed conditions with the MDI2 having the maximum plant height of 86.4 cm followed by LEPA (80.9 cm), while the rainfed registered the lowest cotton height (58 cm). Among the plant densities, there was no statistical significance ($p<0.05$), and the lowest density had the maximum cotton height (77.2 cm) at 123 DAP. The same results have been found by Zhang et al. (2019) who reported that the surface drip irrigation increased cotton plant height by 19% and 8% compared with border irrigation and micro-sprinkling hose irrigation, respectively. Similarly, Spivey et al. (2019) showed that in North Carolina, plant height responded positively to subsurface drip irrigation. The authors reported that in 2015, the maximum plant heights were attained at 86, 76, and 65 DAP for the early-, mid-, and late-planted cotton, respectively. In sum, drip irrigation is found to positively influence the height of the cotton crop.

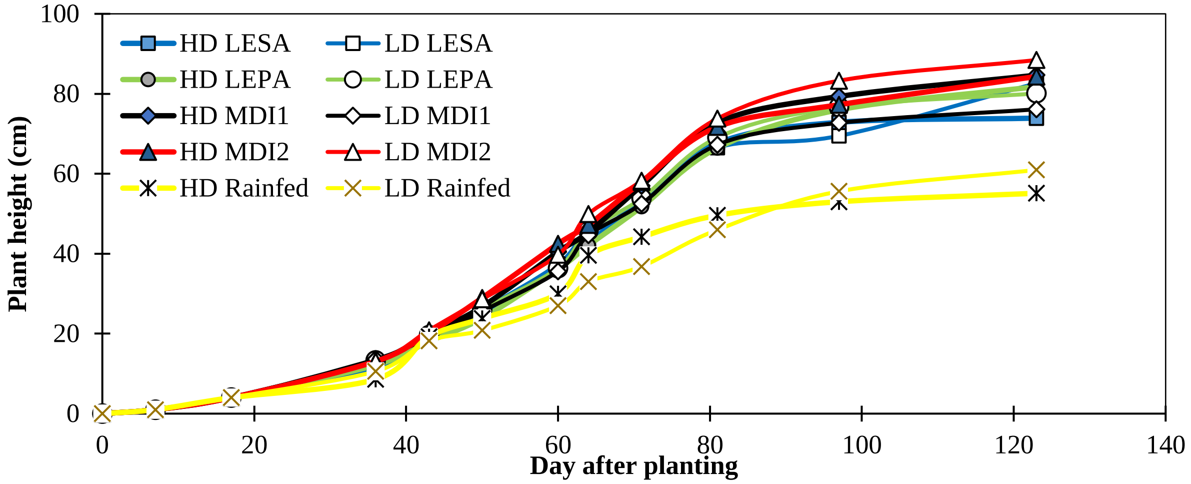


Figure 3.6 Plant growth under different treatments as function of Thermal Unit (TU) during the growing season (HD = high density, LD = low density)

3.2.2.2 Variation of canopy cover under different treatments as function of days after planting

Cotton canopy cover varied with irrigation technologies and plant densities (Figure 3.7). Canopy cover increased after emergence and reached the maximum values at 80 DAP, and it decreased thereafter to the lowest value. Among the irrigation technologies, MDI2 had the highest canopy covers throughout the season, while the dryland registered the lowest value. At 80 DAP, MDI2 registered 77.66%, while the dryland recorded 38.50%. Among the plant densities, the low density and high density provided the highest and lowest canopy cover, respectively, throughout the growing season. At 80 DAP, the low density registered 68.5 %, while the high density indicated

65.2% of canopy cover. Our results confirmed the findings by Shao et al. (2008), who showed that water stress conditions result in a decrease in ground cover fraction. Similarly, Sharma and Ritchie (2015) reported that the highest irrigation treatment using subsurface drip system reached a maximum of ground cover fraction of 80% and decreased thereafter due to decrease in growth induced by dry weather.

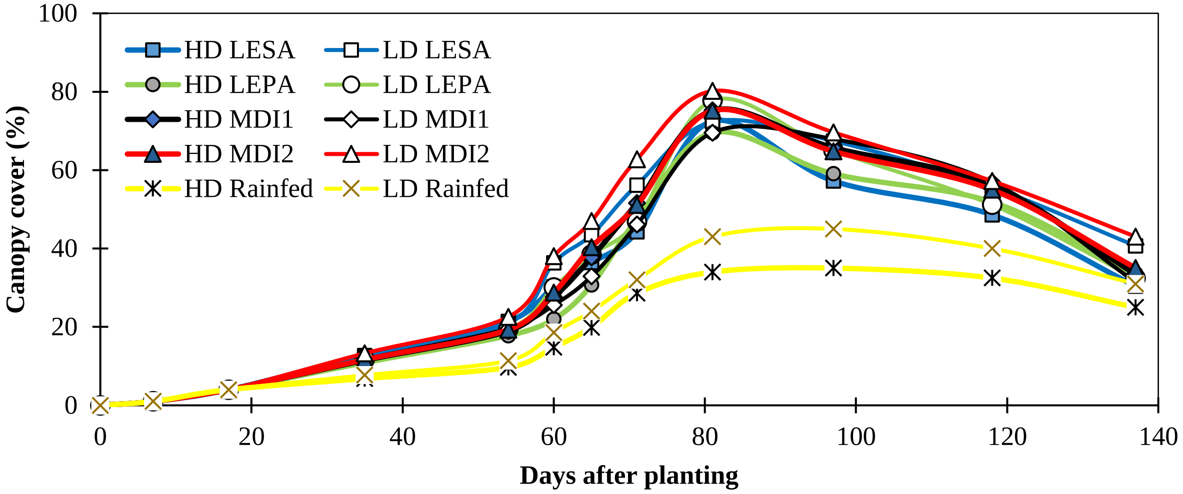


Figure 3.7 Canopy cover under different treatments as function of days after planting

3.2.2.3 Variation of leaf area index under different treatments as function of days after planting

The leaf area index (LAI) is an essential growth characteristic in plant ecology. The LAI indicates how much foliage there is. It is a measure of the photosynthetic active area, and, at the same time, the area subjected to transpiration. The variation of leaf area index of cotton under different treatments is presented in Figure 3.8. The leaf area index followed the same trend of canopy cover. It increased from emergence to a maximum value at 80 days after planting and decreased thereafter to a minimum value at the late stage of cotton growth. Throughout the growing season, MDI2 recorded the highest leaf area index, while the dryland indicated the lowest value. The lowest density recorded the maximum values, while the high density indicated the minimum values. At 80 DAP, the leaf area index of MDI2 was 4.02, while the dryland recorded 2.2. At the same date, the leaf area index of the lowest density was 3.73, while the high density recorded 3.28. The four irrigation technologies under study provided the same amount of water to the ground but not necessarily the same amount of irrigation water to the plant due to different distributions of water on the ground. Gao et al. (2019) found that decreasing the level of drip irrigation induced a decrease in LAI. The different LAIs under different irrigation technologies could confirm that different irrigation water was available to the plant with the MDI2 providing important irrigation water to the cotton plant compared to other irrigation technologies. Similarly, Zhang et al. (2019) discovered that a surface drip irrigation treatment had the highest increase in leaf area index (LAI). Hick and Lascano (1995) reported that leaf area index (LAI) is an important index for understanding cotton growth and water use. Our LAI pattern was similar to the finding of Ashley et al. (1965) who revealed that cotton LAI reached 1.0 approximately 6 to 8 weeks after emergence and increased rapidly to 5.0 during the following 6-week period. In conclusion, LAI is a useful cotton growth index that is very sensitive to soil moisture stress (Ennahli and Earl 2005).

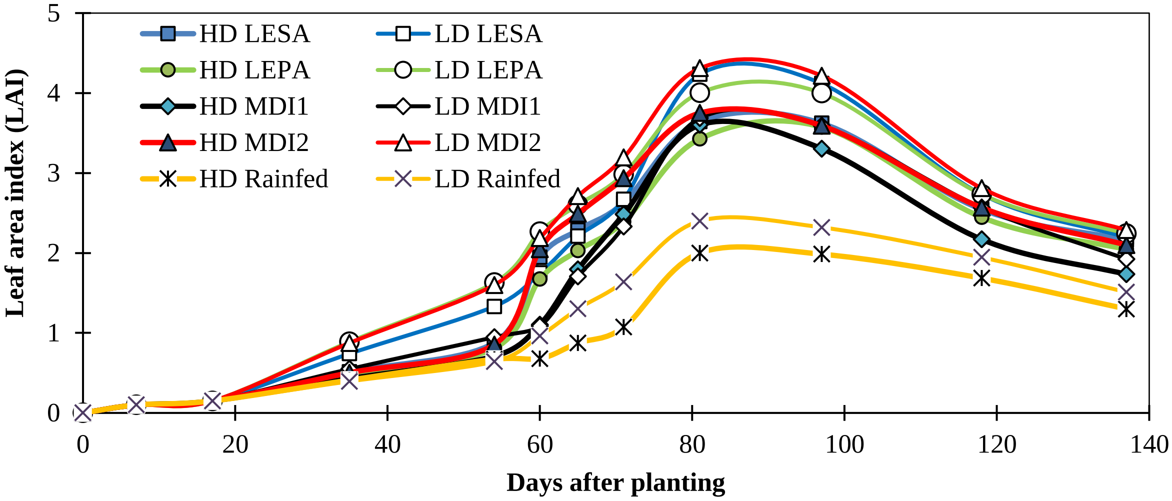


Figure 3.8 Leaf Area Index (LAI) under different treatments as function of days after planting

3.2.2.4 Variation of Normalized Difference Vegetation Index under different treatments as function of days after planting

NDVI is a measure of the state of plant health based on how the plant reflects light at certain frequencies (some waves are absorbed, and others are reflected). Chlorophyll, which is a health indicator, strongly absorbs visible light, and the cellular structures of the leaves strongly reflect near-infrared light. When the plant becomes dehydrated, sick, or affected by biotic or abiotic factors, the spongy layer deteriorates, and the plant absorbs more of the near-infrared light, rather than reflecting it. Thus, observing how NIR changes compared to red light provides an accurate indication of the presence of chlorophyll, which correlates with plant health. The value of the NDVI will always fall between -1 and +1. Values between -1 and 0 indicate dead plants, or inorganic objects such as stones, roads, and houses. NDVI values for live plants range between 0 to 1, with 1 being the healthiest and 0 being the least healthy.

The figure below shows the variation of the NDVI under different irrigation technologies, dryland, and plant density. The results indicated that for all treatments, the NDVI increased from emergence to a maximum value at 88 days after planting and decreased thereafter towards the end of the season. All the irrigated fields showed a high and similar NDVI while the rainfed condition registered the lowest NDVI. Irrigated cotton appeared, therefore, to be healthier than the dryland cotton. At 88 DAP, the average NDVI for irrigated fields was 0.83, while the dryland recorded 0.36. At the same date, the low and the high density recorded similar data of 0.67 and 0.68 respectively. There is no important difference of NDVI between the irrigation technologies. However, the results showed a large difference of NDVI between the irrigated and non-irrigated fields, as also reported by Ozdogan et al. (2012), Shahriar Pervez et al. (2014), and Biggs et al. (2016). The same results have been found by Ambika et al. (2016), who reported that irrigated and non-irrigated crops show considerable differences in NDVI. Pervez and Brown (2010) and Aparicio et al. (2000) found similar results showing that irrigated crops exhibit higher NDVI especially for corn and wheat. Irrigation water application helps the plant to attain high NDVI. In conclusion, irrigated fields in the study area appeared to be healthy compared to the dryland.

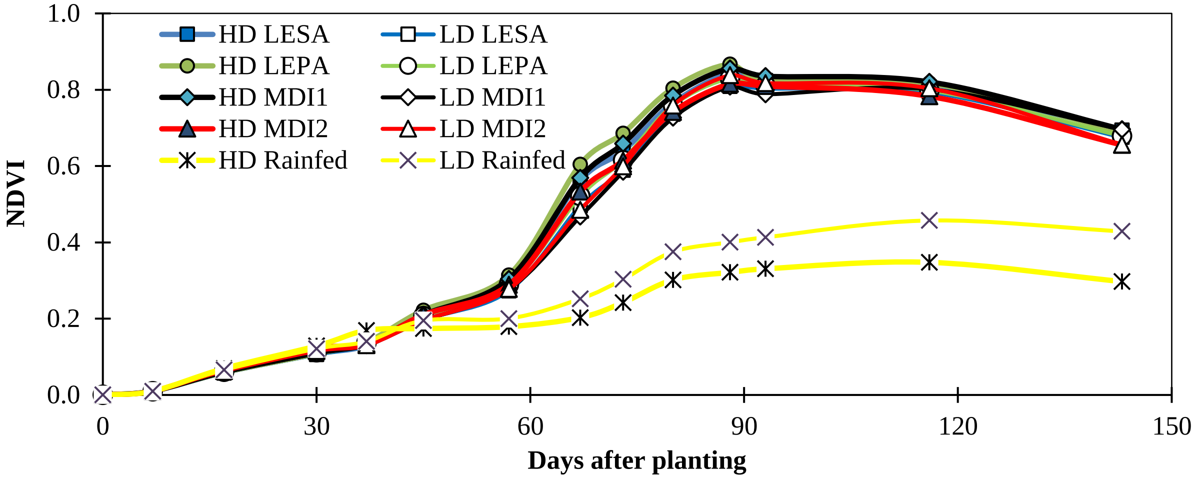


Figure 3.9 NDVI under different treatments as function of days after planting

3.2.2.5 Mean leaf stomatal conductance under different treatments during the growing season

Stomatal conductance (mmol m^{-2} s^{-1}) measured by a leaf porometer is the rate of CO_2 entering, or water vapor exiting, through stomata (Jeanguenin et al. 2017) and is an indicator of plant water status (Gimenez et al. 2005). Urban et al. (2017) reported that increase in canopy stomatal conductance with rise of temperature increases the transpiration rate. Similarly, Devi and Reddy (2018) revealed that cotton genotypes OL220 and LKT 57 with limited transpiration at high vapor pressure deficit are associated with reduced stomatal conductance. Figure 3.10 shows the mean leaf stomatal conductance of cotton under different irrigation technologies and dryland. The results indicated that cotton grown under the MDI2 had the highest stomatal conductance of 411.3 mmol m^{-2} s^{-1}, while the cotton on the dryland registered the lowest value of 359.9 mmol m^{-2} s^{-1}. Results indicated that the water distribution from MDI2 applicator did not put cotton crop under stress while the rainfed did. This result is in line with Azhar and Rehman (2018), who found that a decline in stomatal conductance occurs due to water stress. From the results, we deduced that plants under MDI2 might have a higher transpiration rate compared to other irrigation technologies and rainfed conditions. Ko and Piccinni (2009) found that stomatal conductance had a strong correlation with the transpiration rate.

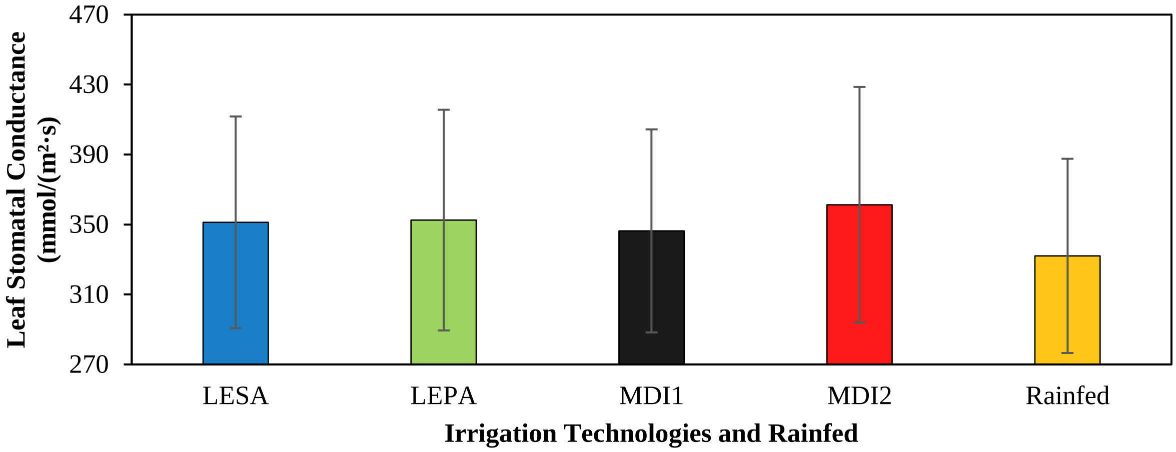


Figure 3.10: Leaf stomatal conductance (mmol/(m²·s) as function of irrigation technologies and rainfed

3.2.3 Relationship between the weather conditions and cotton growth parameters

An accurate approach to assessing crop development relies on the daily temperatures during the season to monitor progress. Figure 3.11 presents the relationship between the plant height and the thermal unit. The results showed a strong third-degree polynomial relationship between the two parameters with the coefficient of determination (R^2) of 0.95. The cotton height can then be predicted using the thermal unit and the equation developed in the study site. Similar trend has been found by Hamed at al. (2011) who reported that an increase of heat units induced an increase of cotton plant height. Skaggs and Irmat (2012) reported that the correlation between plant height and cumulative GDD had a R^2 of 0.99.

The relation between leaf area index (LAI) and canopy cover and between LAI and NDVI are presented in Figures 3.12 and 3.13, respectively. A strong linear relationship was found between the LAI and canopy cover and a polynomial second order relationship was found between the LAI and NDVI with coefficient of determination of 0.98 and 0.92, respectively. The result indicated a significant positive relationship between LAI and canopy cover and between LAI and NDVI ($p<0.05$). The strong relationship indicates that the cotton LAI and NDVI data can be estimated using the equations developed. The LAI and NDVI are important characteristics related to the biomass and plant health, respectively. High value of these indices is an indicator of best yields. There is also a significant positive correlation between the plant height and the LAI at 95 confidence level (Figure 3.14). In Texas, Ko et al. (2005) found a power relationship between the LAI and ground cover (GC) with $LAI=2.94(GC)^{1.33}$ with a strong coefficient of determination of 0.95. Moreover, the authors revealed that while the LAI can be collected via remote sensing data, the LAI estimation from plant sampling represents better crop growth characteristics. In this study, the LAI was collected on plant sampling rather than remote sensing. Ramirez-Garcia et al. (2018) found that a quadratic model fitted the relationship between the GC and LAI for a grass, a legume, and a crucifer crop. Colombo et al. (2003) showed that leaf area index has a positive correlation with NDVI of different crops. In China, Fan et al. (2009) developed general linear and a general exponential relationship ($LAI = -0.0897 + 1.424 * NDVI$, $R = 0.79$; $LAI = 0.128 * \exp(NDVI/0.311)$, $R = 0.77$) between LAI and NDVI. The authors further stated that these equations for estimating LAI are appropriate for the natural range of vegetation in this region during the growing season.

To conclude, the equations developed in this study can be used to estimate the LAI and NDVI for better cotton crop monitoring at different stages.

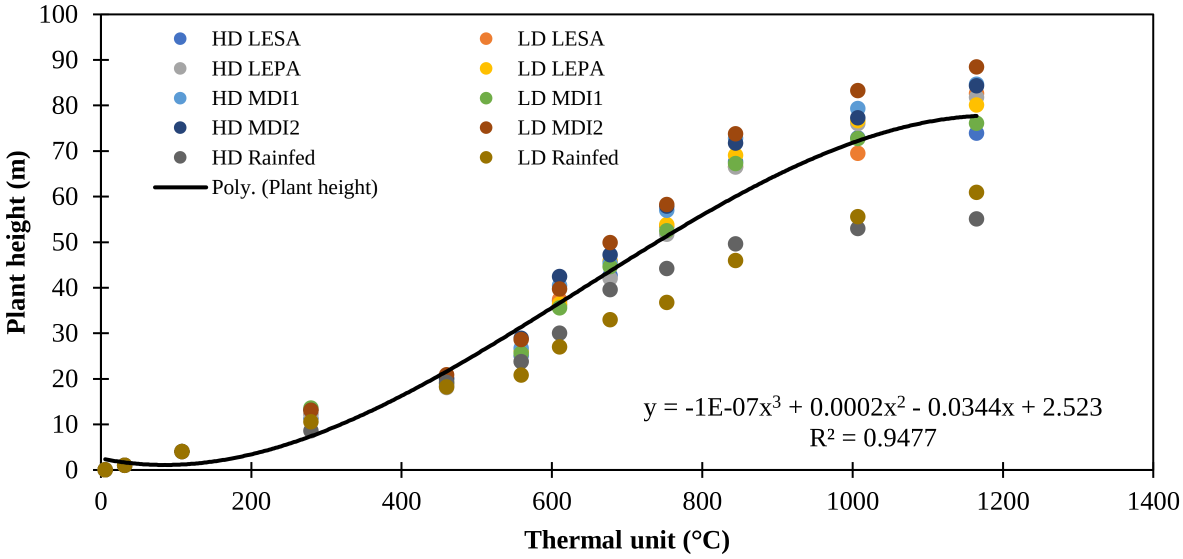


Figure 3.11 Relationship between plant height and thermal unit

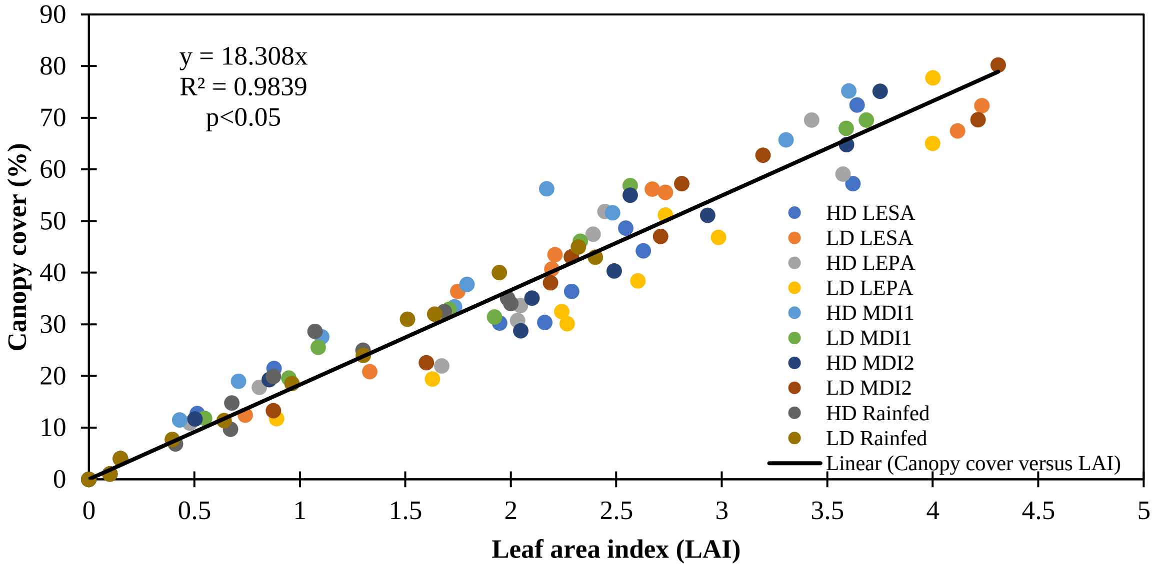


Figure 3.12 Relationship between leaf area index and canopy cover

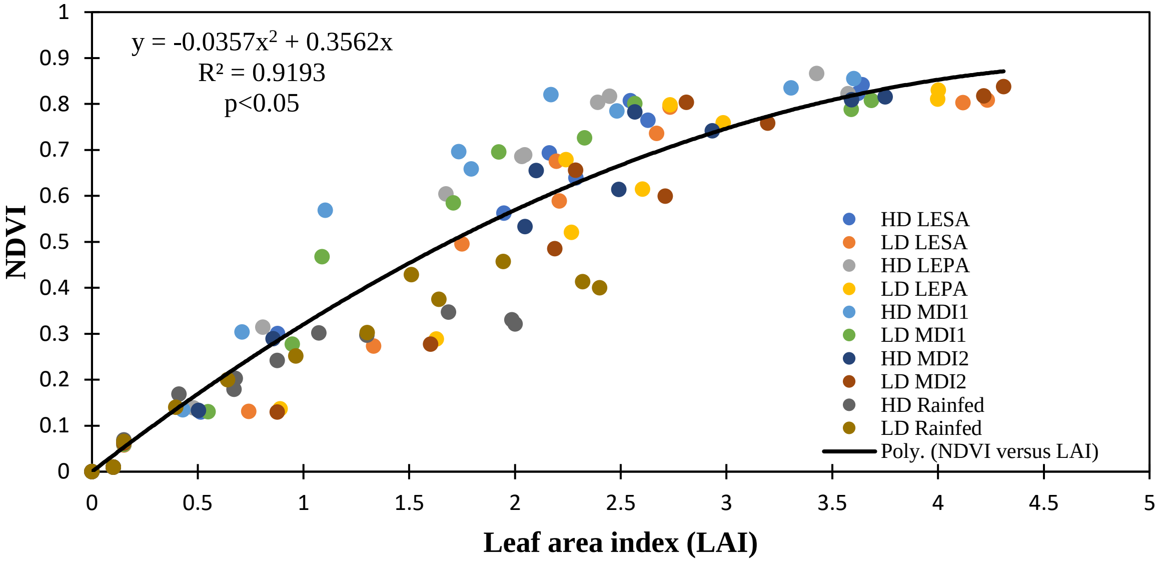


Figure 3.13 Relationship between NDVI and LAI

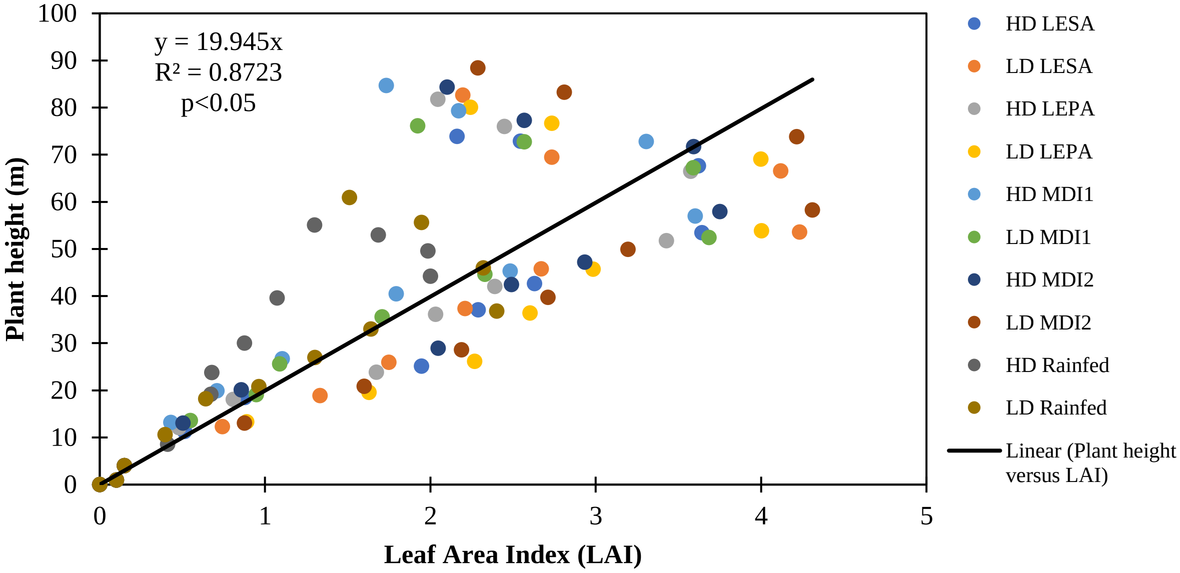


Figure 3.14: Relationship between plant height and LAI

3.2.4 Relationship between the maximum growth parameters and the yield

The figures below present the relationship between the cotton lint yield and the growth parameters such as maximum NDVI, maximum canopy cover, and maximum height. The maximum growing characteristics were obtained during the flowering and early boll formation stage. A linear relationship was fitted between the growth characteristics and the lint yield. The coefficients of determination (R^2) between the yield and the growth characteristics were 0.72 with the maximum NDVI, 0.62 with the maximum canopy cover, and 0.59 with the maximum height. The coefficients of determination of the yield and the maximum growth characteristics were high (0.59-0.72) indicating that the crop growth parameters at flowering and early boll development stage could help to predict the cotton lint yield. Furthermore, the results indicated that there is an optimum growth characteristic ranges for optimum yield. Growth characteristics out of this range leads to low lint yield. After the flowering and early boll development stage, a higher growth characteristic decreased the cotton lint yield. At this stage, the plant needs to concentrate its energy on the boll development instead of production of new leaves or flowers.

In conclusion, if cotton growers can assess the vegetation indices during the flowering and early boll development stages of cotton, they can make field management choices related to irrigation and application of nutrients and plant growth regulators to maximize the yield.

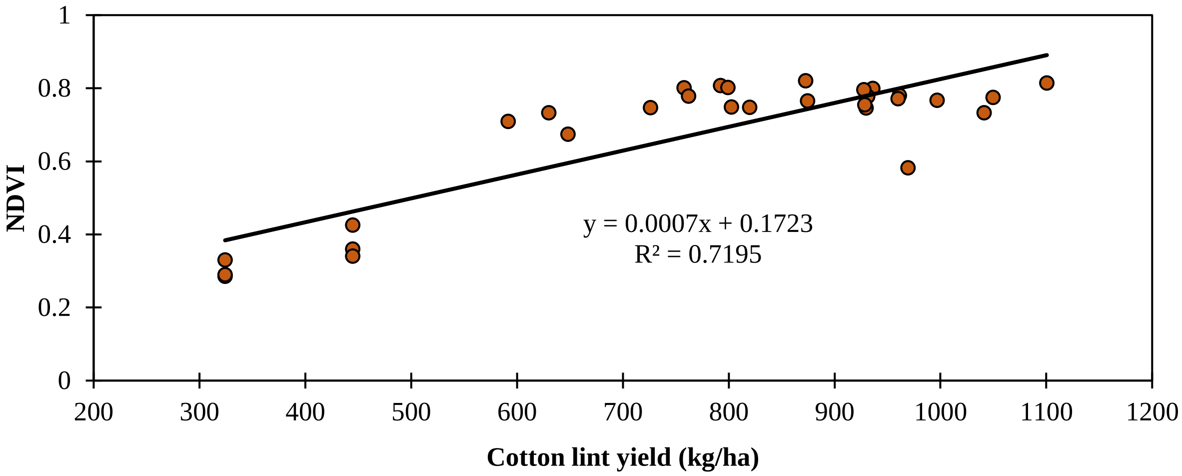


Figure 3.15 Relationship between the NDVI and the cotton lint yield

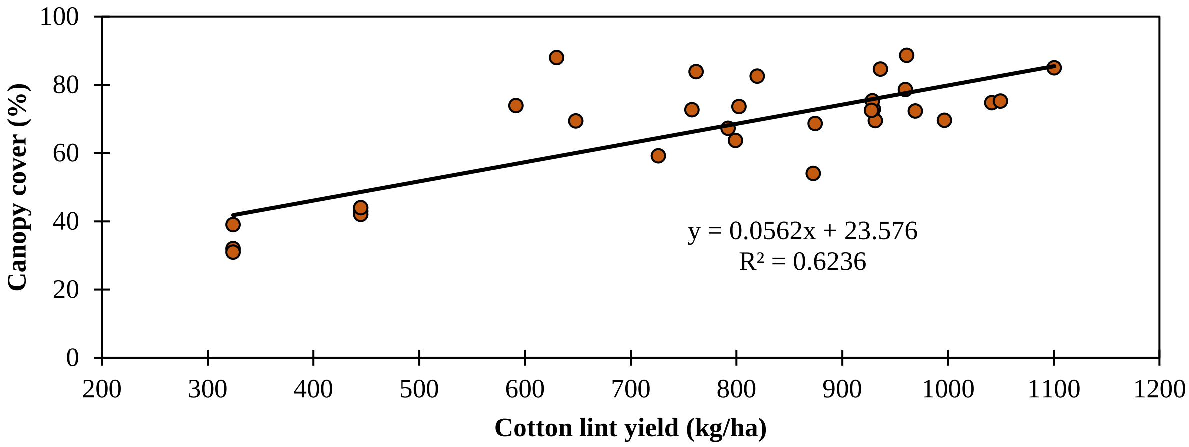


Figure 3.16 Relationship between the canopy cover (%) and the cotton lint yield

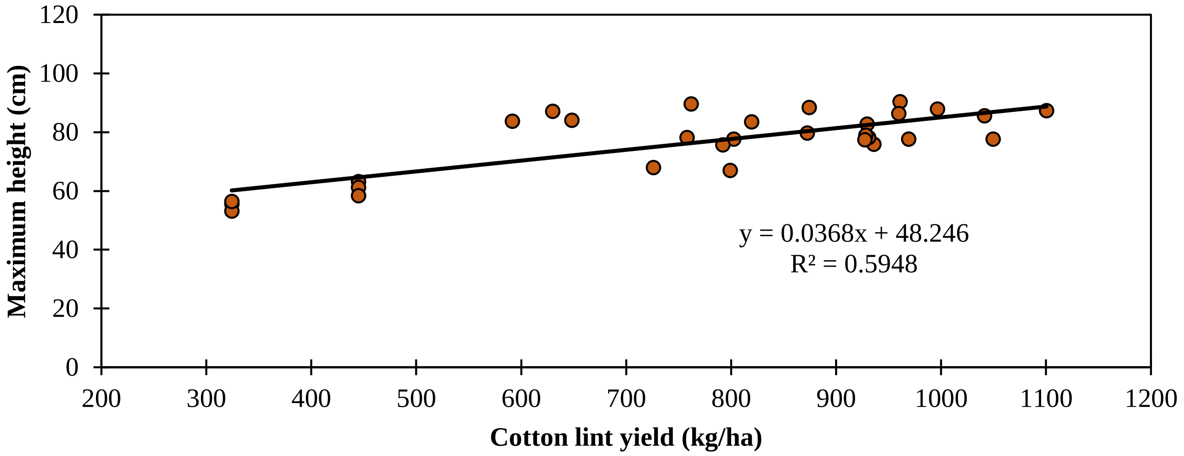


Figure 3.17 Relationship between the maximum height and the cotton lint yield

3.2.5 Variation in cotton yield and yield components under different irrigation technologies, rainfed conditions, and plant densities

Tables 3.3 and 3.4 present the variation in cotton yield and yield components as function of irrigation technologies (including rainfed conditions) and plant density, respectively. Variation in cotton lint yield between the irrigation technologies and rainfed conditions was statistically significant at the 5% confidence level (Table 3.2). The LEPA irrigation technology had the highest numerical yield (950.3 kg ha^{-1}) followed by MDI1 (907.7 kg ha^{-1}) and LESA (818.7 kg ha^{-1}).

Among the irrigation technologies, MDI2, which had the highest growth characteristics, recorded the lowest yield (791.2 kg ha^{-1}) and was not statistically significant compared ($p>0.05$) to LEPA. The rainfed conditions provided the lowest yield (384.5 kg ha^{-1}). In the experiment conditions, irrigated cotton lint yield increased by 106%, 113%, 136%, and 147% compared with the rainfed conditions for MDI2, LESA, MDI1, and LEPA, respectively. Similar results have been found in the United States and around the world. Lyle and Bordovsky (1983) reported LEPA as the best irrigation technology compared to furrow and sprinkler systems because it better distributes water and had a higher water use efficiency. Likewise, Yazar et al. (2002) reported LEPA in southeast Anatolia to enhance cotton yield. As found under the experimental conditions in this study, yield with LEPA and MDI did not differ significantly ($p>0.05$). Other studies identified drip irrigation as the best irrigation technology, especially with the lowest flow rate (Colaizzi 2005, Cetin et al. 1994). Bordovsky et al. (1984) scheduled irrigation based on soil matric potential and discovered that drip irrigation provided the highest yields for cotton, corn, and soybeans. However, other studies found that, while the drip irrigation with the lowest flow rate contributes to higher yield, it might negatively affect seed germination, if the soil has less soil moisture at the beginning of the season. Between the plant densities, there was no significant variation of the yield.

The mean weight per boll and the weight of seeds per boll varied significantly ($p<0.05$) among the irrigation technologies and the rainfed treatments. LEPA had the highest weight per boll (8.3 g), but it did not vary significantly among the irrigation technologies. The rainfed condition had the lowest weight per boll (7.4 g). LEPA and MDI1 recorded the maximum weight of seed per boll (3.2 g), and, compared to other irrigation technologies, it did not vary significantly at the 5% significance level. The rainfed treatment had the lowest seed weight per boll (2.8 g). The biomass, the number of bolls per plant, and the number of open bolls per plant in the experiment conditions varied significantly at the 5% confidence level. The MDI2, which recorded the highest growth characteristics such as plant height, LAI, canopy cover, NDVI, had the highest biomass of 19313.7 kg ha^{-1} while the rainfed recorded the lowest value of 5896 kg ha^{-1}. However, LESA recorded the maximum number of bolls per plant and the number of open bolls per plant with average values of 27.6 and 7.8, respectively. The number of seeds and lint weight per boll varied non significantly between the irrigation technologies and rainfed conditions. The results indicated that the cotton lint yield and yield components did not significantly vary between the plant densities ($p>0.05$). Koudahe et al. (2021) reported planting density to affect cotton yield and yield components, and its optimum value is, therefore, crucial under each climatic condition. In the experimental conditions, the lowest density of 135,908 plants per ha was, therefore, found as the optimum plant density. Guzman et al. (2019) reported reduction in yield and yield components at the highest density in an experiment with four planting densities. The authors further suggested 83,333 and 100,000 plants per ha as an optimum planting rate in a Venezuelan tropical dry climate. Late boll maturity was found by Kerby et al. (1990) due to an increase in seedling density from 10 to 15 plants per m^2. In Georgia (Bednarz et al. 2005) and Arizona (Kawakami et al. 2012), optimum plant density was found to be 12.6 and 10 plants per m^2, respectively.

Table 3.3: Variation in cotton yield and yield components as function of irrigation technologies *

Irrigation technology	Lint yield (kg/ha)	Biomass (kg/ha)	Number of bolls per Plant	Number of open bolls per Plant	Seeds per boll	Weight boll (g)	Weight lint per boll (g)	Weight seeds per boll (g)
MDI2	791.2 b	19313.7 a	18.5 b	7.5 a	33.1 ab	8.2 a	2.9 ab	3.0 ab
LESA	818.7 ab	17800.8 a	27.6 a	7.8 a	31.2 b	8.1 a	2.9 ab	3.1 a
MDI1	907.7 ab	14186.7 ab	14.8 b	5.1 b	34.1 a	8.2 a	3.0 a	3.2 a
LEPA	950.3 a	10720.2 bc	13.8 b	6.6 ab	32.5 ab	8.3 a	3.0 a	3.2 a
Rainfed	384.5 c	5896 c	15.8 b	2.8 c	31.5 ab	7.4 b	2.7 ab	2.8 b

Table 3.4: Variation in cotton yield and yield components as function of plant densities *

Plant density	Lint yield (kg/ha)	Biomass (kg/ha)	Number of bolls per Plant	Number of open bolls per Plant	Seeds per boll	Weight boll (g)	Weight lint per boll (g)	Weight seeds per boll (g)
D1	771.5 a	14683.3 a	16.0 a	5.5 a	33.0 a	7.9 a	3.0 a	3.1 a
D2	769.4 a	12483.7 a	20.3 a	6.4 a	31.9 a	8.1 a	2.8 a	3.0 a

3.3 Conclusions

Under the climatic conditions of the High Plains of Kansas, a field experiment was carried out to assess the effect of different irrigation technologies and plant densities on cotton growth, yield, and yield components. The results indicated that the Mobile Drip Irrigation 2 (MDI2) had the highest growth characteristics such as plant height, leaf area index, canopy cover, and NDVI, while the rainfed treatment registered the lowest growth performance. Likewise, MDI2 had the highest mean leaf stomatal conductance. Results also showed a good correlation between the weather conditions and the growing parameters. The coefficient of determination was 0.95 between the plant height and thermal unit, 0.98 between the canopy cover and LAI, and 0.92 between the NDVI and LAI. Likewise, the coefficients of determination of the yield and the maximum growth characteristics were high (0.59-0.72) indicating that the crop growth parameters at flowering and boll development stage could help to predict cotton lint yield. Cotton lint yield between the irrigation technologies and rainfed conditions was statistically significantly different ($p<0.05$). LEPA had the highest cotton lint yield (950.3 kg ha^{-1}). Irrigated cotton lint yield increased by 106%, 113%, 136%, and 147% compared with the rainfed for MDI2, LESA, MDI1, and LEPA, respectively. Under the experimental conditions, the lowest density of 135,908 plants per ha was found as the optimum plant density.

Chapter 4 - Actual Evapotranspiration, Water Use Efficiency and Grass-reference Crop Coefficients of Cotton under different Irrigation Technologies and Rainfed Conditions

4.1 Materials and methods

4.1.1 Measurement of soil water status

Soil water status was monitored using CPN 503 Depth Moisture Gauge soil moisture meter (InstroTek Company, 4495, 44th St. SE Suite A, Grand Rapids, Michigan 49512) (Photo 4.1) at the 0.31-, 0.61-, 0.91-, 1.22-, 1.52-, 1.83-, 2.13-, and 2.44 m soil depths once a week throughout the growing season. Neutron probe access tubes were installed in the middle of two plants on the row of representative experimental units.

Photo 4-1 Picture of Neutron probe

4.1.2 Cotton actual evapotranspiration

Soil water data obtained using a neutron probe soil moisture meter was used in the soil water balance calculation for actual evapotranspiration ETa. Seasonal ETa (mm) was calculated using a general soil water balance equation:

$$\boldsymbol{P + I + U = R + D \pm \Delta W + ETa} \qquad Equation\ 4.1$$

where P = effective rainfall (mm), it was collected from the weather station in the experiment site; I = irrigation water applied (mm); U = upward vertical soil moisture flux from below the crop root zone (mm); R = surface runoff (mm); ΔW = change in soil moisture storage in the crop root zone (mm); and D = water lost through deep percolation, vertically downward from the root zone (mm). The change below the root zone represents deep percolation. The runoff and the deep percolation were assumed to be zero in the study fields as all rainfall was consumed within the field and irrigation water was well managed. Assuming that the upward flux was negligible because the water table was more than 30 m below soil surface, equation (3) can be reduced to the following form for calculating ETa:

$$\boldsymbol{ETa = P + I - D - R - \Delta W} \qquad Equation\ 4.2$$

4.1.3 Water use efficiency

Crop water use efficiency related to total water supply (CWUE), seasonal irrigation water (IWUE), and evapotranspiration water (ETWUE), and were estimated by the following equations:

$$CWUE = \frac{Yield_{irr}}{Seasonal\ water\ supply} \qquad Equation\ 4.3$$

$$ETWUE = \frac{Yield_{irr}}{Seasonal\ ETa\ irrigated} \qquad Equation\ 4.4$$

$$IWUE = \frac{Yield_{irr} - Yield_{rainfed}}{Seasonal\ irrigation\ amount} \qquad Equation\ 4.5$$

where CWUE, ETWUE, and IWUE are in kg m^{-3}, yield in kg ha^{-1}, cotton seasonal ETa is the seasonal cumulative ETa (mm), the seasonal irrigation amount is the sum of the irrigation amounts throughout the season (mm), and seasonal water supply is the sum of seasonal precipitation and seasonal irrigation amount (mm). The season in the experimental conditions refers to the period from planting to the harvest.

4.1.4 Calculation of crop coefficients under different irrigation technologies and rainfed conditions

Crop coefficient (Kc) was calculated using the two-step approach of estimating ETa and ETo independently first and then dividing them, such as:

$$K_c = \frac{ETa}{ETo} \qquad Equation\ 4.6$$

The estimated Kc values for all irrigation technologies and rainfed treatments were expressed as a function of days after planting.

Further the actual evapotranspiration of cotton during the growing season was also calculated as a sum of daily ETa. Allen et al. (1998) established a standard crop coefficient of cotton under a standard climatic condition as 0.35, 1.15-1.2, and 0.70-0.50 for the initial, mid-season and late-season, respectively, and they were used to assess cotton ETa for the growing period. The crop coefficient Kc was linearly estimated between two typical Kc values during the mid-development and late season stage. During the initial stage, the ETa estimated consists mainly of evaporation. Thus, adjustment of Kc for this stage mainly depends on climatic factors. With the FAO-56 method, many factors affected the crop coefficient, among which is the plant height (Djaman et al. 2018). The FAO typical mid- and late-season stage Kc values were adjusted according to the climatic conditions and cotton plant height using the equation below.

$$KcStage_{adj} = KcStage_{FAO} + [0.04(U_2 - 2) - 0.004(RHmin - 45)]\left(\frac{h}{3}\right)^{0.3} \quad Equation\ 4.7$$

where $KcStage_{adj}$ is the adjusted FAO crop coefficients, $KcStage_{FAO}$ is the standard value according to FAO-56 approach (Allen et al. 1998), U_2 is the daily wind speed at 2 m height over grass during the growth stage (m s^{-1}), RHmin is the daily minimum relative humidity during the growth stage (%), and h is the cotton plant height for each growth stage (m).

The ETa estimated using the water balance approach and the FAO adjusted recommended Kc were compared.

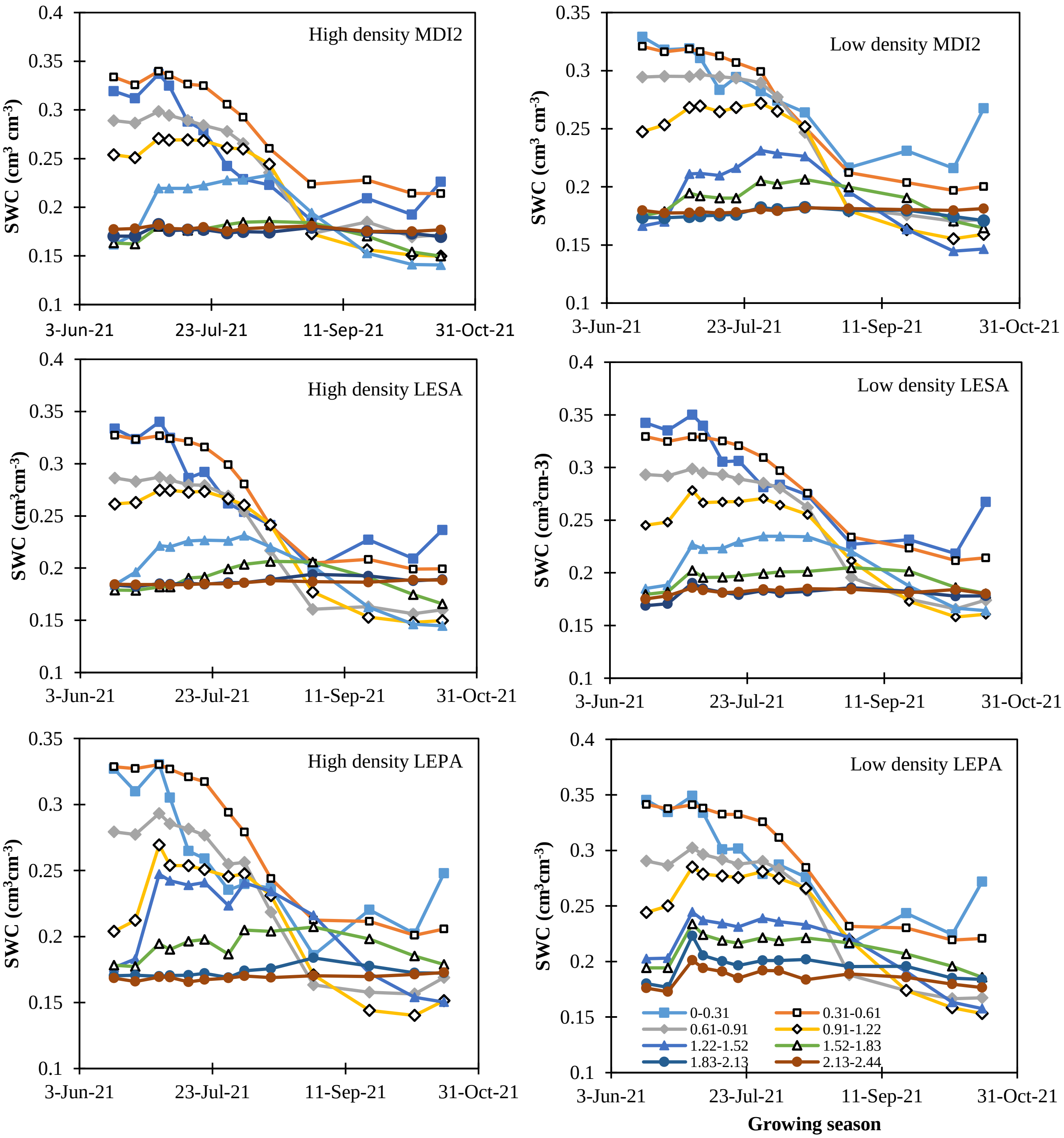
4.2 Results and discussion

4.2.1 Soil water dynamics under different irrigation technologies and rainfed treatments

Initial soil water contents were similar among the irrigated treatments at the beginning of the growing seasons, indicating uniform soil water distributions in the field under the center pivot system from winter and spring precipitation (Figure 4-1). The difference in initial soil water content appeared from the irrigated to the rainfed. In the previous growing season, corn was grown under the center pivot system, while on the dryland sorghum was grown without irrigation. This could explain the difference in initial water content between the irrigated and rainfed plots. Throughout the growing season, the depletion of available water content increased from irrigated treatments to the rainfed. Under all the treatments, the water content in the top layer was lower than in the second layer from the emergence to the boll formation and filling. This might be the result of a greater rate of plant water uptake and soil water evaporation from the topsoil than from deeper soil layers. Similarly, in Texas AgriLife Research and Extension Center at Uvalde, Wen et al. (2013) found highest soil water content variation at the 20-cm layer due to high temperature, which caused greater water consumption by plants and loss in the soil. From this growth stage to the late stage, the water content in the topsoil (0-0.31 m) became important because of the late season precipitation. The sharp increase after August 30 was due to the rainfall events (39.36 mm) that occurred from September 2 to 4. At that period, the water content in the other soil layers decreased because all the fields were under stress to force cotton to concentrate in boll filling instead of producing new bolls that could not have the time necessary to mature.

From emergence to the boll development and filling, the water content of rainfed treatments, in the deep layers such as the layers below 1.22 m did not change. For instance, in the high density rainfed, the water content was 13% at the beginning of the season and at the mid stage. In the irrigated settings, during the vegetative growth, the water content in the deep layer (from 1.83 m) did not change during the season, while the water content in the top six layers varied indicating that irrigated cotton extracted soil water from the top to 1.83 m soil layer in these experimental conditions. For instance, the average water content of the first six layers (top to 1.83 m soil depth) in LESA high density decreased from 26% at the beginning of the season to 17% in mid stage. Under the same treatment and same period, the water content of the last two layers, that is seventh layer (1.83-2.13 m) and eighth layer (2.13 to 2.44 m) did not change during the season. For example, the average soil water content was 18% for both at the beginning and at the end in LESA high density. Our results indicated that under the experimental conditions, the deep percolation is negligeable below the 1.83 soil depth. Djaman et al. (2013) reported uniform soil water distribution because the initial soil water contents were similar among irrigated and rainfed treatments at the beginning of growing seasons. Like in the study conditions where the topsoil (0-0.31 m) had less water content compared to the second layer (0.31-0.61), Djaman et al. (2013) found similar results indicating that the topsoil (0-30 m) had the least water content due to transpiration and evaporation. Furthermore, the authors reported that maize could extract water in 1.80 m, while we found under the experimental conditions that cotton can extract water from 1.83 m. In the same way, Wen et al. (2013) reported that all depths (0-100 cm), soil moisture decreased slightly over the growing season indicating that under the experimental conditions, the cotton crop extracted water from 1.00 m below soil.

In conclusion, under the experimental conditions, evaporation and transpiration caused a rapid decrease in the soil water content in the topsoil and cotton extracted water to 1.83 m of soil depth.



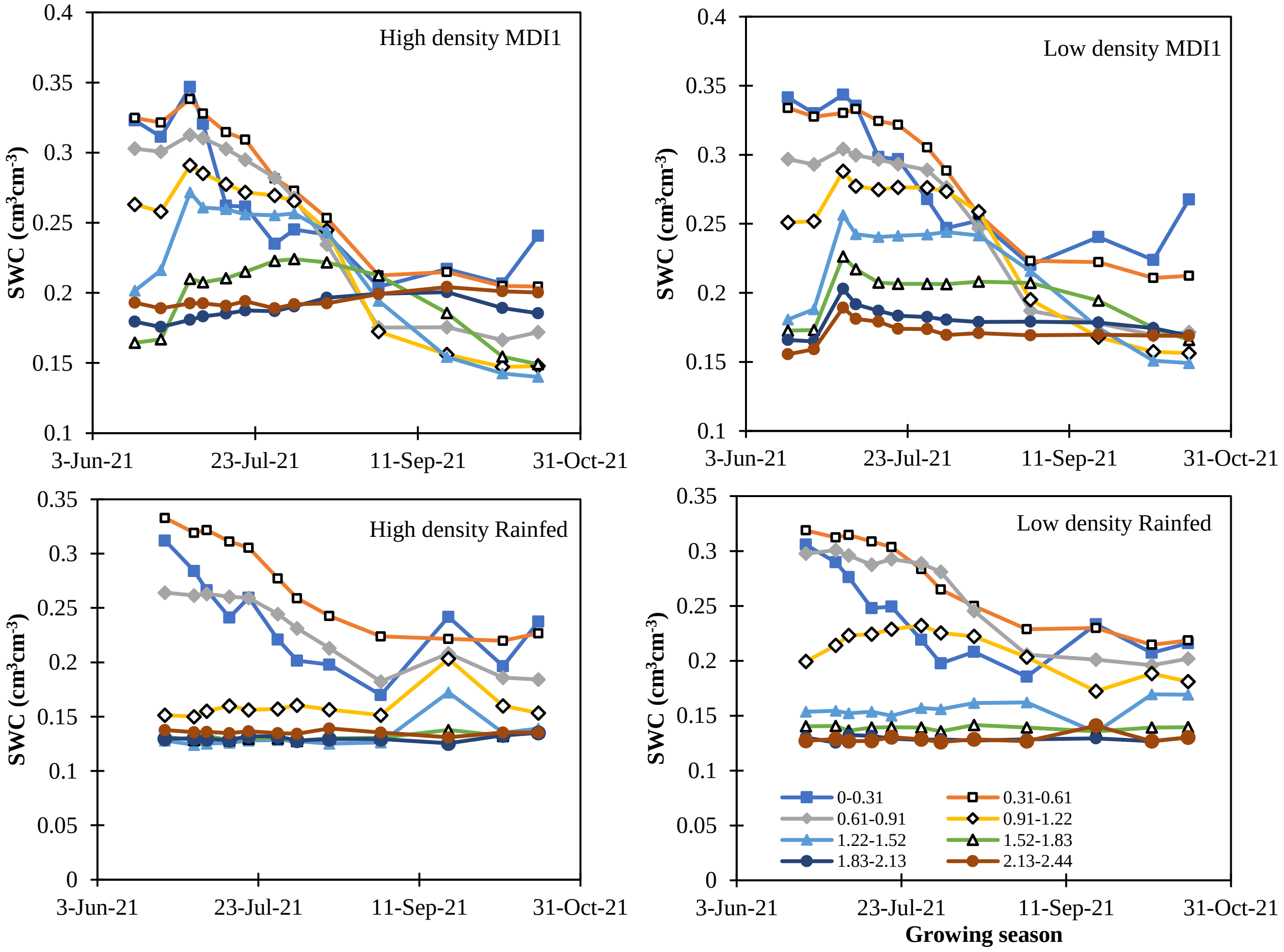


Figure 4.1 Neutron probe-measured soil water content in the soil depth (0-1.83 m) during the growing season under different treatments

4.2.2 Effect of different irrigation technologies and plant densities on crop evapotranspiration

Cotton seasonal ETa under different irrigation technologies and plant densities computed using the soil water balance approach is presented in Table 4.1. ETa varied from 280.8 mm for the rainfed conditions under high density to 500.5 mm for MDI1 under high density. During the growing season, MDI1 had the maximum ETa (500.5 mm) followed by LEPA (498.9 mm) both with high density, while the rainfed conditions had the lowest ETa with the high density (280.8 mm). A similar result was found by Baumhardt et al. (2021), who revealed that cotton seasonal water use ranged from 448 to 480 mm and from 440 to 481 in Garden City, Kansas and Colby, Kansas, respectively. Evett et al. (2012) stated a variation of cotton water use (410 to 780 mm) based on the irrigation methods. Our results indicated that ETa varied for irrigation technologies with MDI recording the highest values. Furthermore, there is an important decrease of ETa from irrigated fields (483.5 mm) to rainfed conditions (287.2 mm), which confirms reported results from other studies that ETa depends on the irrigation regimes (Koudahe et al. 2021, Colaizzi et al 2005). In Bushland, Texas, Howell et al. (2004) reported measured actual evapotranspiration of 775 mm and 397 mm under full irrigation and dryland in 2000, respectively, and 739 mm and 386 mm under full irrigation and dryland in 2001, respectively.

Koudahe et al. (2021) stated that ETa was climate dependent. In Turkey, cotton water use ranged from 272 to 882 mm in 2003 and from 242 to 855 mm in 2004 due to changes in climatic factors (Dagdelen et al. 2006). At the South-Central Agricultural Laboratory (SCAL) in Lincoln, Nebraska, Djaman and Irmak (2013) reported that corn ETa varied from 579 mm for rainfed plots to 634 mm for full irrigation in 2010. The differences in ETa also depend on the length of the growing season and management practices, among other factors. In conclusion, our study found that different irrigation technologies induced different ETa in cotton production, and MDI provided the highest ETa.

Table 4.1 Seasonal rainfall, irrigation, change in total soil water in the initial and end season (ΔTSW), seasonal and daily actual evapotranspiration (ETa) for all treatments in the 2021 growing season

Treatment		Rainfall (mm)	Irrigation (mm)	ΔTSW (mm)	Seasonal ETa (mm)	Daily ETa (mm/day)
LESA	D1	171.704	146.05	-181.1	498.9	3.35
	D2	171.704	146.05	-152.0	469.8	3.15
LEPA	D1	171.704	146.05	-148.0	465.7	3.13
	D2	171.704	146.05	-168.1	485.9	3.26
MDI1	D1	171.704	146.05	-182.8	500.5	3.36
	D2	171.704	146.05	-162.3	480.1	3.22
MDI2	D1	171.704	146.05	-171.9	489.6	3.29
	D2	171.704	146.05	-159.4	477.2	3.20
Rainfed	D1	171.704	0	-109.0	280.8	1.88
	D2	171.704	0	-121.7	293.5	1.97

D1: High density, D2: Low density

4.2.3 Total water, actual evapotranspiration, and irrigation water use efficiency under different irrigation technologies and rainfed treatments

The total water, crop evapotranspiration, and irrigation water use efficiency are presented in Table 4.2. The relationship between the CWUE and the yield is presented in Figure 4.3a. Overall, the CWUE varied from 0.19 kg m^{-3} in the high-density dryland to 0.30 kg m^{-3} in the high-density LEPA. The results also indicated that the CWUE in the low-density dryland (0.26 kg m^{-3}) was similar to the CWUE in the LESA and MDI2. The LEPA irrigation technology had the maximum averaged CWUE of 0.30 kg m^{-3} followed by the MDI1 with 0.29 kg m^{-3}, while the rainfed resulted in the lowest CWUE of 0.22 kg m^{-3}. Baker et al. (2015) reported that cotton lint yield increases linearly with crop water use. The different CWUE under the experimental conditions indicated that, while all the irrigation technologies provided the same amount of water to the ground, different amounts were available to the plants. This is the same line with Koudahe et al. (2021), who indicated that some irrigation technologies limit the water to the root zone, while others supply it to the all surface of soil. The results also indicated that CWUE increased linearly with the cotton lint yield with R^2 equal to 1.

The irrigation water use efficiency varied from 0.21 kg m^{-3} in the low-density MDI2 to 0.44 kg m^{-3} in the high-density LEPA with an average of 0.33 kg m^{-3} for all the irrigation technologies. The average IWUE of LESA, LEPA, MDI1, and MDI2 were, respectively, 0.30, 0.39, 0.36, and 0.28 kg m^{-3}. Among the irrigation technologies under the experimental conditions, LEPA had the maximum IWUE followed by the MDI1. There was a gradual increase of IWUE with the yield with R^2 of 0.66. Different IWUE values have been found around the globe, because it varies according to the climate, management practices, and genotypes. In Bornova-Izmir, Turkey, IWUE was found to vary from 0.48 to 0.65 kg m^{-3} (Anac et al. (1999). Yazar et al. (2002) reported IWUE values of 0.60–0.81 kg m^{-3} and 0.58-0.77 kg m^{-3} for drip-irrigation and LEPA, respectively.

Like CWUE, the high-density rainfed and the high-density LEPA had the lowest ETWUE of 0.12 kg m^{-3} and maximum ETWUE of 0.21 kg m^{-3}, respectively. Among the irrigation technologies, the ETWUE of LEPA was 18%, 8%, 22%, and 50% higher than the ETWUE of LESA, MDI1, MDI2, and rainfed, respectively. Also, the yield increased with increase in ETWUE, and the R^2 of the relationship was 0.85. The results also indicated a strong positive relationship between ETWUE and CWUE with R^2 equal to 0.92. An increase of evapotranspiration water use efficiency induced a rapid rise of total water use efficiency. This indicated the importance of evapotranspiration in cotton yield under the experimental conditions. In Texas and California, ETWUE varied from 0.15 kg m^{-3} to 0.33 kg m^{-3} (Evett et al. 2012). Grismer (2002) found in

Arizona and California that upland cotton ETWUE ranged from 0.127-0.138 and 0.134-0.210 kg m^{-3}, respectively, in 1999-2000.

Table 4.2 Irrigation, actual evapotranspiration (ETa), cotton lint yield, crop water use efficiency (CWUE), evapotranspiration water use efficiency (ETWUE) and irrigation water use efficiency (IWUE) of cotton lint under different irrigation technologies and rainfed conditions.

Treatment		Irrigation (mm)	ETa (mm)	Yield (kg ha^{-1})	CWUE (kg m^{-3})	ETWUE (kg m^{-3})	IWUE (kg m^{-3})
LESA	D1	146.05	498.9	821.6	0.26	0.16	0.34
	D2	146.05	469.8	815.8	0.26	0.17	0.25
LEPA	D1	146.05	465.7	968.1	0.30	0.21	0.44
	D2	146.05	485.9	932.6	0.29	0.19	0.33
MDI1	D1	146.05	500.5	916.7	0.29	0.18	0.41
	D2	146.05	480.1	898.7	0.28	0.19	0.31
MDI2	D1	146.05	489.6	827.0	0.26	0.17	0.34
	D2	146.05	477.2	755.5	0.24	0.16	0.21
Rainfed	D1	0	280.8	324.2	0.19	0.12	-
	D2	0	293.5	444.9	0.26	0.15	-

D1: High density, D2: Low density

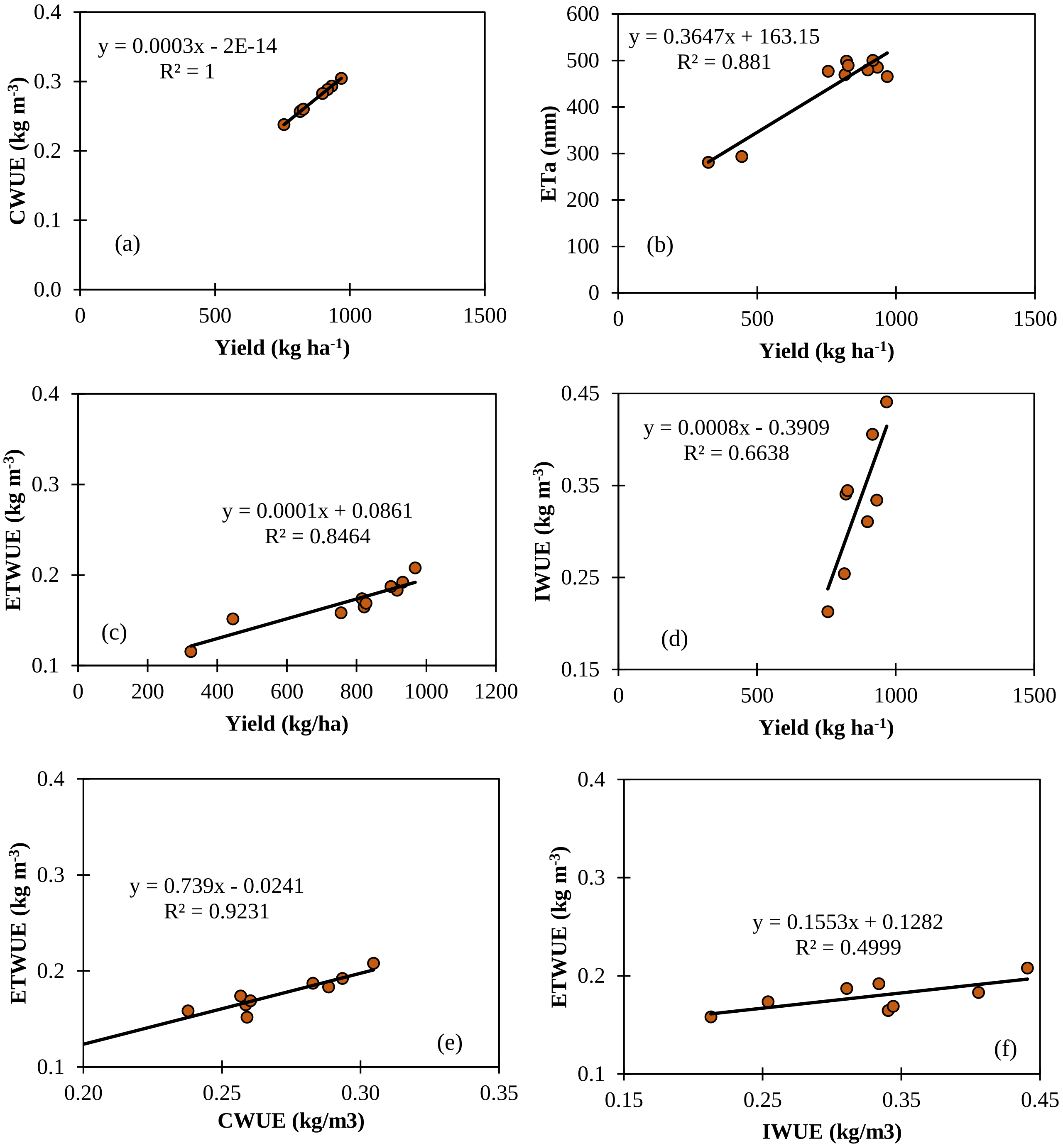


Figure 4.2 Relationship between cotton lint yield and (a) CWUE, (b) ETa, (c) ETWUE, (d) IWUE, between ETWUE and (e) CWUE, (f) IWUE

4.2.4 Locally developed grass-reference cotton crop coefficients

According to Fan et al. (2011) and Pereira et al. (2021), the Kc which is the ratio of actual crop evapotranspiration and reference evapotranspiration, is an essential parameter in irrigation scheduling. For efficient irrigation planning, it is important to develop a local Kc experimentally that characterizes local climate, water requirement, and cotton management practices (Koudahe et al. 2021). In this study, a local Kc curve was developed under different irrigation technologies and rainfed conditions. Seasonal distribution of Kc as function of days after planting is presented in Figure 4.3. The results indicated that the cotton Kc is function of the amount of water used by the crop. During the growing stages, the dryland treatment had the lowest Kc compared to the irrigated fields. The values for Kc for the rainfed conditions Kc were 0.18, 0.46 to 0.48, and 0.10 to 0.28 for initial, mid, and late season stages, respectively. The crop coefficient for all the irrigation technologies follows the same patterns during the growing season. The irrigated Kc was lowest for the emergence and greatest during the flowering and the boll formation stages. The Kc of the different irrigation technologies such as LEPA, LESA, MDI1, and MDI2 were similar. On average, the irrigated cotton crop coefficients were estimated at 0.35, 0.92 to 1.04, and 0.39 to 0.48 for initial, mid, and late season stages, respectively. The annual Kc for the entire growing season was 0.62.

The results of our study indicated that, for all the treatments, the Kc for initial stage stabilized and then increased rapidly during the development to attain the highest Kc in mid-season. It decreased later as the growing season advanced toward the late season. The same patterns of crop coefficients were found by Kumar et al. (2015) and Yang et al. (2016). According to the Food and Agricultural Organization (FAO) of the United Nations, 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 (Allen et al. 1998). Our results indicated that irrigated initial Kc is similar to the FAO initial Kc, while mid and late season Kc are lower than the FAO values by 15% and 4%, respectively. Koudahe et al. (2021) reported that cotton water use is overestimated when it is computed using FAO Kc values that are greater than the locally developed Kc values, and irrigation scheduling based on the high Kc values increases the cost of cotton production.

Over-irrigation decreases yields because the plant root system has less oxygen for respiration. Grismer (2002) found locally developed initial Kc to be similar with FAO estimates in the Sacramento and San Joaquin valleys, California, USA. According to the authors, the cotton mid and late season Kc were 1.15 and 0.87, respectively, which were higher than the Kc found under the experimental conditions in West Kansas. Many other studies found cotton crop coefficients locally developed to be different from the ones developed by the FAO, which are suggested to be used worldwide (Hunsaker 1999; Farahani et al. 2008; Bezerra et al. 2012). At Uvalde, Texas, USA, Ko et al. (2009) stated that cotton Kc increased from 0.40 at the initial stage to 1.25 in mid-season and decreased later to 0.60 towards the end of the season. In conclusion, our results indicated that the crop coefficients varied less among the irrigation technologies, while it varied more under contrasting climates and management practices.

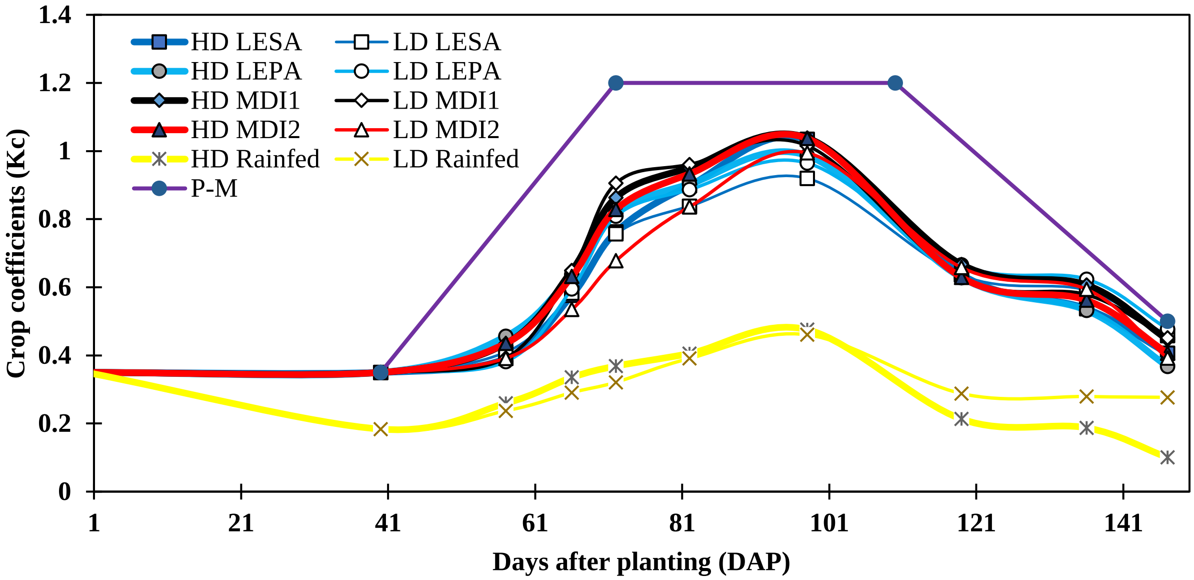


Figure 4.3 Grass-reference cotton crop coefficient (Kc) simulated using the two-step approach under different treatments during the growing seasons.

4.2.5 Comparison of the cotton ETa from soil water balance and two-step approach (ETa = ETo × Kc) using FAO adjusted Kc

The ETa estimated using the Kc × ETo using the FAO adjusted Kc values is presented in Table 4.3. The results indicated that from the irrigated to rainfed conditions there was a decrease of ETa. The same results have been found by Djaman et al. (2013), who reported a steady decrease in estimated ETa from the full irrigation to dryland plots in 2009 and 2010. A factor that may play a role in a difference between the soil water balance-estimated versus ETo × Kc approach-estimated ETa is the assessment of deep percolation, although it is difficult to estimate. Another important factor is the uncertainty in estimation the runoff as null, if the irrigation is well managed or as an average value of the whole field rather than computing a subfield value from the individual treatments.

The difference of the two ETa ranged 26% to 35% for the irrigated field averaging 30%, while for the rainfed treatments, it averaged 118%. Djaman et al. (2013) reported an overestimation of maize ETa using the two-step approach compared to soil water balance-estimated. Similarly, for non-stressed maize canopy, Irmak et al. (2008a) and Lopez-Urrea et al. (2006) reported overestimation of the two-step approach. Djaman et al. (2013) reported that the overestimation of the two-step approach can be explained by the uncertainty of the crop coefficients in the initial and the late stages, especially for the rainfed because the rainfed attained senescence earlier. Also, Irmak et al. (2008b) found that the poor performance of the FAO-56 could be attributed to the uncertainties of the crop coefficients developed by the FAO. The authors revealed sensible heat losses during the initial and late stages of season and suggested that Kc should be revised as function of the difference of the net available energy between reference and actual conditions of the field for the well irrigated treatments. The important difference of 118% for the rainfed and 30% for the irrigated fields is an indication that the two-step approach does not consider the water-limiting conditions effects on Kc in ETa estimation. Similar results were found by Djaman et al. (2013) with maize under deficit conditions. Furthermore, the difference between the two approaches of estimating ETa could be due to the fact that the FAO procedure fixes a certain value for the initial, mid, and late season, which is not true in reality because they are not constant under different management, climate, and soil conditions. Using eddy-covariance ETa and ETo to estimate the Kc, Payero and Irmak (2011) found a significant difference between the local Kc and the FAO Kc. The FAO Kc has a fixed number of days for each stage of the crop growth. In other words, FAO assigned a Kc value for the whole duration of the growth stage. However, there are newly developed hybrids that have different growing periods under different management practices that can significantly cause a bias in ETa estimation. In conclusion, there is a necessity to locally develop a crop coefficient under specific water, soil, and climate conditions for effective cotton production.

Table 4.3 Cotton ETa determined using the soil water balance and estimated from the two-step approach (ETa = ETo × Kc.adj.)

Treatment		ETa from water balance (mm)	ETa from ETo × Kc.adj. (mm)	Difference (%)
LEPA	D1	498.9	628.88	26
	D2	469.8	629.22	34
LESA	D1	465.7	629.13	35
	D2	485.9	629.19	29
MDI1	D1	500.5	629.74	26
	D2	480.1	628.97	31
MDI2	D1	489.6	629.88	29
	D2	477.2	629.95	32
Rainfed	D1	280.8	627.42	123
	D2	293.5	625.99	113

D1: High density, D2: Low density

4.3 Conclusions

Actual evapotranspiration, water use efficiency, and grass-reference crop coefficients of cotton under different irrigation technologies and rainfed conditions were assessed for Western Kansas. The results indicated that, under the experimental conditions, evaporation and transpiration caused a rapid decrease of the soil water content in the topsoil and cotton extracted water to 1.83 m depth. A soil water balance analysis showed that, of all irrigation technologies, cotton under MDI1 had the highest ETa of 490.3 mm, while the rainfed treatments had the lowest ETa of 287.1 mm. In terms of the impact of crop density, high-density plots registered a higher ETa of 447.1 mm compared to 441.3 mm for the low-density plots. The LEPA irrigation technology resulted in the highest CWUE of 0.30 kg m^{-3}; ETWUE had a value of 0.21 kg m^{-3}, and IWUE had a value of 0.44 kg m^{-3}. Irrigated cotton crop coefficients were estimated at 0.35, 0.92

to 1.04, and 0.39 to 0.48 for initial, mid, and late season stages, respectively. Under rainfed conditions, the crop coefficients were 0.18, 0.46 to 0.48, and 0.10 to 0.28 for the respective growth stages. Irrigated initial Kc was similar to the FAO initial Kc, while mid and late season Kc were lower than the FAO values by 15% and 4%, respectively. On average, the two-step approach overestimated cotton ETa by approximately 30% for irrigated fields and 118% for rainfed conditions. For optimum yield and resource use efficiency, our results indicated the importance of locally developed crop coefficients. Further studies of irrigation scheduling based on these locally developed crop coefficients under farmers' field conditions are important.

Chapter 5 - Summary and future research

5.1 Findings

This study investigated the effect of irrigation technology and plant density on cotton growth, yield, and yield components, and determined the actual evapotranspiration, water use efficiency, and grass-reference crop coefficients of cotton under different irrigation technologies and rainfed conditions for effective cotton production in the High Plains of Kansas.

- ▪ From the first specific objective, we concluded under the experimental conditions that:

- Mobile drip irrigation 2 (MDI2) had the highest growth characteristics such as plant height, leaf area index, and canopy cover, while the rainfed treatment registered the lowest growth performance.
- Crop growth parameters at flowering and boll development stage could help to predict the cotton lint yield.
- Differences in cotton lint yield among the irrigation technologies and rainfed conditions were statistically significant ($p<0.05$), and LEPA had the highest cotton lint yield (950.3 kg ha^{-1}).
- Low-density provided the optimum yield.

- ▪ From the second specific objective, the results indicated that:

- Cotton under the irrigation technology of MDI1 had the highest ETa of 490.3 mm, while the rainfed treatment had the lowest ETa of 287.1 mm.
- LEPA irrigation technology resulted in the highest CWUE, ETWUE, IWUE of 0.30, 0.21, and 0.44 kg m^{-3}, respectively.

- Irrigated cotton crop coefficients were estimated at 0.35, 0.92 to 1.04, and 0.39 to 0.48 for initial, mid, and late season stages, respectively.
- The two-step approach overestimated cotton ETa by approximately 30% for irrigated fields and 118% for rainfed conditions compared to the water balance approach.

5.2. Future research

Studies on the effect of irrigation technology and plant density on cotton growth, yield, yield components and water use efficiency are crucial to identify the best irrigation technology and optimum plant density for effective cotton production in the High Plains of Kansas. New and alternative drought resistant crops in the study area are being developed. They need to be studied to provide cotton producers, universities, crop management institutions, and crop consultants with important information for sustainable cotton production. The best irrigation technology and optimum density identified during this study should be conducted under the conditions of farmers' field. Because the cotton variety used in this experiment cannot sustain growth under rainfed conditions, other genotypes should be tested for rainfed production. Also, the local crop coefficients developed in this study should be tested in other experiments and under farmers' field conditions. We propose the development of local Kc in other regions in Kansas State. We suggest that other irrigation scheduling methods, such as those based on sensors and neutron probe readings, should be compared with the ETa based method using the locally developed crop coefficients. Testing different irrigation terminations will also be important to tell cotton farmers the time to stop irrigation during the growing period for optimum yield, yield components, and resource use efficiency. Another important irrigation water management strategy is deficit irrigation. We suggest that deficit irrigation studies under the irrigation technologies be conducted to identify the best irrigation strategies for maximum lint and seed yield.

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Appendix

Appendix A: Analysis of variance

```
  Y Column: 5) Yield (kg/ha)
  1st Factor: 1) Density
  2nd Factor: 2) IT
  Blocks: 3) Rep
Keep If:

Rows of data with missing values removed: 0
Rows which remain: 30

Source                     df   Type III SS       MS          F             P
------------------------ -------- ----------- ---------   --------- ----- ---
Blocks                      2   23064.45967  11532.23   0.7171674   .5016 ns
Main Effects
  Density                   1   30.24780101   30.247801   0.0018811 .9659 ns
  IT                        4   1217396.561   304349.14   18.926893 .0000 ***
Interaction
  Density x IT              4   31917.82896    7979.4572   0.4962272 .7387 ns
Error                      18  289444.4697     16080.248<-
------------------------ -------- ----------- ---------   --------- ----- ---
Total                      29  1561853.567

Model                      11  1272409.097     115673.55   7.1935179   .0001 ***

R^2 = SSmodel/SStotal = 0.81467886885
Root MSerror = sqrt(MSerror) = 126.807918993
Mean Y = 770.50361677
Coefficient of Variation = (Root MSerror) / abs(Mean Y) * 100% = 16.457797%

Compare Means
Factor: 1) Density
Test: LSD
Significance Level: 0.05
Variance: 16080.2483193
Degrees of Freedom: 18
Keep If:

n Means = 2
LSD 0.05 = 97.2804746633

 Rank Mean Name          Mean       n Non-significant ranges
----- --------- ------------- ------- ----------------------------------------
    1 HD        771.507738293      15 a
```

```
    2 LD        769.499495247      15 a
Compare Means
Factor: 2) IT
Test: LSD
Significance Level: 0.05
Variance: 16080.2483193
Degrees of Freedom: 18
Keep If:

n Means = 5
LSD 0.05 = 153.813935899

 Rank Mean Name          Mean       n Non-significant ranges
----- --------- ------------- ------- ----------------------------------------
    1 LEPA      950.347485867       6 a
    2 MDI1      907.673902067       6 ab
    3 LESA       818.70041975       6 ab
    4 MDI2      791.278900317       6  b
    5 RAINFED    384.51737585       6   c

Compare Means
Factor: 3) Rep
Test: LSD
Significance Level: 0.05
Variance: 16080.2483193
Degrees of Freedom: 18
Keep If:

n Means = 3
LSD 0.05 = 119.14376243

 Rank Mean Name          Mean       n Non-significant ranges
----- --------- ------------- ------- ----------------------------------------
    1 2          796.45885201      10 a
    2 3           782.9812011     10 a
    3 1           732.0707972     10 a
```