Evapotranspiration, fiber yield and quality, and water productivity of cotton (*Gossypium hirsutum* L.) under different irrigation technologies in a semiarid climate[1]

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Abstract: Cotton is a relatively new crop in southern Kansas, and its effective irrigation scheduling requires information on crop water requirement and water productivity in a given climatic condition. This study aimed to: (i) assess cotton crop actual evapotranspiration, irrigation water requirement, (ii) evaluate lint yield and quality, and (iii) determine the water productivity related to total water (irrigation and rainfall), irrigation, and evapotranspiration under different irrigation technologies and rainfed conditions in semi-arid climate of western Kansas. Field experiments were conducted in 2020, 2021, and 2022 at the Southwest Research and Extension Center (SWREC) in Garden City, KS, to evaluate cotton production under four irrigation technologies which were low elevation spray application (LESA), low energy precision application (LEPA), mobile drip irrigation 1 (MDI1 with 3.79 L/hour), mobile drip irrigation 2 (MDI2 with 7.57 L/hour) and a rainfed treatment under a randomized complete block design with the variety PHY 205 W3FE. Crop management was similar across all treatments for three growing seasons. The results showed that the seasonal actual evapotranspiration (ETa) varied among the irrigation technologies, the rainfed treatment, and years. On average, LESA recorded the highest ETa value of 463.9 mm and LEPA had the lowest ETa value of 457.2 mm. The lint yield and lint quality (micronaire, length, strength, uniformity, color grade) varied significantly among the irrigation technologies and the rainfed setting. The highest lint yield of 1061.94 kg ha^{-1} was obtained under LEPA, while the rainfed registered the lowest lint yield of 224.13 kg ha^{-1}. The irrigated cotton had a high value for lint quality parameters with the LEPA having the best lint quality. Furthermore, on average, LEPA recorded the highest evapotranspiration-water, total-water, and irrigation-water use efficiencies, and the values were 0.23, 0.33, and 0.39 kg m^{-3}, respectively. The cotton ETa and water productivity are valuable parameters for effective irrigation scheduling for cotton production under similar climate and soil conditions.
Keywords: Cotton, Lint yield and quality, Evapotranspiration, Water use efficiency.

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1. Introduction

Environmental variability, change in genotypes, and management practices across time have affected cotton (*Gossypium hirsutum* L.) crop water requirement, yield, and water productivity worldwide (Li et al. 2021, Anapalli et al. 2020, Yang et al., 2020). Cotton is an important natural textile fiber with the purest source of cellulose (Hsieh 2007) and a source of cotton seeds that provide edible oil and seed by-products (Hinze and Kohel 2012). Cotton oil contains a high number of antioxidants for maintaining good health and the seed byproducts are an input for animal feed (Hinze and Kohel 2012). The United States is ranked third among cotton producing countries worldwide (USDA 2022) with a total production of 4.34 million tons which amounts to one fifth of the world production in 2019 (Faostat 2022). 35% of the total cotton acreage is irrigated in the U.S. (Farahani and Munk 2012).

Effective irrigation scheduling requires information on crop water requirement and water productivity in a given climatic condition. A review by Koudahe et al. (2021) of the studies on cotton water requirements concluded that crop

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[1] This is the accepted version of the manuscript. Full published version can be found at Gao, J., Sheshukov, A.Y., Yen, H., White, M.J., 2017. Impacts of alternative climate information on hydrologic processes with SWAT: A comparison of NCDC, PRISM and NEXRAD datasets. CATENA 156, 353–364. https://doi.org/10.1016/j.catena.2017.04.010

evapotranspiration (ETc) of cotton varies with the genotype, climatic conditions, management practices, and irrigation techniques and rates. In northern Louisiana, Kumar et al. (2015) reported an average daily ETc in mid-season of 7.1 mm day^{-1} and 5.9 mm day^{-1} in 2010 and 2011, respectively. In Brazil under a semi-arid climate of the 2009 growing season, the minimum and maximum daily ETc were 3.7 mm day^{-1} and 9.6 mm day^{-1} (Bezerra et al. 2012). In Mississippi, USA, Anapalli et al. (2020) used the Eddy Covariance method to assess cotton ETc in a clay soil in 2017 and 2018. The authors reported that the daily ETc varied from 2.5 in May to 4 mm day^{-1} in September in 2017, while it ranged from 2.9 mm day^{-1} in May to 4.4 mm day^{-1} in August in 2018. On a seasonal basis, the cotton ETc was 367 mm and 439 mm for the respective years. In Bushland, Texas, USA, Howell et al. (2004) used a weighing lysimeter to evaluate the actual evapotranspiration of cotton in a clay loam soil and found that the ETc was 775 and 739 mm in 2000 and 2001, respectively, under full irrigation. Cotton lint yield and quality also vary across the world depending on the climatic zone, genotype, and management practices. Anapalli et al. (2020) reported cotton lint yield in Mississippi to be 1269 kg ha^{-1} and 1569 kg ha^{-1} in 2017 and 2018, respectively. In Texas, Howell et al. (2004) reported the yield of 1313 kg ha^{-1} in 2000 and 1022 kg ha^{-1} in 2001 under spray application. Colaizzi et al. (2005) reported lint yields of 1229, 1208, 1153, and 1150 kg ha^{-1} for mid-elevation spray application (MESA), low elevation spray application (LESA), low energy precision application (LEPA), and subsurface drip irrigation (SDI), respectively, in Bushland, Texas. At Darlington and Florence, SC, Holladay et al. (2021) assessed fifty cotton genotypes in 2018 and reported an average mean lint yield of 447 kg ha^{-1}. The genotypes Deltapine 1646B2XF and Bleak Hall had the maximum and the minimum lint yield of 1281 and 152 kg ha^{-1}, respectively. In Southeast USA, Whitaker et al. (2008) compared subsurface drip irrigation (SDI) and overhead sprinkler irrigation and found no lint yield difference. However, they mentioned that the two irrigation technologies had, on average, a 54% higher lint yield compared to the rainfed cotton.

Table 1: Summary of studies on cotton actual evapotranspiration and yield including year, location, and irrigation technology.

Study	Year	Locations	Climate	Irrigation technology	ETc (mm)		Yield (kg ha^{-1})
					Daily	Seasonally	
Kumar et al. (2015)	2010	Northern Louisiana	Humid	Furrow	7.1	-	1480
	2011				5.9	-	
Bezerra et al. 2012	2008	Brazil	Semi-arid	Sprinkler system	3.7 to 9.3	716	3448
	2009				3.7 to 9.6	754	3586
Anapalli et al. (2020)	2017	Mississippi, USA	Sub-tropical humid	Furrow	2.5 to 4	367	1269
	2018				2.9 to 4.4	439	1569
Howell et al. (2004)	2000	Bushland, Texas, USA	Subtropical	Spray application	-	775	1313
	2001				-	739	1022

Profitability of the cotton production system relates directly to the quality of cotton, such as fiber length, fiber strength, length uniformity, and micronaire. The cotton quality varies by weather, type and rates of irrigation, and crop rotation patterns (Sorensen et al. 2020; Yagmur et al. 2014; Witt et al. 2020; Zhang et al. 2016). Sorensen et al. (2020) reported that, among the irrigation technologies, the shallow subsurface drip irrigation (S3DI) recorded the highest lint quality with 1.13 inch (2.87 cm), 31.0 g tex^{-1}, 82.3%, for fiber length, fiber strength, and length uniformity, respectively, and the dryland operation had the maximum micronaire of 4.9. Holladay et al. (2021) indicated that the Pima genotypes are found to have a good fiber quality compared to the upland genotypes and the fiber quality increased in 2019 with optimum climatic conditions compared to the 2018 with severe weather conditions. However, Nilesh et al. (2015) revealed that among the irrigation technologies or rates, cotton quality did not vary significantly in India.

Water productivity related to total water (irrigation and rainfall), irrigation, and evapotranspiration is used worldwide as a factor to adjust cotton water use and optimize the lint yield. In West Texas, Snowden et al. (2013) reported total water use efficiency (WUE) of 0.33 and 0.22 kg m^{-3} in 2010 and 2011, respectively. In Bushland, Texas, WUE was 0.164, 0.143, 0.158, and 0.159 for MESA, LESA, LEPA, and SDI, respectively, in 2003 (Colaizzi et al. 2005). In the Harran Plain, Turkey, WUE under LEPA varied from 0.55 to 0.67, while under drip irrigation, it ranged from 0.50 to 0.74 kg m^{-3} (Yazar et al. 2002). Sorensen et al. (2020) recorded an irrigation water use efficiency (IWUE) of 140 lb $acre^{-1}$ $inch^{-1}$ (0.62 kg m^{-3}) for sprinkler, 105 lb $acre^{-1}$ $inch^{-1}$ (0.46 kg m^{-3}) for subsurface drip irrigation (SDI), and 143 lb $acre^{-1}$ $inch^{-1}$ (0.63 kg m^{-3}) for shallow subsurface drip irrigation (S3DI). In Texas, California, and Uzbekistan, evapotranspiration water use efficiency varied from 0.15 to 0.33 kg m^{-3} (Evett et al. 2012).

Table 2: Summary of studies on cotton water productivity including year, location, irrigation technology, and water use efficiency indexes.

Study	Year	Locations	Climate	Irrigation technology	Water productivity (kg m^{-3})	
					WUE	IWUE
Snowden et al. (2013)	2010 2011	West Texas	Semi- arid	SDI	0.33 0.22	-
Colaizzi et al. 2005	2003	Bushland, Texas	Semi- arid	MESA LESA LEPA SDI	0.164 0.143 0.158 0.159	-
Yazar et al. 2002	1999	Harran Plain, Turkey	semi-arid	LEPA Drip	0.55 to 0.67 0.50 to 0.74	-
Sorensen et al. (2020)	2001-2013	Shellman, GA	mild humid	sprinkler SDI Shallow SDI	-	0.62 0.46 0.63

In the central and southern parts of the United States where agriculture depends heavily on irrigation, many studies have revealed that the Ogallala aquifer, which the main source of irrigation water, is decreasing, and it might no longer support irrigation in the future (Ajaz et al. 2020; McGuire 2017; Luckey et al. 2000). Kramer and Boyer (1995) found water stress inhibited the development and production of the cotton plant. Even though cotton is known to be a drought resistant crop, it still needs irrigation during critical stages to optimize production. Therefore, it is important to provide information related to water management to cotton growers, consultants, and scientists for irrigation planning. This study aimed to: (i) assess the crop actual evapotranspiration and irrigation water requirement, (ii) evaluate cotton lint yield and quality, and (iii) determine the water productivity related to total water (irrigation and rainfall), irrigation, and evapotranspiration under different irrigation technologies and rainfed conditions in a semi-arid climate.

2. Data and Methods

2.1. Study area

The field experiment was conducted during growing seasons from 2020 to 2022 at the center-pivot field of 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), in Garden City, Kansas. The climate of the study area is semi-arid. The source of irrigation water is Ogallala aquifer. According to McGuire (2017), the Ogallala aquifer has been depleted in the last 70 years, and it may have insufficient water level to support irrigation in the future. The soil at the experiment site was classified as Ulysses silt loam (Stone et al. 2011). The field capacity of the study location is 0.30 cm^3 cm^{-3} and the permanent wilting point is 0.15 cm^3 cm^{-3}, as resulted from study area soil sample analysis by Ward Laboratories, Inc. (Kearney, Nebraska). The field was in no-till with fertilizer applications before and during the growing seasons. Cotton was in a two-year crop rotation system with corn.

2.2. Experiment design and crop management

The center-pivot system on the experimental field presented in Fig. 1 was set up with four types of irrigation technology, low energy precision application (LEPA), low elevation spray application (LESA), and two types of mobile drip irrigation (MDI1 with flow rate of 3.79 liters/hour and MDI2 with flow rate of 7.57 liters/hour). In addition, an area outside of the center-pivot field was used for three rainfed treatments of dryland cotton. A randomized complete block design with three replications was used to design plot areas of planted cotton using cotton variety PHY 205 W3FE (PhytoGen Seed Company, LLC, 9330 Zionsville Road, Indianapolis, IN 46268). The size of each plot was 6 m by 12 m. The three center (3) rows plants in the plot were harvested. The irrigation pivot at the experiment site had a total of four spans. The first span closest to the center was not used in the experiment. The spans 2, 3, and 4 represented the replications 1, 2 and 3. Figure 1 shows the layout of the experimental plots randomized for irrigation technology and replication.

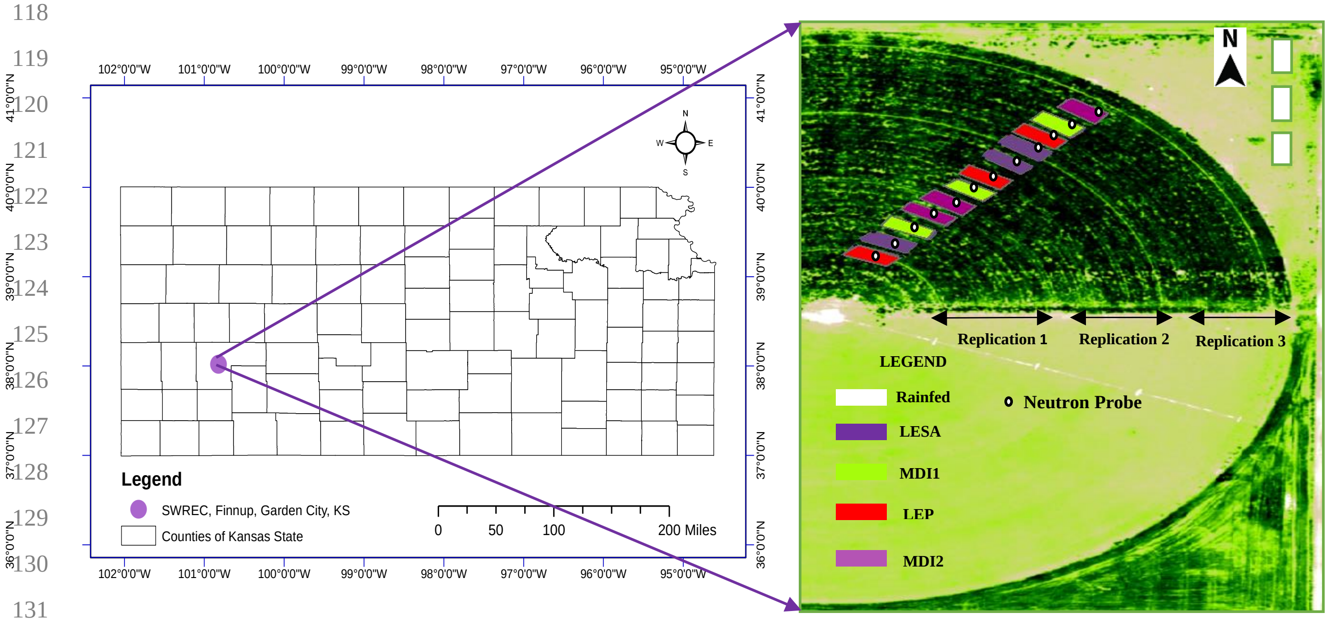


Figure 1: Presentation of study location at SWREC in Kansas State (purple dot on Kansas state map) and plot layout of the experimental design under the center pivot system

The experiment was conducted for three growing seasons of 2020, 2021, and 2022. The dates of cotton planting, seed emerging, and harvesting, cotton seed variety, and planting densities in 2020, 2021, and 2022 were listed in Table 1. For all growing seasons, corn was the previous years' crop. The cotton was planted using a John Deere 7200 six-row planter with 80-cm row spacing. At the beginning of each growing season, a sprinkler irrigation was applied with the same amount of water to bring the soil water content close to field capacity and to provide a uniform water distribution in the soil for better germination of the seeds. A 74.6 kW three-phase electrical pump (North American Electric Inc, model NAE-VHS-100-4, 350 Vaiden Dr, Hernando, MS 38632) was used to supply water to the center pivot system. For irrigation scheduling during the season, 25.4 mm (1 inch) of water was provided each week until boll filling stage, after which no water was applied through irrigation. Lack of applied water during the final growing stage stressed the crop and forced it to develop fiber in bolls instead of green biomass, which accelerated the maturity stage prior to the first frost.

In 2020, 112.08 kg/ha of dry urea (N P K 46-0-0) was applied. In 2021, the fertilizer application rates were 67.25 kg/ha of dry urea (N P K 46-0-0) and 93.54 kg/ha of N P K 10-34-0. An herbicide was used to keep the experimental location weed-free, and the cotton was harvested using a combine in 2020 and 2021, while in 2022, cotton was manually harvested.

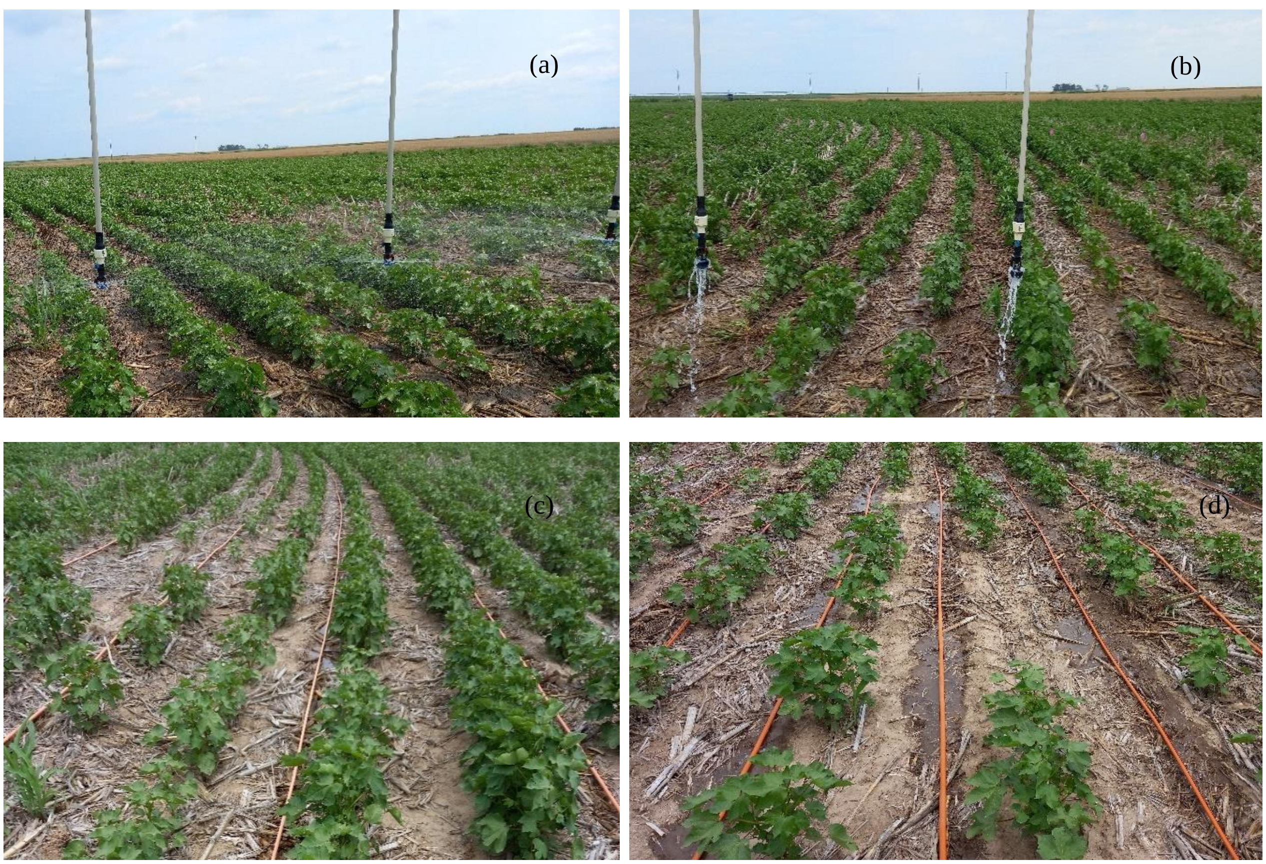


Figure 2: Cotton grown under four irrigation technologies (a) LESA, (b) LEPA, (c) MDI1, (d) MDI2

Table 3: Growth dates, variety, seeding rates in the three growing seasons

	Growth dates			Seed	
Year	Planted	Emerged	Harvested	Variety	Seeds per ha
2020	18-May	22-Jun	10-Dec	PHY 205 W3FE	161300
2021	24-May	11-Jun	8-Nov	PHY 205 W3FE	160600
2022	23-May	8-Jun	3-Nov	PHY 205 W3FE	148300

2.3. Data collection

A dataset of seven climate variables was downloaded for the period of the experiment on the daily time-step from the weather station in Garden City (ID: GCUK1; Latitude: 37.997, Longitude: -100.815, Elevation: 882) of the Kansas Mesonet network (http://mesonet.k-state.edu/). The variables were daily 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 irradiance (Rs).

A CPN 503 Depth Moisture Gauge (InstroTek Company, 4495, 44th St. SE Suite A, Grand Rapids, Michigan 49512) (Fig. 3) was used to measure soil water at 0.31-, 0.61-, 0.91-, 1.22-, 1.52-, 1.83-, 2.13-, and 2.44-m soil depths once a week during the growing season. Neutron probe access tubes were set up within a plant row representative of experimental plots. Volumetric water content θ obtained by the neutron probe was calibrated using the following equation:

$$\theta = CoefA * Count\ Ratio + CoefB \quad (1)$$

where $Count\ Ratio$ is ratio of relative to standard counts provided by the neutron probe reading, $CoefA = 0.212$, and $CoefB = -0.0197$. The calibration was obtained by cross-calibrating the neutron probe to an older probe which was calibrated with soil samples. Soil samples were collected at each 30 cm (or one foot) depths when tubes were installed from four representative plots. Samples were weighed immediately after collection for wet values. Neutron probe measurements were read immediately after the access tube was installed. Soil samples were oven dried for 24 hours at 105 ^{o}C to obtain dry mass values and volumetric water content was calculated. The obtained volumetric water content values from soil samples were plotted against $CountRatio$ obtained from the tube readings and $CoefA$ and $CoefB$ were derived from the regression analysis. These coefficients were then entered and stored in the neutron probe memory. The count duration was 15 sec.

The access tube used was 1-5/8 in. (outside diameter) x 0.035 in (wall thickness), wall Aluminum 6061 T6 Tubing. It was installed using Giddings hydraulic soil probe manufactured by Giddings Machine Company in Windsor, CO.

Fig. 3: Picture of a CPN 503 Depth Moisture Gauge set on top of the access tube

At the maturity, cotton was harvested, and the fiber yield was reported in kg ha^{-1}. The fiber samples were sent to Fiber and Biopolymer Research Institute, Texas Tech University, for fiber quality analysis and the results were reported as micronaire, fiber length, uniformity, fiber strength, fiber elongation, degree of reflectance, degree of yellowness.

2.4. Standardized reference evapotranspiration model

The Penman–Monteith (PM-ETo) equation (Equation 2) was used to obtain the daily grass-referenced evapotranspiration rate (Allen et al. 1998):

$$ET_o = \frac{0.408\Delta(Rn - G) + (\gamma CnU_2/(T + 273))(es - ea)}{\Delta + \gamma(1 + CdU_2)} \quad (2)$$

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

2.5. Thermal unit (TU)

Thermal unit (TU), also known as accumulative unit of growing degree days (GDDs), is an indicator of the cotton plant phenology. GDDs link crop phenological stages with air temperature change and can be used to determine the development stage of cotton crop (Anandhi 2016). GDD and TU are obtained using the following equations:

$$GDD = \frac{T_{max}^{*} + T_{min}^{*}}{2} - T_{base} \quad (3)$$

$$TU = \sum_{i=1}^{n} \left(\frac{T_{max}^{*} + T_{min}^{*}}{2} - T_{base} \right) \quad (4)$$

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

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

where T_{max} is daily maximum air temperature, T_{min} is daily minimum air temperature, T_{base} is the base temperature threshold for cotton (15.6 °C or 60 °F), T_{opt} is the optimal temperature (32.2 °C or 90 °F), and *n* is the number of growing days. The base temperature is the minimum air temperature at which plant growth begins, while optimal temperature indicates the upper threshold at which plant growth and development are restricted due to water uptake limitation of the root system (Wright et al. 2005). If air temperature is above or below the corresponding upper or lower thresholds, the optimal temperature is taken as maximum temperature and the base temperature is considered as minimum temperature. The TU values were taken as zero when the mean daily air temperature was less than the base temperature.

2.6. Actual evapotranspiration estimation (ETa)

A general soil water balance in a root zone soil system was used to estimate actual evapotranspiration ETa (mm) from the crop-soil system in each plot during a given time interval:

$$P + I + U = R + D + \Delta W + ETa \quad (5)$$

where P is effective rainfall (mm), I is applied irrigation water (mm), U is upward vertical soil moisture flux from below the root zone (mm), R is soil surface runoff (mm), ΔW is the change in soil moisture storage within the root zone (mm), and D is water permanently lost through deep percolation downward from the root zone (mm). Since the studied field had a minimal slope (Oker et al. 2021) and the rainfall and irrigation events were well managed within the field, surface runoff R and deep percolation losses D were assumed negligible. The upward flux below the root zone U was assumed to be zero because of the depth of the water table. The change in soil moisture was evaluated from interpolated neutron probe dataset at the eight depths. After solving Equation (5) for ETa, the actual evapotranspiration rate can be expressed as:

$$ETa = P + I - \Delta W \quad (6)$$

2.7. Gross returns of cotton lint

Fiber and Biopolymer Research Institute at Texas Tech University provided the lint loan estimates for each treatment. The gross return of the lint was computed by multiplying the lint yield by the loan value and was reported in dollar per ha. It represents the impact of the lint quality.

2.8. Crop water use efficiency

Crop water use efficiency is defined as a fraction of crop yield to crop water supply. Three water use efficiency coefficients were used in this study (all in kg m^{-3}) (Irmak et al. 2015, Djaman et al. 2012):

$$CWUE = \frac{Yield_{irr}}{Seasonal\ (\mathrm{P + I})} \quad (7)$$

$$ETWUE = \frac{Yield_{irr}}{Seasonal\ ETa} \quad (8)$$

$$IWUE = \frac{Yield_{irr} - Yield_{rainfed}}{Seasonal\ I} \quad (9)$$

where CWUE relates to total seasonal water supply through precipitation and irrigation, ETWUE relates to total seasonal evapotranspiration, and IWUE is based on the total seasonal irrigation. are in kg m^{-3}, yield in kg ha^{-1}. Total seasonal values (irrigation, precipitation, and actual evapotranspiration) were calculated as a sum of daily values throughout the season in mm.

2.9. Statistical analysis

The effects of irrigation technologies and rainfed conditions on cotton lint yield and quality including micronaire, length, strength, elongation, degree of reflectance, and yellowness were analyzed using the analysis of variance (ANOVA) in R program (Heumann et al. 2016). The means were separated with the least significant difference (LSD) at 5% significance level to identify any potential significant differences between the irrigation technologies and rainfed conditions.

A regression analysis was performed to develop the relationships between crop evapotranspiration and lint yield and quality, and between cotton lint yield and water productivity. The coefficient of determination R^2 was used to quantify the fitness of the relationships.

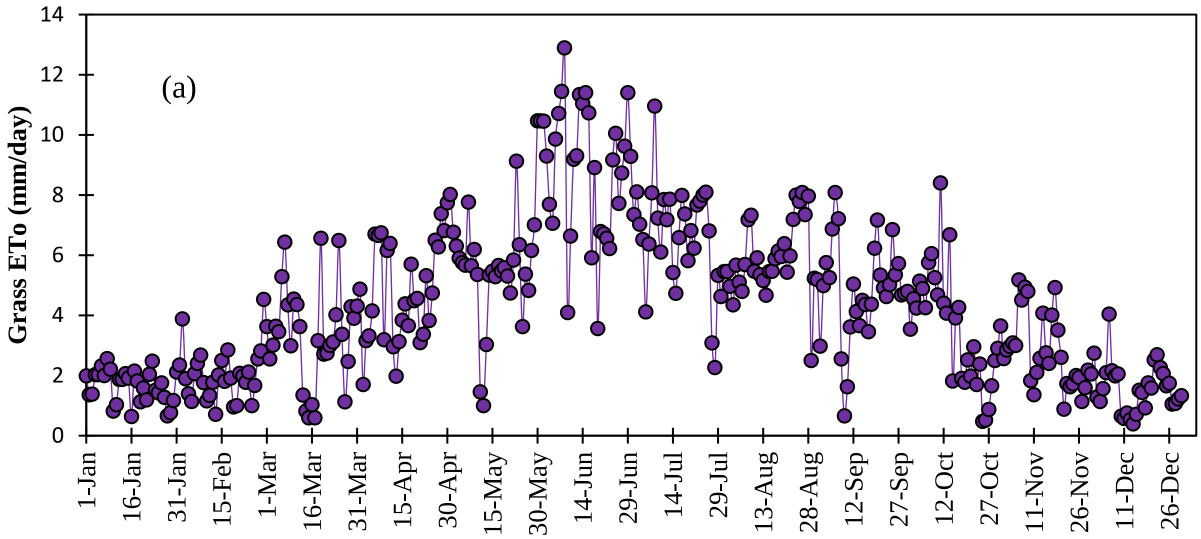
3. Results and Discussion

3.1. Thermal unit and weather conditions during the 2020, 2021, and 2022 growing seasons and average weather data

Monthly average climate variables for the 2020, 2021, and 2022 seasons and three-year average values are presented in Table 2. The 2022 growing season was the warmest with a mean temperature of 21.4°C which is 1.1°C higher than the mean temperature of 20.3°C in 2021 and 4.2°C higher than the mean temperature of 17.2°C in 2020. Cotton growth is temperature associated, and the warmer temperature affected the physiological maturity of the crop in 2022. The growing season length of 2022 was 4 days less than the 2021 growing season length of 169 days, and 42 days less than the 2020 growing season of 207 days. 2021 growing season length had 38 days less than 2020 growing season. This caused large differences in the cumulative TU between the three years. The results revealed that higher temperatures reduced the growing season length. The thermal unit, also called cumulative growing degree days (CGDD) is related to crop performance and lasts until freezing. The 2020, 2021, and 2022 freezing was obtained on October 23, October 15, and October 17, respectively. The number of days from planting to freezing was 159, 145, and 148 in 2020, 2021, and 2022, respectively. At the study field, desiccant was applied just before freezing and therefore, thermal unit was computed from the planting to freezing. TU depends on the duration of the period and the temperature recorded. The thermal unit in 2020, 2021, and 2022 were 1198.9, 1165.1, and 1205.9°C days, respectively. 2021 recorded the lowest TU because it had the lowest number of growing days till freezing. The highest TU recorded in 2022 can be explained by the high temperature obtained during the period under consideration. The three year results indicated that a minimum TU of 1165.1°C days is sufficient to growth cotton to maturation in the study area and similar environment.

Baumhardt et al. (2021) reported that the TU changes with the climatic conditions, latitude, and elevation. Several crop models include a GDD to mimic crop growth and development, and it is considered a critical parameter in yield prediction (Thorp et al. 2014). In Garden City, the thermal unit has been found to range from 753°C days to 1288°C days by Baumhardt et al. (2021). In Lubbock, Texas, the TU has been found to vary from 1092 to 1576°C days (Wanjura et al. 2002). At a cumulative GDD less than 800°C days, Gowda et al. (2007) showed crop development is affected. A high correlation between cotton fiber yields and GDD was reported by Wanjura et al. (2002). In the Texas High Plains, Peng et al. (1989) reported an approximate TU of 1450°C days and in Bushland, Texas, a TU less than 1130°C days was reported (Howell et al. 2004). Our study revealed that Garden City TU meets the cotton TU requirement for growth and development. It also shows that, in the study area, air temperature does not represent a risk for cotton growers.

On average, the seasonal mean relative humidity of 2021 was 8.3% higher than the mean relative humidity of 2020 growing season (57.5%), and 18.7% higher than the mean relative humidity of 2022 growing season (52.5%). The average wind speed during the growing season was 3.2, 2.9, and 3.8 m s^{-1} in 2020, 2021, and 2022, respectively. The average incoming solar radiation was 3.4% higher in 2021 than 2020, which was 17.9 MJ m^{-2}. 2021 solar irradiance was 0.5 MJ m^{-2} higher than 2022, which was 18.0 MJ m^{-2}. For the three years under study, June registered the highest incoming solar radiation in 2020 and 2021, while July had the highest value in 2022. The vapor pressure deficit (VPD) value in 2022 was 30.6% higher than the VPD in 2020 which was 1.485 KPa and 26.1% higher than the VPD in 2021 which was recorded as 1.537 KPa. Net solar radiation values in 2020, 2021, and 2022 were 9.0, 10.0, and 9.7 MJ m^{-2} day^{-1}, respectively, making 2021 net solar radiation 11.4% and 3.4% higher than the net solar radiation in 2020 and 2022, respectively. The dew temperature (Tdew) averaged 8.5, 12.5, and 10.9°C in the 2020, 2021, and 2022 growing seasons, respectively, making the 2021 Tdew value 47.9 and 14.7% higher compared to 2020 and 2022, respectively. All these climatic data impacted the reference evapotranspiration. The daily reference evapotranspiration (ETo) of 2020, 2021, and 2022 is presented in Fig. 2. The three-year reference evapotranspiration followed the same trend. The ETo increased from January to a maximum value in June and decreased thereafter to a minimum value in December. The minimum daily ETo values were 0.39, 0.37, and 0.46 mm obtained on 14 December 2020 and 9 January 2021, and 20 December 2022, respectively. The maximum daily ETo values were 12.89, 10.29, and 14.25 mm obtained on 8 June 2020, 16 June 2021, and 6 June 2022, respectively. The annual ETo of 2022 was 1714.06 mm which was 9% higher than the ETo value of 1572.89 mm in 2020, and 15.3% higher than the ETo value of 1486.41 mm recorded in 2021.


(a)
Grass ETo (mm/day)
0
2
4
6
8
10
12
14
1-Jan
16-Jan
31-Jan
15-Feb
1-Mar
16-Mar
31-Mar
15-Apr
30-Apr
15-May
30-May
14-Jun
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14-Jul
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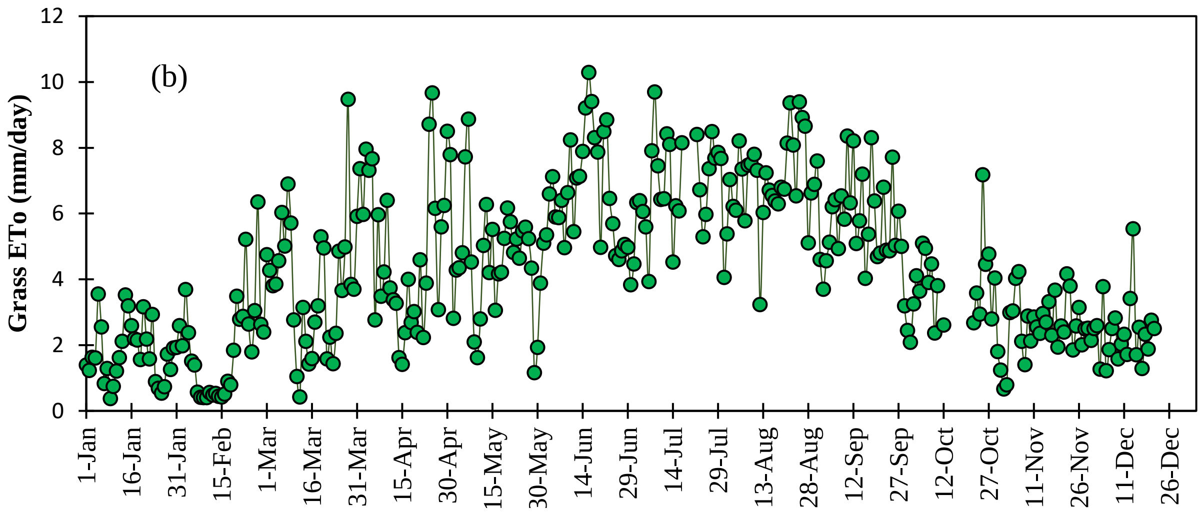
(b)
Grass ETo (mm/day)
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1-Jan
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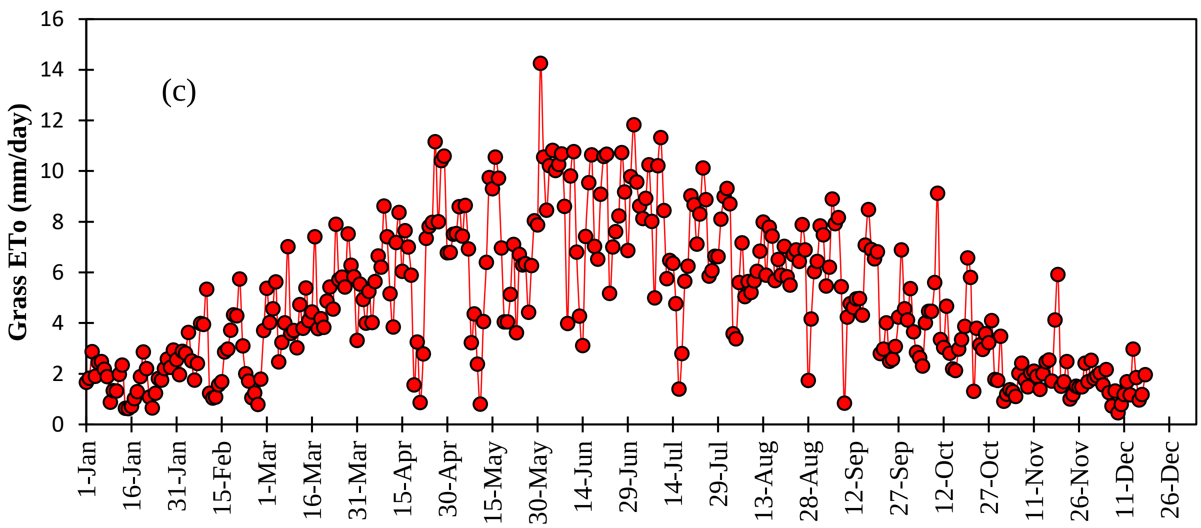
(c)
Grass ETo (mm/day)
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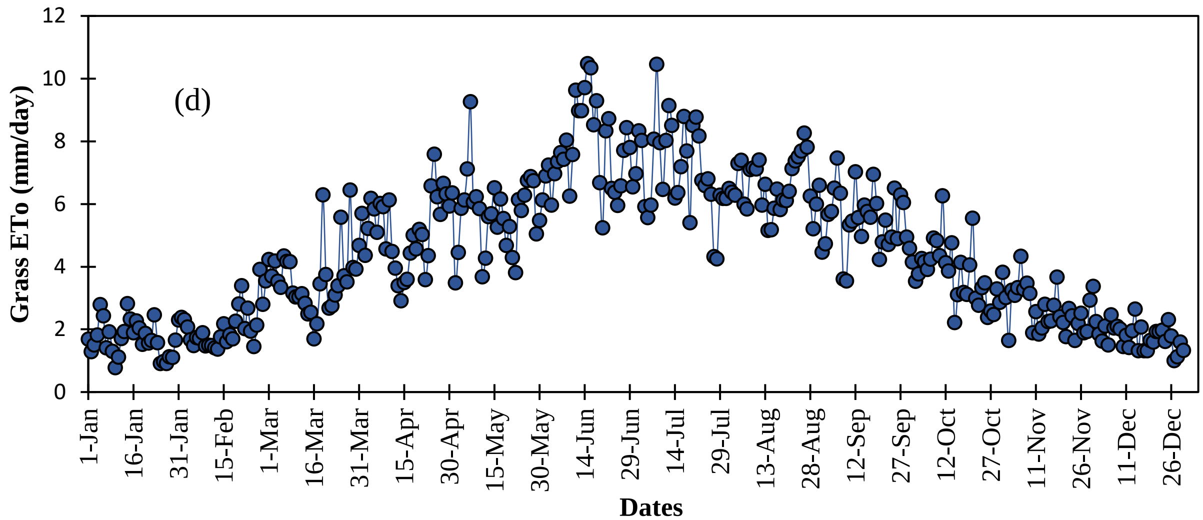


Fig. 4 Daily grass reference evapotranspiration in (a) 2020, (b) 2021, (c) 2022, and (d) average 2020-2022

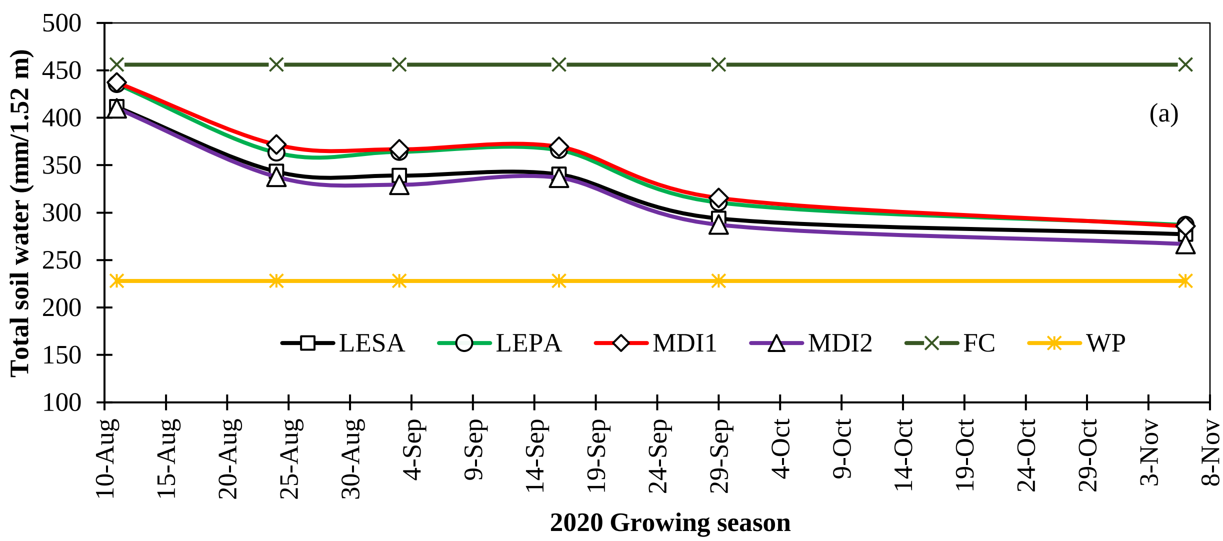
Table 4 : Average climatic conditions during 2020, 2021, and 2022 growing seasons of cotton, Garden City, Kansas. Tmax: maximum temperature; Tmin: minimum temperature; Tmean: mean temperature; RHmax: maximum relative humidity; RHmin: minimum relative humidity; RHmean: mean relative humidity; U_2: wind speed; Rs: solar irradiance; VPD: vapor pressure deficit; Rn: net radiation; Tdew: dew temperature.

Year	Month	Tmax (°C)	Tmin (°C)	Tmean (°C)	RHmax (%)	RHmin (%)	RHmean (%)	U_2 (m/s)	Rs (MJ/m2)	VPD (KPa)	Rn (MJ/m2/day)	Tdew (°C)
2020	May	28.3	10.8	19.5	88.4	30.1	59.2	3.7	23.2	1.5	13.3	11.2
	June	34.6	17.1	25.9	77.7	21.6	49.6	4.4	24.6	2.5	14.0	14.2
	July	33.3	18.5	25.9	93.2	37.0	65.1	3.2	22.8	1.8	13.8	18.8
	August	31.9	17.3	24.6	90.3	37.3	63.8	2.8	21.9	1.6	12.6	17.1
	September	27.8	10.4	19.1	87.3	29.3	58.3	2.8	17.7	1.6	8.7	10.3
	October	19.9	2.8	11.4	80.5	29.0	54.8	2.8	13.4	1.2	5.2	2.0
	November	17.7	-1.1	8.3	85.7	26.4	56.0	3.0	10.6	0.9	2.7	-0.2
	December	15.6	-9.3	3.2	82.0	24.6	53.3	2.4	9.3	0.8	1.6	-5.6
Seasonal average 2020		26.2	8.3	17.2	85.6	29.4	57.5	3.2	17.9	1.485	9.0	8.5
2021	May	23.4	12.0	17.7	98.0	52.7	75.4	3.5	18.7	0.8	11.6	13.2
	June	32.0	16.5	24.3	92.5	32.9	62.7	2.9	24.0	1.7	14.3	16.5
	July	34.0	18.0	26.0	93.1	31.9	62.5	2.9	23.3	1.9	13.9	18.2
	August	35.1	18.2	26.6	87.0	25.6	56.3	3.1	21.8	2.3	12.2	17.0
	September	31.8	14.4	23.1	83.9	25.9	54.9	3.0	18.7	2.0	9.3	13.2
	October	24.2	6.3	15.3	88.7	25.9	57.3	2.8	13.6	1.3	5.4	6.6
	November	16.6	1.4	9.0	94.1	40.2	67.1	2.4	9.7	0.8	3.4	2.9
Seasonal average 2021		28.2	12.4	20.3	91.0	33.6	62.3	2.9	18.5	1.537	10.0	12.5
2022	May	26.5	10.0	18.3	84.8	26.7	55.8	4.2	20.8	1.8	11.6	8.4
	June	32.3	16.8	24.5	81.3	25.2	53.2	3.8	22.7	2.2	13.2	14.0
	July	35.8	19.8	27.8	82.2	25.7	54.0	3.2	23.2	2.6	13.4	17.1
	August	34.8	17.5	26.2	85.3	23.5	54.4	2.8	22.4	2.3	12.3	16.1
	September	31.7	13.0	22.4	82.9	24.1	53.5	3.1	18.8	2.1	9.1	12.1
	October	23.7	4.2	13.9	74.5	19.4	46.9	2.7	14.4	1.4	5.2	2.5
	November	23.5	10.3	16.9	74.1	25.5	49.8	6.5	3.9	1.3	2.9	6.3
Seasonal average 2022		29.7	13.1	21.4	80.7	24.3	52.5	3.8	18.0	1.939	9.7	10.9
Seasonal average 2020-2022		28.0	11.3	19.6	85.8	29.1	57.4	3.3	18.2	1.7	9.6	10.6
Annual average 2020-2022		21.8	4.8	13.3	84.2	28.8	56.5	3.3	16.8	1.3	8.2	4.5

3.2. Soil water dynamics under different irrigation technologies and rainfed conditions

The distribution of measured soil moisture in the top 1.52 m soil depth under different irrigation technologies and the rainfed condition is presented in Fig. 3a, 3b, and 3c for 2020, 2021, and 2022, respectively. The soil water content varied with years, irrigation technologies, and rainfed conditions. The results indicated that the irrigation scheduling strategy kept soil water content between field capacity and the wilting point in 2020 and 2021, while in 2022, due to the drought, the soil measured water reached the wilting point.

The results indicated that, for all years, soil water decreased from emergence to boll development and filling. During this period, irrigation water was provided, and soil water was kept close to field capacity. Cotton water use reduced the water content in soil during that period. From the former stage to the late stage, the soil water decreased or became constant. The plants were under stress to force the plant to concentrate its energy in boll filling instead of producing new bolls that would not have the time necessary to mature. Before the water stress on the plant, the results indicated a slight difference in the water distribution among the irrigation technologies, which indicated that the water distribution was different under different applicators. This result confirmed the findings of Oker et al. (2020), who reported different irrigation efficiency with four irrigation applicators used in their research, because they result in various water distributions in the soil profile, in particular the effective root zone. How the water was applied among the irrigation technologies was not the same. MDI, which is known as an adapted drip irrigation system under center pivot irrigation, wets a small area of the soil surface, while LESA distributed water across the surface of the soil and had, then, a greater wetting area. In 2020 and 2021, the results indicated that, before water stress was applied, soil under MDI1 had a slightly higher moisture content compared to other irrigation technologies under the experimental conditions while in 2022, soil under LEPA recorded the highest soil water content. Between the three years, 2022 had the lowest soil water content with the dryland reaching 0.10 cm^3 cm^{-3} in June and July. Further, the difference in soil water content between the irrigated and rainfed treatments was evident. The soil water content in the dryland treatment was lower than the soil moisture in the irrigated fields. In summary, soil water varied little under the four irrigation technologies under the experimental conditions.



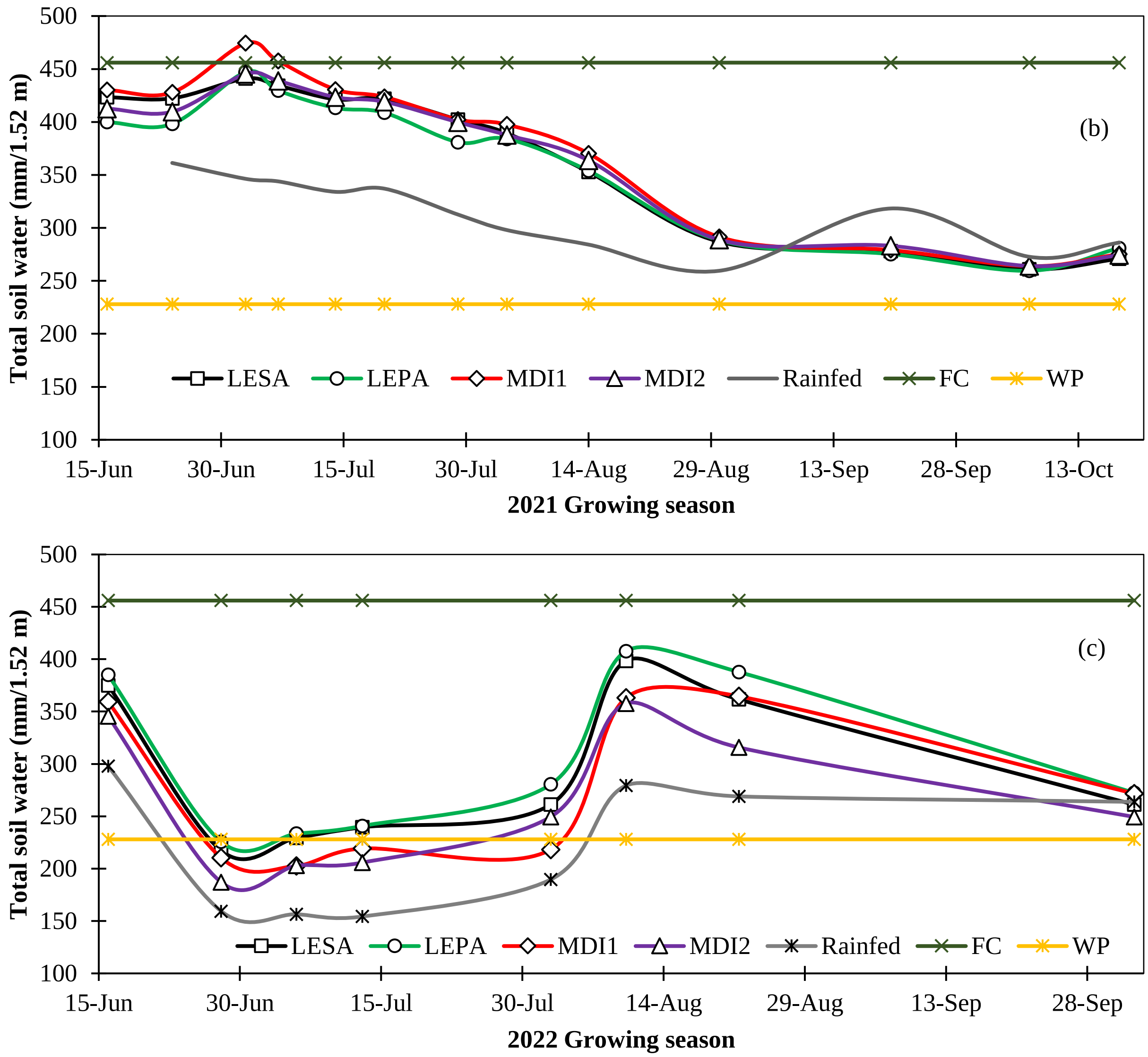


Fig. 5 Total soil water in the crop root zone (0-1.52 m) in growing seasons: (a) 2020; (b) 2021, (c) 2022

3.3. Cotton actual evapotranspiration in 2020, 2021, and 2022 growing seasons

Cotton seasonal ETa in 2020, 2021 and 2022 under different irrigation technologies and rainfed conditions are presented in Table 3. In 2020 the rainfall and the total irrigation amount were respectively 289.1 mm and 19.1 mm. The seasonal ETa varied among the irrigation technologies with the MDI1 having the highest ETa value of 459.6 mm followed by LEPA with 456.7 mm. The LESA recorded the lowest actual evapotranspiration with 442.3 mm. Similarly, on a daily basis, MDI1 and LESA recorded the maximum (3.33 mm day^{-1}) and minimum (3.21 mm day^{-1}) daily ETa, respectively. The 2021 growing season had less rainfall and a higher amount of irrigation water compared to 2020. Compared to 2020, rainfall decreased by 41% and in-season irrigation water increased by 665%. There were pre-irrigation events in 2020 with a total amount of 63.5 mm, while the 2021 recorded no pre-irrigation. During 2021, MDI1 had the highest seasonal ETa and the rainfed treatment had the lowest ETa. The daily ETa followed the same trend. On average, among the irrigation technologies, MDI1 had the maximum seasonal and daily ETa of 500.5 mm and 3.36 mm day^{-1}, respectively.

LEPA showed the lowest seasonal and daily ETa of 465.7 mm and 3.13 mm, respectively. The three-year average showed that LESA recorded the highest seasonal ETa of 463.9 mm. The lowest records were obtained under LEPA with a seasonal ETa of 457.2 mm.

Our results are in line with those of Anapalli et al. (2020), who found minimum and maximum daily ETa of 2.5 and 4 mm in 2017, and 2.9 mm and 4.4 mm in 2018, respectively. The authors also indicated that seasonal ETa were 367 mm and 439 mm for the 2017 and 2018 growing seasons, respectively. Similar results were found by Bezerra et al. (2012), who showed that cotton ETa ranged from 3.7 mm d^{-1} to 9.6 mm d^{-1} in a semi-arid climate. In the same way, in three regions of Hebei Province, Lui et al. (2013) reported a mean seasonal cotton water requirement of 619.1, 673.6, and 651.4 mm. However, other authors have reported higher cotton actual evapotranspiration (Grismer et al. 2002, Kumar et al. 2015, Howell et al. 2004). Kumar et al. (2015) found daily mid-season ETa of 7.1 and 5.9 mm d^{-1} in 2010 and 2011, respectively. Howell et al. (2004) reported high actual evapotranspiration of 775 mm and 739 in 2000 and 2001, respectively, using a weighing lysimeter in Texas under sprinkler irrigation. In St. Joseph, Texas, Ko et al. (2009) found in 2006 and 2009 an ETa of 830 and 689 mm, respectively, using sprinkler irrigation. In Syria, Farahani et al. (2008) recorded in 2006 a cotton water use of 813 mm. Cotton ETa is crucial for irrigation scheduling, and many studies have found different results across the globe, because it depends on length of the growing season, varieties, irrigation technologies, and local climate conditions.

Table 5: Rainfall, seasonal irrigation, change in total soil water between the initial and end of season (ΔTSW), seasonal and daily actual evapotranspiration (ETa), for all treatments in the 2020 2021, and 2022 growing seasons

Treatment		Rainfall	Irrigation	ΔTSW	Seasonal ETa	Daily ETa
		(mm)	(mm)	(mm)	(mm)	(mm/day)
2020	LESA	289.1	19.1	-134.2	442.3	3.21
	LEPA	289.1	19.1	-148.6	456.7	3.31
	MDI1	289.1	19.1	-151.5	459.6	3.33
	MDI2	289.1	19.1	-143.1	451.2	3.27
2021	LESA	171.7	146.1	-181.1	498.9	3.35
	LEPA	171.7	146.1	-148.0	465.7	3.13
	MDI1	171.7	146.1	-182.8	500.5	3.36
	MDI2	171.7	146.1	-171.9	489.6	3.29
	RAINFED	171.7	-	-109.0	280.7	1.88
2022	LESA	82.6	254.0	-114.0	450.5	3.82
	LEPA	82.6	254.0	-112.6	449.1	3.81
	MDI1	82.6	254.0	-87.7	424.3	3.60
	MDI2	82.6	254.0	-96.1	432.6	3.67
	RAINFED	82.6	-	-34.1	116.6	0.99
Average 2020-2022	LESA	181.1	139.7	-143.1	463.9	3.46
	LEPA	181.1	139.7	-136.4	457.2	3.42
	MDI1	181.1	139.7	-140.7	461.5	3.43
	MDI2	181.1	139.7	-137.0	457.8	3.41
Average irrigation technologies		181.1	139.7	-139.3	460.1	3.4
Average rainfed		127.2	-	-71.6	198.7	1.43

3.4. Variation of fiber yield, quality, and gross return under different irrigation technologies

The variation of the average lint yield and quality of 2020, 2021, and 2022 among irrigation technologies and the rainfed conditions is presented in Table 4. Lint yield varied at the 5% significance level between the irrigation technologies and the rainfed conditions. LEPA recorded the highest lint yield of 1061.94 kg ha^{-1}, followed by MDI2 with 1007.19 kg ha^{-1}, while the rainfed registered the lowest cotton lint yield of 224.13 kg ha^{-1}. Among the irrigation technologies, the variation of the lint yield was not statistically significant at the 5% significance level and LESA had the lowest yield of 965.55 kg ha^{-1}.

Colaizzi et al. (2004) found in Bushland, Texas, that lint yield increased with LEPA irrigation technology under full irrigation. In the same way, LEPA had a better performance than sprinkler and furrow irrigation systems (Lyle and Bordovsky 1983). However, other studies found drip irrigation to provide a greater lint yield (Segarra et al. 1999, Bordovsky 2019). No significant lint yield difference was found between SDI and overhead sprinkler irrigation by Whitaker et al. (2008), who further reported that the yield from the two irrigation technologies were 54% higher than the rainfed lint yield. In Mississippi, furrow irrigation resulted in a higher lint yield of 1569 kg ha^{-1} compared to the lint yield obtained under our experimental conditions (Whitaker et al. 2008). Our results confirm the findings of Sui et al. (2017), who reported that irrigation improves the lint yield.

The quality of cotton lint is an important component in cotton cropping systems because it determines the profitability of the production system. Many factors have been found to affect the quality of the cotton lint, such as genotype, climate, soil, irrigation technology, and quantity of irrigation water (Ramey 1986; Tokatlidis et al. 2008; Yagmur et al. 2014; Sorensen et al. 2020). Cotton quality is determined by measuring key parameters, such as micronaire, length, strength, elongation, degree of the reflectance, and yellowness of the lint.

The micronaire is a measure of fiber fineness and maturity. A micronaire value that is too high or too low represents a problem for the textile industry. Cotton buyers and textile manufacturers prefer a micronaire range of 3.5 to 4.9 (Hake et al. 1990), and cotton outside of this range may receive deductions. Under the experimental conditions in Garden City, KS, results indicated that the micronaire varied significantly between the irrigation technologies and the rainfed condition. The rainfed treatment recorded the highest micronaire of 4.09, and MDI2 had the lowest micronaire of 3. Studies have revealed that high micronaire ratings can be associated with drought or water stress (Sorensen et al. 2020; Hu et al. 2018). Under water limiting conditions, a cotton plant sheds the upper bolls early in the season leaving the bottom bolls. Consequently, carbohydrates will concentrate in the few bolls resulting in a high micronaire. Among dryland, S3DI, SDI, and sprinkler treatments, Sorensen et al. (2020) found that the dryland treatment had a maximum micronaire of 4.9. Further, Dagdelen et al. (2009) reported that micronaire decreases if soil water increases, and Hu et al. (2018) showed that micronaire increases under severe drought stress. However, Basal et al. (2009) found that micronaire under a limited water treatment had no consistent trend among the genotypes and across the years. In summary, water content affects the micronaire, and it is necessary to find the optimum irrigation rate that can provide farmers the optimum micronaire for a base or premium cotton lint range.

According to Bajpai (2018), the fiber length is the average length of fibers inside the pulp, and largely depends on the cultivar. However, many studies have reported that exposure of the plant to high temperatures above optimal, deficit water, or lack of nutrients may lead to shorter fibers (Yagmur et al. 2014; Gao et al. 2020). The results indicated that lint length varied significantly among the irrigation technologies and rainfed conditions, with MDI2 and the rainfed treatment having the highest and the lowest length values of 27.54 mm and 23.88 mm, respectively. However, among the irrigation technologies, there was no significant variation of the lint length. Our results confirm that variation of lint yield is based on the water status. Similarly, Gao et al. (2020), Meredith and Bridge (1973), and Wang et al. (2016) found that drought reduces lint length. However, Liu et al. (2022) discovered that overirrigation of cotton affected cotton quality by decreasing the lint length. Luo et al. (2008) stipulated that cotton lint length increases under moderate-drought conditions. This calls for a need to search for the optimum irrigation rates or strategies for long lint length to maximize farmer's profits.

According to the USDA (2018), the fiber strength (grams per tex) is the force in grams needed to break one tex fiber. The lint strength is variety dependent, but the weather and nutrients can also affect this parameter. The lint is very strong if the strength is 31 g tex^{-1} and above, while it is average if the strength is from 26 to 28 g tex^{-1}. Under the experimental conditions, the fiber strength varied significantly between the irrigation technologies and the rainfed treatment. MDI2 had the maximum strength of 30.32 g tex^{-1}, and the rainfed treatment had the minimum strength of 25.38 g tex^{-1}. Based on the USDA classification, all the irrigation technologies recorded a strong lint while the dryland had an average strength. Among the irrigation applicators, there was no significant difference. Colaizzi et al. (2004) reported that MESA, LESA, LEPA, and SDI had fiber strength values of 30.3, 30.0, 30.8, and 30.6 g tex^{-1}, respectively. However, Sorensen et al. (2020) found no significant variation of the lint strength among dryland, S3DI, SDI, and sprinkler treatments. Under a center pivot system, lint strength did not vary at the 5% level of significance among full, reduced, and no irrigation treatments (Masasi et al. 2020).

The degree of reflectance and yellowness determines the color grade of the cotton lint. Reflectance shows the brightness or dullness, and yellowness implies the extent of pigmentation (USDA 2018). A high value of reflectance shows brightness, while a small value of the yellowness indicates lower pigmentation. In this study, the degree of reflectance varied significantly between the irrigation technologies and the dryland treatment. The degree of reflectance varied from 72.73 in the dryland treatment to 76.66 with LEPA, while yellowness varied from 9.69 with LESA to 10.28 in the dryland treatment. LEPA was found to induce slightly high color grade.

The three-year average indicated that the gross return varied significantly at 5% level between the treatments under study. It ranged from 141.5 US dollar on dryland to 1010 US dollar in LEPA irrigation treatment.

In summary, LEPA irrigation technology had the highest lint yield and gross return, and the dryland treatment recorded the lowest lint yield and gross return. The irrigated cotton had a high value for quality parameters with LEPA having the best quality. The dryland treatment had the lowest cotton quality for all parameters except micronaire. Our study confirms the findings of many studies, which showed that irrigation systems and rates influence lint quality, specifically the lint length, strength, and color grade (Pettigrew 2004; Witt et al. 2020; Feng et al. 2014; Zhang et al. 2016).

Table 6: Variation in cotton lint yield, quality, and gross return between irrigation technologies and rainfed conditions*

Irrigation technology		Lint yield	Fiber quality							Gross return
			Micronaire	Fiber length	Fiber uniformity	Fiber strength	Fiber Elongation	Degree of reflectance	Degree of yellowness	
		kg/ha	-	mm		g/tex	%	-	-	$/ha
2020	LESA	1029.6a	2.1a	28.3a	78.9a	28.9a	6.0a	76.1a	9.7a	806.8a
	LEPA	1142.3a	2.2a	28.5a	80.1a	29.9a	6.2a	75.1a	10.1a	895.2a
	MDI1	942.1a	2.1a	28.8a	79.6a	29.9a	6.1a	75.1a	10.0a	749.0a
	MDI2	1008.2a	2.1a	28.5a	79.6a	29.7a	6.0a	74.6a	10.4a	743.5a
2021	LESA	821.6a	4.0a	27.1a	82.4a	32.2a	5.8a	73.6a	10.1b	892.9a
	LEPA	968.1a	4.1a	26.9a	82.7a	32.2a	5.9a	74.6a	9.7b	1108.9a
	MDI1	916.7a	4.0a	27.0a	82.1a	32.3a	5.9a	74.6a	9.9b	1045.0a
	MDI2	827.0a	3.8a	27.1a	82.9a	32.4a	5.8a	73.5a	10.6ab	892.9a
	RAINFED	324.2b	4.1a	25.9b	80.2b	27.9b	6.0a	72.4a	11.3a	307.8b
2022	LESA	1045.5a	3.0b	26.7a	80.8a	28.1a	6.2a	80.2a	9.3ab	1030.2a
	LEPA	1075.5a	2.9b	26.6a	81.3a	28.0a	6.1a	80.3a	9.4ab	1025.8a
	MDI1	1075.4a	2.9b	26.8a	81.5a	28.1a	6.1a	79.9a	9.6a	1024.4a
	MDI2	1186.3a	3.1b	27.1a	81.0a	28.9a	6.1a	80.4a	9.0b	1227.0a
	RAINFED	124.1b	4.1a	21.9b	75.1b	22.9b	6.4a	79.1a	9.3ab	116.9b
Average	LESA	965.55a	3.01b	27.36a	80.7b	29.73a	6.01b	76.63a	9.69b	910.0a
	LEPA	1061.94a	3.06b	27.35a	81.4a	30.02a	6.06ab	76.66a	9.72b	1010.0a
	MDI1	978.05a	3.01b	27.53a	81.1ab	30.10a	6.03ab	76.51a	9.84b	939.5a
	MDI2	1007.19a	3.00b	27.54a	81.2ab	30.32a	5.99b	76.14a	10.01ab	954.5a
	RAINFED	224.13b	4.09a	23.88b	77.7c	25.38b	6.18a	75.73b	10.28a	141.5b

* Values followed by the same letter are not significantly different at the 5% level.

3.5. Effect of crop evapotranspiration on lint yield and quality

Various biotic and abiotic factors are reported to affect cotton lint yield and quality across the world. In this study, we report the relationship between crop evapotranspiration and lint yield and quality (Fig. 4). The three-year data indicated a strong second order polynomial relationship with R^2 of 0.74 between the lint yield and the cotton crop evapotranspiration. The results indicated that the lint yield increased with ETa and attained an optimal value. A further increase of ETa resulted in a decline of lint yield. Tolk and Howell (2010) reported that lint yield and crop evapotranspiration were linearly related each year in Pullman and Ulysses soils. For an Amarillo soil, the authors found that they were significantly related ($P < 0.01$) in 2005 and 2007, while in 2006, there was a weak relationship ($P = 0.07$). A positive linear relationship was found by Tennakoon and Milroy (2003) and Orgaz et al. (1992) between lint yield and ETa, up to around 700 mm, in Australia and Spain, respectively. At this ETa, the correlation stagnated. After 700 mm, Orgaz et al. (1992) reported that some varieties showed a curvilinear relationship between the ETa and lint yield. Howell et al. (2004) reported that, for one year, the relationship between lint yield and ETa was linear. They further found that it was curvilinear for the next year in Bushland, Texas. In addition, a curvilinear correlation was found by Basal et al. (2009). Further, Howell et al. (1984) reported yield of cotton lint to be directly related to crop evapotranspiration, although the correlation was a little non-linear. A negative correlation between the ETa and lint yield was reported by Karam et al. (2006). In California and Arizona, Grismer (2002) found a weak relationship between yield and ETa.

The relationships between lint yield and the cotton quality parameters, such as micronaire, fiber length and strength, degree of reflectance, and yellowness are presented in Fig. 4. Fiber length is strongly correlated with cotton ETa by a second order polynomial with an R^2 of 0.74 based on the data from 2020 to 2022. An increase of ETa to an optimal value might induce a long fiber, and any further increase of ETa would reduce the length.

The pooled data indicated that the fiber strength is strongly correlated with the crop ETa by a second degree polynomial function with an R^2 of 0.83. Strong cotton fiber is reported to have 31 g tex^{-1} and above (USDA 2018), and our results indicated that an ETa around 500 mm yielded a strong lint, as requested by the industry and the market. Under the experimental conditions, lower ETa resulted in lower fiber strength.

The relationships between the degree of reflectance and ETa, and between the degree of yellowness and ETa were found to be low, indicating that the crop ETa has low impact in fiber degree of reflectance and yellowness. A greater value of reflectance shows a good cotton lint, while a lower value of yellowness indicates a good quality of the lint. Overall, cotton ETa was found to affect the lint yield and some quality parameters. More studies are needed to find the tradeoff between crop evapotranspiration and yield and quality of the lint for maximum farmers' profit.

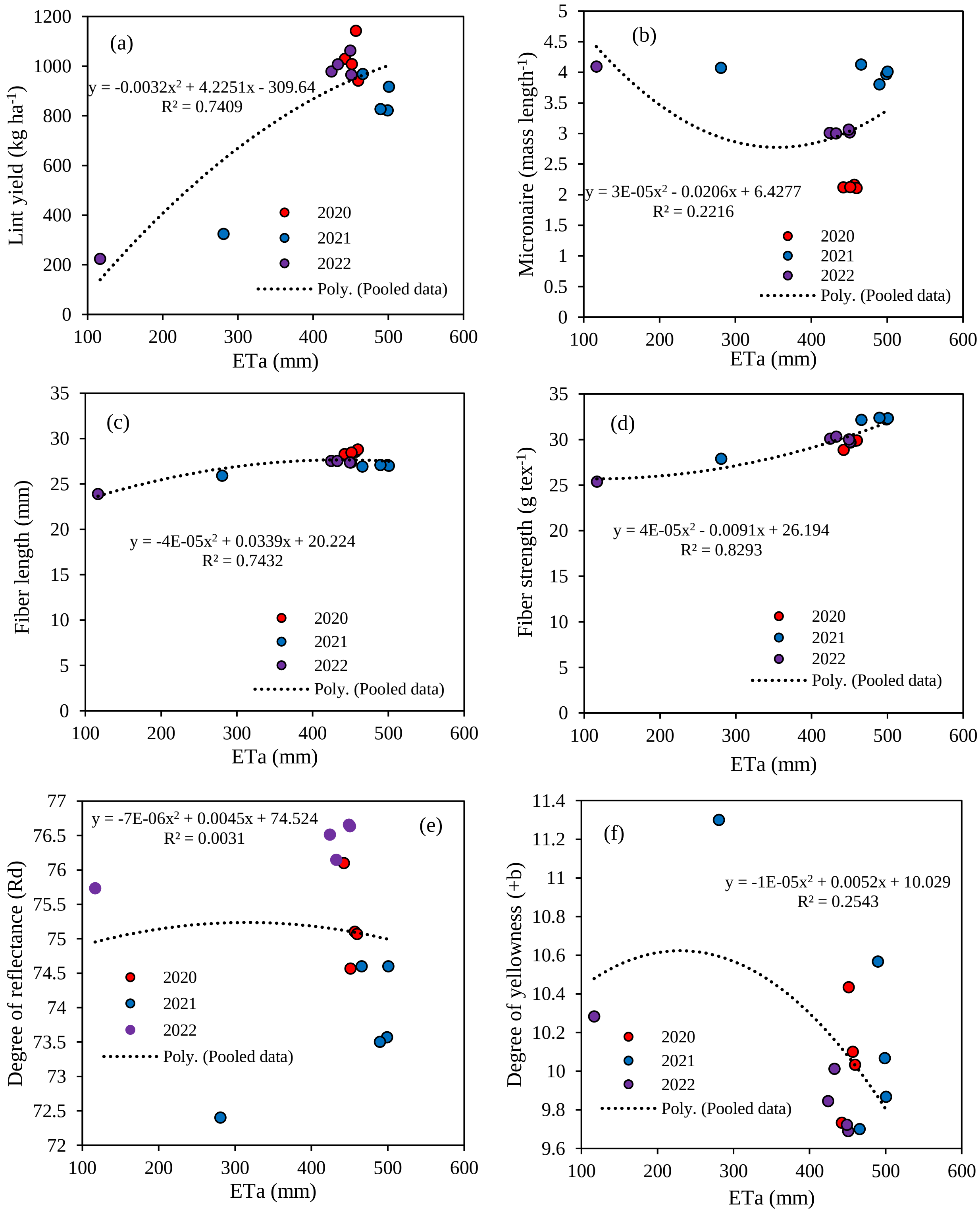


Fig. 6 Relationship between crop evapotranspiration and lint yield and quality under the experimental conditions

3.6. Water productivity

ETWUE varied with irrigation technologies, rainfed conditions, and years. Among the irrigation technologies, ETWUE ranged from 0.20 to 0.25 kg m^{-3} in 2020 and from 0.16 to 0.21 kg m^{-3} in 2021, and from 0.21 to 0.24 kg m^{-3} (Table 5). For the three growing seasons, LEPA recorded the highest ETWUE, and the lowest value was obtained by MDI1 in 2020 and LESA in 2021 and 2022. On average ETWUE varied from 0.20-0.23 kg m^{-3}, among the irrigation technologies, and the overall ETWUE for irrigated fields was 0.21 kg m^{-3}. Between the treatments, the highest ETWUE, on average, was achieved by LEPA, while the dryland recorded the lowest value. The IWUE varied among the irrigation technologies. In 2021, LEPA achieved the highest IWUE of 0.44 kg m^{-3} and MDI2 and LESA recorded the lowest value of 0.34 kg m^{-3}. Like 2021 results, LEPA had the highest IWUE of 0.33 kg m^{-3}, while LESA obtained the lowest value of 0.29 kg m^{-3} in 2022. Cotton under LEPA was found to efficiently use the irrigation water.. Similar to ETWUE and IWUE, CWUE was found to vary among the irrigation technologies, rainfed treatment, and years. The results indicated that among the irrigation technologies, it ranged from 0.31 to 0.37 kg m^{-3} in 2020, from 0.26 to 0.30 kg m^{-3} in 2021, and from 0.29 to 0.32 kg m^{-3} in 2022. The rainfed treatment registered 0.19 and 0.27 kg m^{-3} in 2021 and 2022, respectively. On a three-year average, LEPA recorded the highest CWUE with 0.33 kg m^{-3}.

Similar to our results, ETWUE was found to vary from 0.15 to 0.33 kg m^{-3} (Evett et al. 2012). Grismer (2002) reported similar ETWUEs ranging from 0.134 to 0.210 kg m^{-3} in California, USA. The authors showed small values for upland cotton ETWUE, and they ranged from 0.127 to 0.138 kg m^{-3} in Arizona, USA. Oweis et al. (2011) reported mean ETWUE for lintseed (lint + seed) of 0.36 kg m^{-3}. Management practices that reduce evaporation and increase transpiration might improve the ETWUE by reducing water stress on plant in critical growth stages. Higher irrigation water use efficiency was found in other studies (Anac et al. 1999, Ertek and Kanber 2001). IWUE ranged from 0.48 to 0.65 kg m^{-3} in Bornova-Izmir, Turkey, which is characterized by a Mediterranean climate (Anac et al. 1999). IWUE values were found to vary from 0.75 to 0.94 kg m^{-3} (Ertek and Kanber 2001), and Yazar et al. (2002) reported that, under LEPA, the IWUE ranged from 0.58–0.77 kg m^{-3}. Similar to our findings, the total water use efficiency value was 0.33 kg m^{-3} in West Texas in 2010 (Snowden et al. 2013). Colaizzi et al. (2005) reported a low WUE of 0.164 kg m^{-3} for MESA, 0.143 kg m^{-3} for LESA, 0.158 kg m^{-3} for LEPA, and 0.159 kg m^{-3} for SDI. Low WUE might be caused by many factors, such as the genotype, climate, and management practices. Site-specific experiments are required to find the best factors for optimum WUE. In summary, among the irrigation technologies, LEPA recorded the highest ETWUE, IWUE, and CWUE.

Table 7: Irrigation-water, evapotranspiration-water, and total-water use efficiency in 2020, 2021, and 2022 growing seasons

Year	Treatment	IWUE (Kg m^{-3})	ETWUE (Kg m^{-3})	CWUE (Kg m^{-3})
2020	LESA	-	0.23	0.33
	LEPA	-	0.25	0.37
	MDI1	-	0.20	0.31
	MDI2	-	0.22	0.33
2021	LESA	0.34	0.16	0.26
	LEPA	0.44	0.21	0.30

	MDI1	0.41	0.18	0.29
	MDI2	0.34	0.17	0.26
	RAINFED	-	0.12	0.19
2022	LESA	0.29	0.21	0.29
	LEPA	0.33	0.24	0.32
	MDI1	0.30	0.23	0.29
	MDI2	0.31	0.23	0.30
	RAINFED	-	0.19	0.27
Average	LESA	0.32	0.20	0.29
	LEPA	0.39	0.23	0.33
	MDI1	0.35	0.21	0.29
	MDI2	0.33	0.21	0.30
	RAINFED	-	0.15	0.23

The relationships between lint yield and ETWUE, lint yield and CWUE in different irrigation technologies are presented in Fig. 5. The results indicated a positive linear relationship between lint yield and ETWUE and between lint yield and CWUE with an R^2 of 0.91 and 0.85, respectively. Lint yield increased linearly with ETWUE and CWUE values. ETWUE and CWUE are known as a ratio of lint yield and the ETa and total water, respectively. Any increase in the yield will result in an increase of ETWUE and CWUE.

The relationships between ETWUE and ETa, CWUE and ETa in different irrigation technologies are presented in Fig. 6. Under the experimental conditions, ETWUE and ETa have a negative linear relationship as well as CWUE and ETa. The former relationship has a coefficient of determination of 0.73, while the latter relationship has a coefficient of determination of 0.22. ETWUE and CWUE increase to an optimum value with a given optimum ETa and decrease for further increase in ETa. In conclusion, an optimum ETa for a variety in a given climatic condition might be important to manage water for optimum yield.

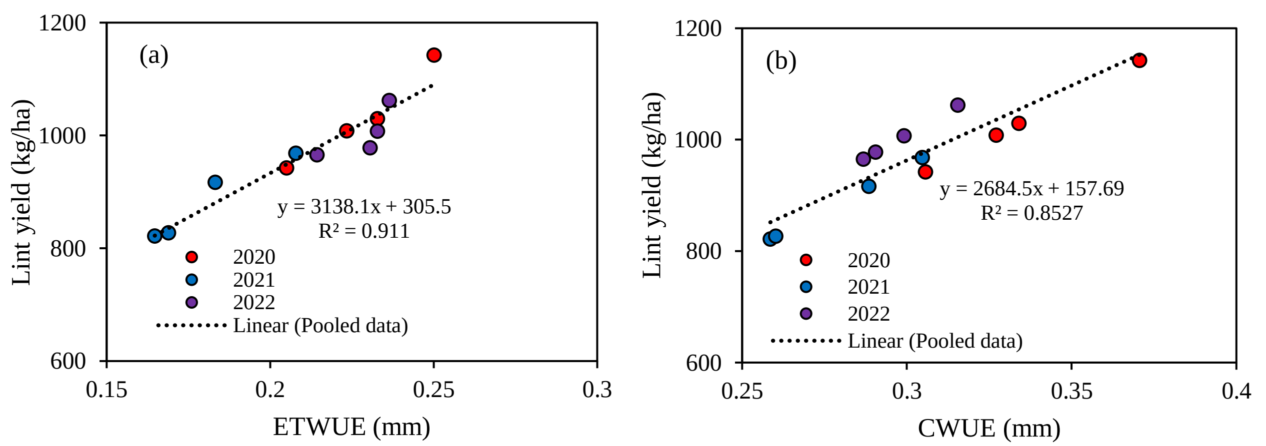


Fig. 7 Relationship between (a) lint yield and ETWUE, (b) lint yield and CWUE

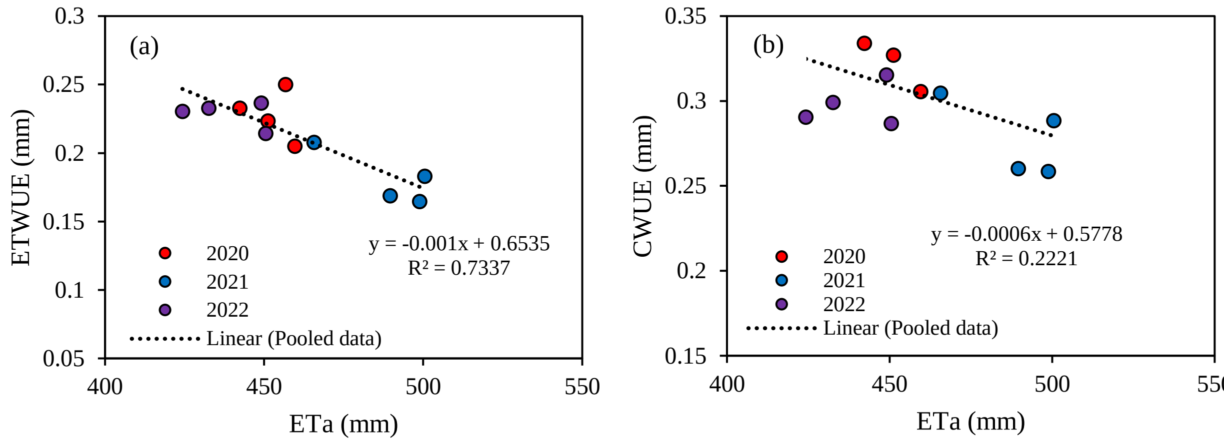


Fig. 8 Relationship between (a) ETWUE and ETa, (b) CWUE and ETa

Conclusions

The High Plains Aquifer has been depleting over the last several decades due to partially unsustainable water removal for agriculture. For efficient irrigated agriculture, applied water must meet the crop requirement, which depends on climate, genotype, and management practices. In this study, we assessed crop evapotranspiration, lint yield and quality, and determined water productivity under different irrigation technologies and dryland conditions. Results indicated that crop water requirements depend on irrigation technologies, rainfed conditions, and climate of individual years. On average, among the irrigation technologies, LESA and LEPA recorded the highest and the lowest crop evapotranspiration, respectively, and the highest and lowest irrigation water requirement, respectively. Lint yield and lint quality (micronaire, length, strength, degree of reflectance) varied at the 5% level of significance between the irrigation technologies and the rainfed setting. On average, LEPA recorded the highest lint yield of 1061.94 kg ha^{-1}, while the rainfed treatment had the lowest lint yield of 224.13 kg ha^{-1}. Irrigated cotton had the best lint quality compared to rainfed. Among the irrigation technologies, LEPA recorded the highest irrigation water use efficiency, evapotranspiration water use efficiency, and total water use efficiency. Further studies are needed to develop crop coefficients for local cotton varieties. Studying limited irrigation approaches will contribute to better water-saving strategies. This research is of the utmost importance for cotton growers, researchers, extension agents, and consultants for sustainable irrigated agriculture.

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