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Radiation, water, and nitrogen use efficiencies of *Gossypium hirsutum* L.

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Abstract: Resource use efficiency is a baseline for productive agriculture and proper management of different resources (water, nitrogen, light, and land), and it plays a pivotal role in the accomplishment of this goal. Three field experiments were carried out at the experimental farm area of the Central Cotton Research Institute, Multan, Pakistan, in 2009 and 2010 to investigate the effects of different resources on cotton crops. Treatments for the first experiment included 4 cultivars and 6 nitrogen levels. The second experiment comprised 3 variables, irrigation methods, cultivars, and plant spacing, whereas 2 variables, including different irrigation regimes and glycinebetaine application, were used in the third experiment. Different attributes, such as physiological efficiency, irrigation water use efficiency, and agronomic and economic nitrogen use efficiency, were studied during the course of experimentation. The statistical results revealed that cumulative intercepted photosynthetically active radiation, radiation use efficiencies, water use efficiencies for total biomass, seed cotton, lint, and cottonseed yield were enhanced with the addition of each incremental dose of nitrogen fertilizer and were also recorded as higher for the application of irrigation water through the drip method at the narrow plant spacing of 10 cm. Furthermore, exogenously applied glycinebetaine also significantly increased the attributes studied. Different agronomic and economic nitrogen use efficiencies for seed cotton, lint, and cottonseed yield were notably increased with the application of different nitrogen fertilizer levels and were greater at 160 kg N ha^{-1}.

Key words: *Gossypium hirsutum* L., glycinebetaine, irrigation regimes, nitrogen use efficiency, radiation use efficiency, water use efficiency

1. Introduction

Proper management of agro-based resources is a major baseline for precision agriculture (Lambin and Meyfroidt, 2011). In Pakistan, cotton (*Gossypium hirsutum* L.) is a widely cultivated fiber crop with limited available resources, namely selection of low-graded cultivars, imbalanced nutrient application, inadequate irrigation water supply, and so on, which contributes towards lower per capita yield production (Bibi et al., 2011; Ahmad and Raza, 2014; Ahmad et al., 2014). Among the different resources, nitrogen is an important plant nutrient required in larger quantities by the cotton crop to enhance its productivity (Hallikeri et al., 2010; Ibrahim et al., 2010; Rashidi et al., 2011, Alitabar et al., 2012; Ahmad et al., 2014). Nitrogen nutrition plays a significant role in recording greater radiation use efficiency for total dry matter as well as for seed cotton yield (Wajid et al., 2010; Iqbal et al., 2012). Nitrogen use efficiency refers to the recovery of the nitrogen fertilizer by the crop plants and is usually expressed in percentage (Parr, 1973). Nitrogen fertilizer imparts a positive and linear impact on agronomic and economic nitrogen use efficiencies (Ahmad et al., 2009). The limited availability of irrigation water is a major threat for potential crop yield, especially under the conditions of extremely high temperature during the hot summer in the region. Irrespective of the traditional furrow irrigation methods practiced by the large farming community in the region, there is a dire need to adopt new advanced technology in the form of irrigation water supply through the drip method, especially in view of upcoming water scarcity. Per capita production can be increased by increasing the water use efficiency of crop plants, which generally refers to the total biomass production of the plants with respect to efficient consumption of irrigation

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water in plant metabolism. Drip irrigation usually accounts for uniform water application, which has contributed to harnessing greater water use efficiency compared to the furrow irrigation method (DeTar et al., 1999; Khalifa, 2006, Ibragimov et al., 2007). It is also adaptable to a variety of topographical and soil conditions (Cetin and Bilgel, 2002). Different irrigation regimes showed greater variations of radiation use efficiency for total dry matter and seed cotton yield (Rosenthal and Gerik, 1991; Maqsood et al., 2006). In addition, cotton grown with narrow plant density is helpful for better irrigation water utilization (Nicholos et al., 2004; Larson et al., 2005). Another important resource that can contribute towards higher crop productivity is glycinebetaine application, as it is mostly absorbed by the plant leaves and plays a proactive role under conditions of drought stress (Naidu et al., 1998; Mahmood et al., 2009; Shallan et al., 2012). There is a scarcity of literature regarding radiation, water, and nitrogen use efficiencies of cotton; previous studies researched the combined effects of plant density, N fertilizer, irrigation, and glycinebetaine application. The main focus of our study was to draw the relationships between different attributes in order to discover the optimum combinations of the existing available resources for profitable cotton production under the irrigated environmental conditions of the Southern Punjab.

2. Materials and methods

Field experiments were carried out at the Agronomic Research Area of the Central Cotton Research Institute, Multan (30°12′N, 71°28′E; 123 m a.s.l.) using acid-delinted seed of improved cotton cultivars sown on a fragile seedbed and prepared by deep plowing, followed by planking with a tractor-driven implement during the cropping seasons of 2009 and 2010 (Ahmad and Raza, 2014; Ahmad et al., 2014). The features of the site include a relatively hot summer (45 ± 2 °C) and mild winter (8.0–14.0 °C) (Figure 1). The treatments for experiment 1 included 4 cotton cultivars (CIM-496, CIM-557, CIM-573, and CIM-588) and 6 nitrogen fertilizer levels (control, 40, 80,

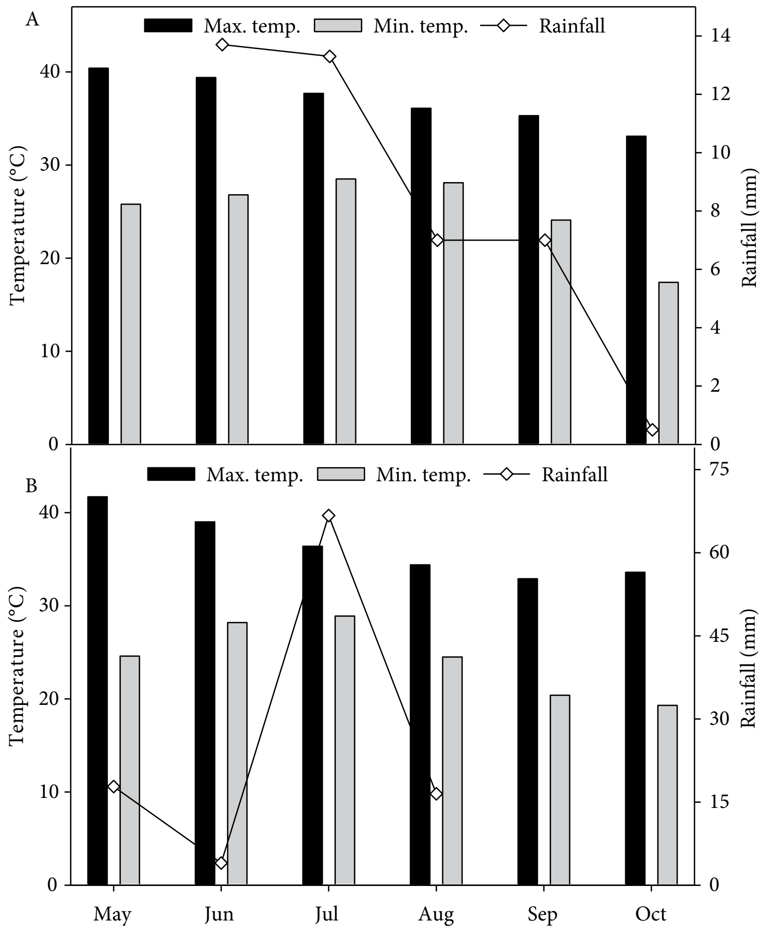

Figure 1. Monthly mean weather data during both crop seasons (A: 2009, B: 2010).

120, 160, and 200 kg of N ha^{-1}) (Ahmad and Raza, 2014). The experiment was laid out in a split plot design with 4 replications. Experiment 2 included 3 factors, namely 2 irrigation methods (drip and furrow), 2 cultivars (CIM-496 and CIM-557), and 3 plant spacings (S_1 = 10 cm, S_2 = 20 cm, and S_3 = 30 cm) (Ahmad and Raza, 2014). Split plot design was used and was replicated 4 times. Experiment 3 comprised 2 factors, namely 2 irrigation regimes (no water stress and water stress) and glycinebetaine application (foliar spray and untreated control) arranged in a split plot design with 4 replications (Ahmad et al., 2014). Nitrogen application was made in 3 splits, whereas phosphorous and potash were applied at the time of sowing. Irrigation was applied through cut throat flume in the case of the traditional furrow method, whereas one lateral with drippers spaced at 40 cm was used to irrigate 2 rows of the crop with a discharge of 2 L/h according to the drip irrigation method. In experiment 3, the crop without water stress was given 2945 m^3 of water, whereas the water-stressed crop received 1917 m^3 of irrigation water (Table 1). Furthermore, glycinebetaine was sprayed at a rate of 3 kg ha^{-1} after 30, 45, and 60 days of sowing. Other agronomic cultural practices (hoeing, plant protection measures, etc.) were applied according to crop requirements.

2.1. Estimation of physiological efficiency

Cumulative intercepted photosynthetically active radiation (CIPAR) was calculated according to the formula of Szeicz (1974) and accounts for 50% of total incident radiation. CIPAR (Sa) = fraction of radiation intercepted (Fi) × daily incident PAR (S_i), where Fi was calculated as suggested by the exponential equation of Monteith and Elston (1983): $F_i = 1 - \exp(-k \times LAI)$. The radiation use efficiency (RUE) was calculated as RUE_{TDM} = TDM/ΣSa; RUE_{SCY} = Seed cotton/ΣSa; RUE_{CSY} = Cottonseed/ΣSa, and RUE_{LY} = Lint/ΣSa.

2.2. Estimation of water use and water use efficiency

Cumulative crop evapotranspiration was calculated according to the formula suggested by Doorenboss and Pruitt (1977) CCET = PET × K_C, where CCET is cumulative crop evapotranspiration, PET is potential evapotranspiration, and K_C is crop coefficient. A standard CROPWAT package by the FAO (1992) was used to determine daily Penman's potential evapotranspiration. Water use efficiency was recorded according to the following formulas: WUE_{TDM} = TDM/CCET; WUE_{SCY} = Seed cotton/CCET; WUE_{CSY} = Cottonseed/CCET, and WUE_{LY} = Lint/CCET, expressed in kg ha^{-1} mm^{-1}.

2.3. Estimation of nitrogen use efficiency

The agronomic nitrogen use efficiency was calculated according to the formulas suggested by Barbar (1976), Saleem (1994), and Yadav (2003): $ANUE_{SC}$ = Seed cotton (F) – Seed cotton (C) / rate of N applied; $ANUE_{CS}$ = Cottonseed (F) – Cottonseed (C) / rate of N applied, and $ANUE_L$ = Lint yield (F) – Lint yield (C) / rate of N applied. Economic nitrogen use efficiency was estimated according to the formulas suggested by Barbar (1976), Saleem (1994), and Yadav (2003):$ENUE_{SC}$ = Seed cotton (F) – Seed cotton (C) / value of N applied; $ENUE_{CS}$ = Cottonseed (F) – Cottonseed (C) / value of N applied, and $ENUE_L$ = Lint yield (F) – Lint yield (C) / value of N applied.

2.4. Statistical procedures

Field experiment data were analyzed using MSTAT-C standard statistical software. The least significance differences (LSD values at 0.05 and 0.01 probability levels) were used to test the treatments and means significance (Steel et al., 1996).

3. Results and discussion

3.1. Physiological efficiency

Physiological efficiencies for total dry matter, seed cotton, lint, and cottonseed yield were significantly affected by varying nitrogen levels, irrigation regimes, planting geometry, and exogenously applied glycinebetaine (Tables 2–4). Statistically significant variations were noticed for various cultivars and nitrogen fertilizer levels. Among the cultivars, CIM-573 recorded maximum CIPAR (1248 MJ m^{-2}), whereas minimum CIPAR (1108 MJ m^{-2}) was seen for CIM-496. Linear and quadratic equations for

Table 1. Irrigation water applied in experiments 1 and 2.

Irrigation methods	Water applied (mm)		Water savings (%)	
	2009/10	2010/11	2009/10	2010/11
Furrow method	932.74	922.59	-	-
Drip method	701.59	685.84	32.9	34.5
Irrigation regimes	Water use (m^3)			
Water stress	1917			
No water stress	2945			

Table 2. Physiological efficiency as affected by different cultivars and nitrogen levels.

Treatments	CIPAR ($MJ\ m^{-2}$)	RUE_{TDM} ($MJ\ m^{-1}$)	RUE_{SCY} ($MJ\ m^{-1}$)	RUE_{LY} ($MJ\ m^{-1}$)	RUE_{CSY} ($MJ\ m^{-1}$)
A) Cultivar					
CIM-496	1108 d	0.802 c	0.202 c	0.080 d	0.121 b
CIM-557	1205 b	0.869 b	0.239 b	0.100 b	0.139 a
CIM-573	1248 a	0.921 a	0.258 a	0.112 a	0.146 a
CIM-588	1157 c	0.814 c	0.216 c	0.088 c	0.128 b
LSD (5%)	17.07	0.051	0.013	0.005	0.007
Significance	**	**	**	**	**
Linear	NS	*	NS	NS	NS
Quadratic	**	**	**	**	**
Cubic	**	**	**	**	**
B) Nitrogen level ($kg\ ha^{-1}$)					
N0	978 e	0.794 e	0.203 d	0.081 d	0.121 c
N40	1071 d	0.827 d	0.205 cd	0.084 cd	0.122 c
N80	1163 c	0.848 c	0.214 c	0.089 c	0.124 c
N120	1231 b	0.864 b	0.230 b	0.096 b	0.133 b
N160	1302 a	0.885 a	0.257 a	0.109 a	0.148 a
N200	1323 a	0.891 a	0.259 a	0.110 a	0.148 a
LSD (5%)	22.35	0.013	0.010	0.005	0.003
Significance	**	**	**	**	**
Linear	**	**	**	**	**
Quadratic	**	**	**	**	**
Cubic	NS	NS	**	**	**
Quartic	NS	NS	**	**	**
Quintic	NS	NS	NS	NS	NS
Interaction (A × B)	NS	NS	NS	NS	NS

Means sharing different letters differ significantly from each other by LSD at $P \leq 0.05$.
*, **: Significant at 0.05 and 0.01, respectively; NS: nonsignificant.

cultivars were: as follows: CIPAR and RUE_{TDM} {(−0.18 + 0.0009x), (R^2 = 0.93); (7.20 − 0.0117x + 5E-06x^2), (R^2 = 0.99)}, CIPAR and RUE_{SCY} {(−0.25 + 0.0004x), (R^2 = 0.98); (0.97 − 0.0017x + 9E-07x^2), (R^2 = 0.99)}, CIPAR and RUE_{LY} {(−0.17 + 0.0002x), (R^2 = 0.98); (0.69 − 0.0013x + 6E-07x^2), (R^2 = 0.99)}, and CIPAR and RUE_{CSY} {(−0.08 + 0.0002x), (R^2 = 0.99); (0.11 − 0.0002x + 1E-07x^2), (R^2 = 0.99)}. The highest level of nitrogen application, N200, showed a 35.3% increase in CIPAR compared to N0. Radiation use efficiencies for TDM, SCY, LY, and CSY were highest (0.921, 0.258, 0.112, and 0.146 $MJ\ m^{-1}$, respectively) for cultivar CIM-573 as compared to CIM-496. The remarkable influence of nitrogen nutrition in the case of physiological efficiencies for the above listed parameters

Table 3. Physiological efficiency as affected by different irrigation methods, cotton cultivars, and plant spacing.

Treatment	CIPAR ($MJ\ m^{-2}$)	RUE_{TDM} ($MJ\ m^{-1}$)	RUE_{SCY} ($MJ\ m^{-1}$)	RUE_{LY} ($MJ\ m^{-1}$)	RUE_{CSY} ($MJ\ m^{-1}$)
A) Irrigation method					
Drip irrigation	1245 a	0.748 a	0.216 a	0.089 a	0.127 a
Furrow irrigation	1199 b	0.678 b	0.180 b	0.073 b	0.108 b
LSD (5%)	5.73	0.044	0.022	0.009	0.011
Significance	**	*	**	**	**
Linear	**	**	**	**	**
B) Cultivar					
CIM-496	1203 b	0.688 b	0.183 b	0.072 b	0.110 b
CIM-557	1240 a	0.739 a	0.214 a	0.089 a	0.125 a
LSD (5%)	10.79	0.027	0.011	0.008	0.007
Significance	**	**	**	**	**
Linear	**	**	**	**	**
C) Plant spacing (cm)					
S_1 (10 cm)	1256 a	0.752 a	0.232 a	0.094 a	0.137 a
S_2 (20 cm)	1223 b	0.718 b	0.198 b	0.081 b	0.118 b
S_3 (30 cm)	1187 c	0.669 c	0.165 c	0.067 c	0.098 c
LSD (5%)	7.15	0.026	0.014	0.007	0.004
Significance	**	**	**	**	**
Linear	**	**	**	**	**
Quadratic	NS	NS	*	*	*
Interaction					
A × B	NS	NS	NS	NS	NS
A × C	NS	NS	NS	NS	NS
B × C	NS	NS	NS	NS	NS
A × B × C	NS	NS	NS	NS	NS

Means sharing different letters differ significantly from each other by LSD at $P \leq 0.05$.
*, **: Significant at 0.05 and 0.01, respectively; NS: nonsignificant.

was noticed with its concurrent increase, as N200 showed 12.2%, 27.6%, 35.8%, and 22.3% increased values of radiation use efficiencies of these parameters compared to the untreated control, N0 (Table 2). Regression equations (linear and quadratic) for nitrogen levels were as follows: CIPAR and RUE_{TDM} {(0.53 + 0.0003x), (R^2 = 0.99); (0.41 + 0.0005x – 9E-08x^2), (R^2 = 0.99)}, CIPAR and RUE_{SCY} {(0.02 + 0.0002x), (R^2 = 0.88); (0.88 – 0.0013x + 7E-07x^2), (R^2 = 0.99)}, CIPAR and RUE_{LY} {(–0.01 + 9E-05x), (R^2 = 0.92); (0.34 – 0.0005x + 3E-07x^2), (R^2 = 0.99)}, and CIPAR and RUE_{CSY} {(0.03 + 9E-05x), (R^2 = 0.83); (53 – 0.0008x + 4E-07x^2), (R^2 = 0.98)}. With regard to the impact of different irrigation methods, it was concluded that the drip irrigation method gave the maximum CIPAR (1245

Table 4. Physiological efficiency as affected by different irrigation regimes and glycinebetaine.

Treatment	CIPAR (MJ m^{-2})	RUE_{TDM} (MJ m^{-1})	RUE_{SCY} (MJ m^{-1})	RUE_{LY} (MJ m^{-1})	RUE_{CSY} (MJ m^{-1})
A) Irrigation regime					
No water stress	1191 a	0.849 a	0.185 a	0.075 a	0.107 a
Water stress	1078 b	0.743 b	0.167 b	0.068 b	0.098 b
LSD (5%)	35.83	0.025	0.007	0.003	0.005
Significance	**	**	**	**	**
Linear	**	**	*	*	*
B) Glycinebetaine					
Foliar spray	1154 a	0.843 a	0.194 a	0.081 a	0.112 a
Untreated check	1116 b	0.748 b	0.158 b	0.062 b	0.094 b
LSD (5%)	6.69	0.043	0.013	0.005	0.008
Significance	**	**	**	**	**
Linear	**	**	**	**	**
Interaction (A × B)	NS	NS	NS	NS	NS

Means sharing different letters differ significantly from each other by LSD at $P \leq 0.05$.
*, **: Significant at 0.05 and 0.01, respectively; NS: nonsignificant.

MJ m^{-2}) as compared to the traditionally practiced furrow irrigation method. Linear regression equations for irrigation methods were as follows: CIPAR and RUE_{TDM} {(–0.04 + 0.96x), (R^2 = 1.00)}, CIPAR and RUE_{SCY} {(–0.03 + 0.96x), (R^2 = 1.00)}, CIPAR and RUE_{LY} {(–0.01 + 0.96x), (R^2 = 1.00)}, and CIPAR vs RUE_{CSY} {(–0.01 + 0.96x), (R^2 = 1.00)}. Respective equations for cultivars were: CIPAR and RUE_{TDM} {(0.02 + 1.033x), (R^2 = 1.00)}, CIPAR and RUE_{SCY} {(0.03 + 1.03x), (R^2 = 1.00)}, CIPAR and RUE_{LY} {(0.01 + 1.03x), (R^2 = 1.00)}, and CIPAR and RUE_{CSY} {(0.01 + 1.03x), (R^2 = 1.00)}. Furthermore, wider plant spacing (S_3) showed 5.5% reduction in CIPAR over narrower plant spacing S_1. Similarly, it also led to 11%, 28.9%, 28.7%, and 39.8% reduction in RUE for TDM, SCY, LY, and CSY, respectively, compared to S1. Radiation use efficiencies for these parameters were greater in the case of irrigation water applied with the drip method compared to the furrow method (Table 3). Different regression equations (linear and quadratic) for plant spacing were as follows: CIPAR and RUE_{TDM} {(–0.76 + 0.0012x), (R^2 = 0.99); (–7.91 + 0.0129x – 5E-06x^2), (R^2 = 1.00)}, CIPAR and RUE_{SCY} {(–0.99 + 0.0001x), (R^2 = 0.99); (1.47 – 0.0031x + 2E-06x^2), (R^2 = 1.00)}, CIPAR and RUE_{LY} {(–0.40 + 0004x), (R^2 = 1.00); (–0.29 – 0.0002x + 7E-08x^2), (R^2 = 1.00)}, and CIPAR and RUE_{CSY} {(–0.57 + 0.0006x), (R^2 = 0.99); (–0.14 – 0.0002x + 3E-07x^2), (R^2 = 1.00)}. The statistical data in Table 4 present the effect of different irrigation regimes and glycinebetaine application on physiological efficiencies for TDM, SCY, LY, and CSY. Statistical results showed that water stress caused a reduction of 9.5%, 12.5%, 9.7%, 9.3%, and 8.4% in CIPAR, RUE_{TDM}, RUE_{SCY}, $RUE_{LY,}$ and RUE_{CSY}, respectively, compared to the lack of water stress. Exogenous application of glycinebetaine also enhanced the values of these traits over the untreated control. Linear regression equations for irrigation regimes were as follows: CIPAR and RUE_{TDM} {(–0.03 + 0.91x), (R^2 = 1.00)}, CIPAR and RUE_{SCY} {(–0.001 + 0.91x), (R^2 = 1.00)}, CIPAR and RUE_{LY} {(–0.001 + 0.91x), (R^2 = 1.00)}, and CIPAR and RUE_{CSY} {(–0.001 + 0.91x), (R^2 = 1.00)}. Respective equations for glycinebetaine were: CIPAR and RUE_{TDM} {(–0.07 + 0.97x), (R^2 = 1.00)}, CIPAR and RUE_{SCY} {(–0.03 + 0.97x), (R^2 = 1.00)}, CIPAR and RUE_{LY} {(–0.02 + 0.97x), (R^2 = 1.00)}, and CIPAR and RUE_{CSY} {(–0.01 + 0.97x), (R^2 = 1.00)}. The results of the present study are in agreement with the findings of various researchers (Maqsood et al., 2006; Ahmad et al., 2009; Wajid et al., 2010; Iqbal, 2011), who found significant variations in radiation use efficiencies for various traits such as total dry matter production and seed cotton yield. They reported that radiation use efficiencies increased with the incremental dose of nitrogen fertilizer. However, results regarding the influence of various plant spacings on radiation use efficiencies were in contrast to the findings of Roche et al. (2001), who reported lower RUE values in ultranarrow row-spaced compared to conventionally spaced crops.

3.2. Water use efficiency

Cumulative crop evapotranspiration recorded for experiment 1 was 691.19 and 668.69 mm in 2009 and 2010, respectively, whereas it was recorded as 685.76 and 666.06 mm for experiment 2. Furthermore, in experiment 3, CCET values were recorded as 675.09 and 667.06 mm during the crop seasons, respectively (Figure 2). The drip irrigation method showed 34.5% water savings compared to the traditional furrow irrigation method. In experiment 3, 1917 m^3 of water was applied for water stress treatment, whereas 2945 m^3 was applied for crops without water stress. Table 5 illustrates the responses of various cultivars and nitrogen fertilizer levels to water use efficiencies for TDM, SCY, LY, and CSY. Maximum water use efficiencies of 16.95, 4.77, 2.06, and 2.70 kg ha^{-1} mm^{-1} were recorded for CIM-573, whereas CIM-496 had the minimum values of 13.12, 3.31, 1.31, and 2.00 kg ha^{-1} mm^{-1} WUE for TDM, SCY, LY, and CSY, respectively. Linear and quadratic regression equations for cultivars were as follows: WUE_{TDM} and WUE_{SCY} {(–1.59 + 0.38x), (R^2 = 0.99); (–6.53 + 1.04x – 0.02x^2), (R^2 = 0.99)}, WUE_{TDM} and WUE_{LY} {(–1.20 + 0.19x), (R^2 = 0.99); (–2.74 + 0.40x – 0.01x^2), (R^2 = 0.99)}, WUE_{TDM} and WUE_{CSY} {(–0.35 + 0.18x), (R^2 = 0.99); (–4.09 + 0.68x – 0.02x^2), (R^2 = 0.99)}. The addition of an equivalent dose of 40 kg ha^{-1} enhanced the water use efficiency of TDM by 14.2%, 11.2%, 7.8%, 8.9%, and 1.6%, respectively. Maximum water use efficiencies for SCY, LY, and CSY were seen with the addition of the highest nitrogen level, N200, which also had statistically similar results to N160. Nominal increase in WUE was estimated beyond N160, which showed statistically significant differences from the other nitrogen fertilizer levels under investigation (Table 5). Linear and quadratic regression equations for nitrogen levels were as follows: WUE_{TDM} and WUE_{SCY} {(–2.62 + 0.44x), (R^2 = 0.98); (7.74 – 0.93x + 0.05x^2), (R^2 = 0.99)}, WUE_{TDM} and WUE_{LY} {(–1.31 + 0.20x), (R^2 = 0.98); (3.38 – 0.42x + 0.02x^2), (R^2 = 0.99)}, WUE_{TDM} and WUE_{CSY} {(–1.31 + 0.24x), (R^2 = 0.98); (4.55 – 0.53x + 0.03x^2), (R^2 = 0.99)}. Averaged across the treatments, irrigation water applied by drip method maintained 14.2%, 23.9%, 27.1%, and 21.2% increased water use efficiencies for TDM, SCY, LY, and CSY, respectively, compared to the furrow method. Linear regression equations for irrigation methods were: WUE_{TDM} and WUE_{SCY} {(–0.38 + 0.90x), (R^2 = 1.00)}, WUE_{TDM} and WUE_{LY} {(–0.17 + 0.89x), (R^2 = 1.00)}, WUE_{TDM} and WUE_{CSY} {(–0.14 + 0.89x), (R^2 = 1.00)}. Statistically greater water use efficiencies (13.99, 4.30, 1.75, and 2.54 kg ha^{-1} mm^{-1}) were recorded in the case of narrowly spaced plants (S_1) compared to the more widely spaced plants (S_3). Linear and quadratic regression equations for plant spacing were: WUE_{TDM} and WUE_{SCY} {(–4.40 + 0.62x), (R^2 = 0.99); (7.94 – 1.31x + 0.08x^2), (R^2 = 1.00)}, WUE_{TDM} and WUE_{LY} {(–1.82 + 0.25x), (R^2 = 0.99); (2.85 – 0.48x + 0.03x^2), (R^2 = 1.00)}, WUE_{TDM} and WUE_{CSY} {(–2.53 + 0.36x), (R^2 = 0.99); (4.38 – 0.72x + 0.04x^2), (R^2 = 1.00)}. Among the cultivars, CIM-557 was the best cultivar with respect to enhanced water use efficiencies of the attributes studied (Table 6). Linear regression equations for cultivars were: WUE_{TDM} and WUE_{SCY} {(0.45 + 1.07x), (R^2 = 1.00)}, WUE_{TDM} and WUE_{LY} {(0.24 + 1.09x), (R^2 = 1.00)}, WUE_{TDM} and WUE_{CSY} {(0.16 + 1.09x), (R^2 = 1.00). Among the water use efficiencies studied for various parameters, the water-stressed crop exhibited the lowest WUE values of 11.95, 2.69, 1.11, and 1.57 kg ha^{-1} mm^{-1}, respectively, for TDM, SCY, LY, and CSY, as compared to the greatest values recorded for the treatment without water stress of 15.08, 3.26, 1.36, and 1.90 kg ha^{-1} mm^{-1}, respectively. Linear regression equations for irrigation regimes were: WUE_{TDM} and WUE_{SCY} {(0.14 + 0.78x), (R^2 = 1.00)}, WUE_{TDM} and WUE_{LY} {(0.04 + 0.79x), (R^2 = 1.00)}, WUE_{TDM} and WUE_{CSY} {(0.07 + 0.78x), (R^2 = 1.00)}. Likewise, foliar-sprayed glycinebetaine showed 16.7%, 27.1%, 33%, and 23.9% enhanced WUE for the above mentioned parameters, respectively, over the

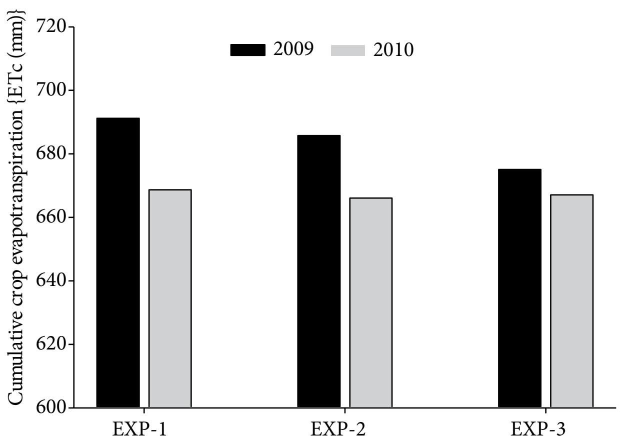

Figure 2. Cumulative crop evapotranspiration for both crop seasons in different experiments.

Table 5. Water use efficiency as affected by different cultivars and nitrogen levels.

Treatments	WUE_{TDM} (kg ha^{-1} mm^{-1})	WUE_{SCY} (kg ha^{-1} mm^{-1})	WUE_{LY} (kg ha^{-1} mm^{-1})	WUE_{CSY} (kg ha^{-1} mm^{-1})
A) Cultivar				
CIM-496	13.12 d	3.31 d	1.31 d	2.00 d
CIM-557	15.44 b	4.26 b	1.78 b	2.48 b
CIM-573	16.95 a	4.77 a	2.06 a	2.70 a
CIM-588	13.91 c	3.69 c	1.50 c	2.19 c
LSD (5%)	1.01	0.24	0.10	0.16
Significance	**	**	**	**
Linear	*	*	**	NS
Quadratic	**	**	**	**
Cubic	**	**	**	**
Nitrogen level (kg ha^{-1})				
N0	11.44 e	2.92 e	1.16 e	1.75 e
N40	13.07 d	3.24 d	1.32 d	1.92 d
N80	14.54 c	3.68 c	1.51 c	2.16 c
N120	15.67 b	4.17 b	1.74 b	2.43 b
N160	17.07 a	4.95 a	2.08 a	2.86 a
N200	17.35 a	5.07 a	2.14 a	2.93 a
LSD (5%)	0.28	0.14	0.06	0.08
Significance	**	**	**	**
Linear	**	**	**	**
Quadratic	**	**	**	**
Cubic	**	**	**	**
Quartic	**	**	**	**
Quintic	**	**	**	**
Interaction (A × B)	NS	NS	NS	NS

Means sharing different letters differ significantly from each other by LSD at P ≤ 0.05.
*, **: Significant at 0.05 and 0.01, respectively; NS: nonsignificant.

untreated control (Table 7). Linear regression equations for glycinebetaine were: WUE_{TDM} and WUE_{SCY} {(–0.30 + 0.88x), (R^2 = 1.00)}, WUE_{TDM} and WUE_{LY} {(–0.16 + 0.87x), (R^2 = 1.00)}, WUE_{TDM} and WUE_{CSY} {(–0.11 + 0.86x), (R^2 = 1.00)}. The results are in line with the findings of DeTar et al. (1999), who determined that an increase in water use efficiency by 39.41 kg ha^{-1} cm^{-1} resulted in the case of irrigation water applied through the drip method compared to the traditional furrow irrigation method, which had WUE of 16.5 kg ha^{-1} cm^{-1}. Similarly, other researchers (Norton and Silvertooth, 2001; Cetin and Bilgel, 2002; Bhattarai et al., 2003; Khalifa, 2006) found a substantial improvement in water use efficiency due to economizing water under drip irrigation. Various scientists (Robertson

Table 6. Water use efficiency as affected by different irrigation methods, cotton cultivars, and plant spacing.

Treatment	WUE_{TDM} (kg ha^{-1} mm^{-1})	WUE_{SCY} (kg ha^{-1} mm^{-1})	WUE_{LY} (kg ha^{-1} mm^{-1})	WUE_{CSY} (kg ha^{-1} mm^{-1})
A) Irrigation method				
Drip irrigation	13.79 a	3.99 a	1.64 a	2.34 a
Furrow irrigation	12.07 b	3.22 b	1.29 b	1.93 b
LSD (5%)	0.75	0.13	0.09	0.05
Significance	**	**	**	**
Linear	**	**	**	**
B) Cultivar				
CIM-496	12.27 b	3.27 b	1.29 b	1.96 b
CIM-557	13.58 a	3.95 a	1.64 a	2.30 a
LSD (5%)	0.57	0.13	0.05	0.09
Significance	**	**	**	**
Linear	**	**	**	**
C) Plant spacing (cm)				
S_1 (10 cm)	13.99 a	4.30 a	1.75 a	2.54 a
S_2 (20 cm)	13.03 b	3.61 b	1.47 b	2.14 b
S_3 (30 cm)	11.76 c	2.91 c	1.18 c	1.73 c
LSD (5%)	0.43	0.14	0.05	0.09
Significance	**	**	**	**
Linear	**	**	**	**
Quadratic	NS	NS	NS	NS
Interaction				
A × B	NS	NS	NS	NS
A × C	NS	NS	NS	NS
B × C	NS	NS	NS	NS
A × B × C	NS	NS	NS	NS

Means sharing different letters differ significantly from each other by LSD at $P \leq 0.05$.
*, **: Significant at 0.05 and 0.01, respectively; NS: nonsignificant.

et al., 2006; Singh et al., 2007; Jonghan and Piccinni, 2009; Singh et al., 2010; Wei et al., 2012) also noticed water savings for the drip method of irrigation compared to the furrow method.

3.3. Nitrogen use efficiency

Statistically significant variations were noticed among the treatments of various cultivars and nitrogen fertilizer levels with respect to agronomic and economic nitrogen use efficiency (Table 8). Averaged across the nitrogen

Table 7. Water use efficiency as influenced by different irrigation regimes and glycinebetaine.

Treatment	WUE_{TDM} (kg ha^{-1} mm^{-1})	WUE_{SCY} (kg ha^{-1} mm^{-1})	WUE_{LY} (kg ha^{-1} mm^{-1})	WUE_{CSY} (kg ha^{-1} mm^{-1})
A) Irrigation regime				
No water stress	15.08 a	3.26 a	1.36 a	1.90 a
Water stress	11.95 b	2.69 b	1.11 b	1.57 b
LSD (5%)	0.19	0.19	0.11	0.08
Significance	**	**	**	**
Linear	**	**	**	**
B) Glycinebetaine				
Foliar spray	14.56 a	3.33 a	1.41 a	1.92 a
Untreated check	12.48 b	2.62 b	1.06 b	1.55 b
LSD (5%)	0.63	0.21	0.09	0.13
Significance	**	**	**	**
Linear	**	**	**	**
Interaction (A × B)	NS	NS	NS	NS

Means sharing different letters differ significantly from each other by LSD at P ≤ 0.05.
*, **: Significant at 0.05 and 0.01, respectively; NS: nonsignificant.

levels, CIM-573 had maximum ANUE and ENUE for seed cotton yield (6.86 kg kg^{-1} and 15.99 Rs kg^{-1}), followed by CIM-557 (6.09 kg kg^{-1} and 14.21 Rs kg^{-1}), CIM-588 (5.42 kg kg^{-1} and 12.65 Rs kg^{-1}), and CIM-496 (4.80 kg kg^{-1} and 11.20 Rs kg^{-1}), respectively. A similar trend was also apparent in the case of agronomic and economic NUE for lint and cottonseed. Different regression equations (linear and quadratic) for the cultivars were: $ANUE_{SCY}$ and $ANUE_{LY}$ {(–0.71 + 0.58x), (R^2 = 0.99); (–1.89 + 0.99x – 0.04x^2), (R^2 = 0.99)}, $ANUE_{SCY}$ and $ANUE_{CSY}$ {(0.69 + 0.42x), (R^2 = 0.99); (1.68 + 0.08x + 0.03x^2), (R^2 = 0.99)}, $ANUE_{SCY}$ and $ENUE_{SCY}$ {(0.04 + 2.33x), (R^2 = 1.00); (–0.29 + 2.44x – 0.01x^2), (R^2 = 1.00)}, $ANUE_{SCY}$ and $ENUE_{LY}$ {(–3.90 + 3.22x), (R^2 = 0.99); (–9.44 + 5.15x - 0.17x^2), (R^2 = 0.99)}, and $ANUE_{SCY}$ and $ENUE_{CSY}$ {(1.33 + 0.78x), (R^2 = 0.99); (3.08 + 0.17x + 0.05x^2), (R^2 = 0.99)}. The effect of different nitrogen fertilizer levels on ANUE and ENUE for SCY, LY, and CSY was statistically significant. Efficiencies from both the agronomic and economic perspectives increased significantly, with maximum values at nitrogen fertilizer level N160. Further increase in nitrogen nutrition to N200 did not have a significant effect with regard to agronomic and economic NUE for seed cotton, lint, or cottonseed. The values of agronomic NUE for seed cotton, lint, and cottonseed varied from 5.41 to 8.59, 2.57 to 3.88, and 2.83 to 4.70 kg kg^{-1}, respectively. Similarly, increase of economic NUE by 59.2%, 51.7%, and 66.1% for seed cotton, lint, and cottonseed, respectively, was noticed by N160 compared to N40, and the response was linear in nature. Linear and quadratic regression equations for nitrogen levels were: $ANUE_{SCY}$ and $ANUE_{LY}$ {(0.34 + 0.41x), (R^2 = 0.99); (0.76 + 0.29x + 0.01x^2), (R^2 = 0.99)}, $ANUE_{SCY}$ and $ANUE_{CSY}$ {(0.34 + 0.59x), (R^2 = 0.99); (–0.89 + 0.75x – 0.01x^2), (R^2 = 0.99)}, $ANUE_{SCY}$ and $ENUE_{SCY}$ {(–0.09 + 2.35x), (R^2 = 1.00); (–0.10 + 2.35x – 0.01x^2), (R^2 = 1.00)}, $ANUE_{SCY}$ and $ENUE_{LY}$ {(1.68 + 2.31x), (R^2 = 0.99); (4.30 + 1.54x – 0.05x^2), (R^2 = 0.99)}, and $ANUE_{SCY}$ and $ENUE_{CSY}$ {(–0.63 + 1.10x), (R^2 = 0.99); (–1.63 + 1.39x – 0.02x^2), (R^2 = 0.99)}. The interaction between the cultivars and different levels of nitrogen fertilizer was insignificant for all parameters studied. The results of the present study are confirmed by the findings of other researchers (Boquet and Breitenbeck, 2000; Sawan et al., 2006; Reddy et al., 2007; Zhang et al., 2008; Seilsepour and Rashidi, 2011),

Table8. Nitrogenuseefficiencyasaffectedbydifferentcultivarsandnitrogenlevels.

Treatments	$ANUE_{SCY}$ ($kgkg^{-1}$)	$ANUE_{LY}$ ($kgkg^{-1}$)	$ANUE_{CSY}$ ($kgkg^{-1}$)	$ENUE_{SCY}$ ($RSkg^{-1}$)	$ENUE_{LY}$ ($RSkg^{-1}$)	$ENUE_{CSY}$ ($RSkg^{-1}$)
A) Cultivar						
CIM-496	4.80 d	2.08 d	2.71 c	11.20 d	11.56 d	5.06 c
CIM-557	6.09 b	2.89 b	3.20 b	14.21 b	16.01 b	5.97 b
CIM-573	6.86 ad	3.25 a	3.60 a	15.99 a	18.05 a	6.71 a
CIM-588	5.42 c	2.41 c	3.00 bc	12.65 c	13.38 c	5.60 bc
LSD (5%)	0.57	0.27	0.32	1.32	1.46	0.59
Significance	**	**	**	**	**	**
Linear	NS	NS	NS	NS	NS	NS
Quadratic	**	**	**	**	**	**
Cubic	**	**	**	**	**	**
B) Nitrogenlevel ($kgha^{-1}$)						
N0	0.00e	0.00 e	0.00 e	0.00 e	0.00 e	0.00 e
N40	5.41 d	2.57 d	2.83 d	12.60 d	14.22 d	5.28 d
N80	6.39 c	2.96 c	3.43 c	14.91 c	16.39 c	6.40 c
N120	7.07 b	3.24 b	3.82 b	16.48 b	17.98 b	7.12 b
N160	8.59 a	3.88 a	4.70 a	20.06 a	21.57 a	8.77 a
N200	7.29 b	3.31 b	3.98 b	17.02 b	18.35 b	7.43 b
LSD (5%)	0.63	0.27	0.37	1.46	1.50	0.68
Significance	**	**	**	**	**	**
Linear	**	**	**	**	**	**
Quadratic	**	**	**	**	**	**
Cubic	**	**	**	**	**	**
Quartic	**	**	**	**	**	**
Quintic	NS	NS	NS	NS	NS	NS
Interaction (A × B)	NS	NS	NS	NS	NS	NS

MeanssharingdifferentlettersdiffersignificantlyfromeachotherbyLSDat$P \leq 0.05$.
*,**:Significantat0.05and0.01,respectively;NS:nonsignificant.

who reported that the efficiency of nitrogen fertilizer was enhanced proportionally by splitting various doses of nitrogen fertilizer. However, there is a scarcity of published data in earlier research studies regarding radiation, water, and nitrogen use efficiencies of cotton having combined effects of plant density, nitrogen fertilizer, irrigation regimes, and glycinebetaine application.

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