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EFFECTS OF SOIL-APPLIED POTASSIUM ON POTASSIUM USE EFFICIENCY, LEAF WATER, AND BIOCHEMICAL ATTRIBUTES OF COTTON CULTIVARS UNDER REDUCED IRRIGATION

MUHAMMAD NAEEM AKHTAR[1*], TANVEER-UL HAQ[2], GHULAM ABBASS[3], TAYYAABA NAZ[4], MUHHAMD MAZHAR IQBAL[5], MUHAMMAD NAUMAN HANIF[2] AND MUHAMMAD WASEEM AKHTAR[6]

[1]*Pesticide Quality Control Laboratory, Multan 60800-Pakistan*
[2]*Department of Soil and Environmental Science, MNS, University of Agriculture, Multan 60800-Pakistan*
[3]*Barani Agricultural Research Institute, Chakwal, Pakistan*
[4]*Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad, 38000-Faisalabad, Pakistan*
[5]*Department of Soil and Environmental Sciences, College of Agriculture, University of Sargodha, 40100-Sargodha, Pakistan*
[6]*Department of Plant Breeding and Genetics, University of Agriculture Faisalabad, Faisalabad, Punjab, Pakistan*
[*]*Correspondence: muhammaduam01@gmail.com*

Abstract

Cotton production in Pakistan is often constrained by limited water resources and inadequate potassium (K) fertilization, leading to lower crop resilience and yield. This study aimed to evaluate the ameliorated effect of potassium on cotton under drought stress and the climatic conditions of Multan by assessing the potassium (K) use efficiency and related physiological attributes in cotton cultivars with varying K efficiency. Moreover, we aimed to identify the K-efficient cotton cultivar to provide a helping hand for breeders in developing high-yielding varieties for low K and water-limiting environments. For this purpose, five cotton cultivars (FH-142, IUB-2013, CIM-554, CYTO-124 [K-efficient], and BH-212 [K non-efficient]) were evaluated under two irrigation regimes (reduced and normal) with a standardized K application (50 kg ha^{-1}) across two growing seasons. Under reduced irrigation with applied K, the K-efficient cultivar FH-142 displayed significantly improved agronomic and physiological K use efficiency compared with the K non-efficient cultivar BH-212. Specifically, FH-142 exhibited 67.3% and 62.5% increases in agronomic and physiological use efficiency, respectively, compared with BH-212. Potassium application under normal irrigation generally increased chlorophyll content across all cultivars, with the greatest improvement observed in FH-142 (7.2%). Reduced irrigation with K application increased leaf osmotic potential in all cultivars, indicating improved drought tolerance. However, the magnitude of this increase varied, with BH-212 showing the highest rise (16.2%) and FH-142 exhibiting moderate increase (7.3%). Interestingly, K application under reduced irrigation mitigated membrane leakage, a measure of cell damage, in all cultivars except BH-212. Notably, BH-212 displayed higher membrane leakage (14.2%) than K-efficient cultivars (3.0% - 9.0%). Overall, the K- K-efficient cultivars' performance order differs from FH-142< CIM-554< CYTO-124< IUB-2013. The key findings highlight the importance of potassium for mitigating the negative effects of water stress on cotton plants. Several cultivars, including FH-142, CIM-554, CYTO-124, and IUB-2013, demonstrated superior performance under both irrigation levels with and without potassium application, suggesting their potassium-efficient nature. FH-142 outperformed other cultivars under water stress with K application, demonstrating exceptional potassium recovery efficiency and reinforcing its suitability for drought-prone, K-deficient soils. These findings suggest that selecting K-efficient cotton cultivars like FH-142, CYTO-124, IUB-2013, and CIM-554 could improve cotton resilience and yield under limited water and K availability, aiding farmers and supporting breeders in developing high-yield, drought-tolerant varieties.

Key words: Cotton cultivars, Leaf area index, Water potentials, Membrane leakage, Physiological use efficiency.

Introduction

Water availability in Pakistan's cotton-growing regions has declined significantly recently, dropping from 103.5 million acre-feet in 2011-2012 to 96.3 million acre-feet in 2020-2021 (Anon., 2021). Climate change predictions suggest further water scarcity alongside rising temperatures, worsening the situation. This has caused substantial damage in drought-stricken cotton districts (Ali *et al.,* 2018).

Water stress is a major abiotic stress that negatively impacts plant growth by reducing leaf area, vegetative growth, transpiration rate, photosynthesis, turgor pressure, and cell water potential, ultimately hindering plant metabolism (Farooq *et al.,* 2009). Prolonged water shortage in cotton leads to yield and quality losses (Zahid *et al.,* 2021). Drought's physiological effects include increased reactive oxygen species formation, decreased carbon dioxide intake due to stomatal closure, and down-regulated non-cyclic electron transport (Ullah *et al.,* 2017). Cotton-growing regions are particularly prone to high evapotranspiration rates, further exacerbating soil moisture loss. These combined factors have harmful effects on cotton production.

Various strategies have been employed to combat drought stress in cotton, including applying multiple inputs, improved seeds, drought-resistant varieties, and water conservation measures (Fang *et al.,* 2015; Unger *et al.,* 2010). However, in Pakistan, excessive and often reckless application of agrochemicals is prevalent among cotton farmers. This incautious use is another major contributor to the decline in cotton production (Tariq *et al.,* 2007; Khan *et al.,* 2020; Mehboob & Ahad, 2021).

In this context, potassium (K) application emerges as a potentially significant factor in crop resilience against drought stress (Kant & Kafkafi, 2002; Ishaq, 2024). Potassium influences cell membrane stability, cell elongation, osmotic adjustment, water uptake, aquaporins, and stomatal regulation, all crucial for plant survival under drought conditions (Wang *et al.,* 2013). Studies have demonstrated improved crop recovery from drought stress with potassium application (Wei *et al.,* 2013; Bahrami-Rad & Hajiboland, 2017; Aksu & Altay, 2020; Anokye *et al.,* 2021), including cotton (Zahoor *et al.,* 2017; Shahzad *et al.,* 2019; Zhou *et al.,* 2019). Potassium application also contributes to osmotic adjustment, lowering osmotic potential, promoting solute accumulation and water uptake, and maintaining turgor pressure (Zhou *et al.,* 2019).

Plants respond to environmental stress by producing lower molecular weight compounds like free amino acids and proline. These compounds play a role in plant structure development (Ashraf *et al.,* 1994a). Thus, potassium plays a vital role in mitigating various environmental stresses.

Potassium-efficient cultivars possess unique physiological mechanisms for achieving sufficient K uptake. These cultivars often have a larger root surface area for better contact with soil, facilitating a greater soil-root spread gradient for efficient nutrient uptake (Rengel & Damon, 2008). Nutrient-efficient cultivars are expected to have a positive environmental impact due to their more efficient use of soil nutrients. They require less fertilizer than less-efficient or non-efficient cultivars (Gourley *et al.,* 1994), potentially reducing overall chemical use in agriculture while maintaining yields. White (2008) described nutrient efficiency as the plant's ability to use nutrients for biomass production. It involves multiple processes, including nutrient acquisition, translocation, and utilization.

Potassium is critical in maintaining the ion flow for transporting other ions across cell membranes. Potassium flux facilitates the transport of sugars, amino acids, and nitrates (Marschner, 1995). Additionally, potassium accumulation within guard cells reduces the water potential inside the cell, along with an anion, providing the osmotic potential for water absorption (Schroeder *et al.,* 2001).

Potassium, along with irrigation water, is a crucial factor limiting cotton yield. However, while initially leading to high yields, excessive chemical fertilizer application can increase input costs and exacerbate environmental issues like eutrophication, soil acidification, and air pollution (Chen & Liao, 2017). Plant uptake of these fertilizers can also be limited in many soils.

There is a significant gap in Pakistani cotton farmers' awareness regarding using potassium fertilizers, particularly for drought-tolerant cotton cultivars. This study aims to address this knowledge gap by evaluating the performance of five cotton cultivars under drought conditions, focusing on their morpho-physiological and biochemical traits. This study aimed to evaluate the ameliorated effect of potassium on cotton under drought stress under the climatic conditions of Multan. Moreover, we aimed to identify the K-efficient cotton cultivar to provide a helping hand for breeders in developing high-yielding varieties for low K and water-limiting environments.

Materials and Methods

A two-year field study was conducted at the Central Cotton Research Institute (CCRI), Multan, Pakistan (30° 8' 55.8528" Latitude, 71° 26' 22.1892" Longitude), to evaluate the effects of potassium nutrition on various morphological and physiological parameters of cotton. This research was built upon preliminary hydroponic studies conducted under controlled conditions (Akhtar *et al.,* 2022a). These initial studies screened and selected five cotton cultivars based on their potassium (K) efficiency: FH-142, IUB-2013, CIM-554, CYTO-124 and K non-efficient cultivar BH-212.

Experimental setup: The field was prepared with raised beds measuring 0.2 m high, 3 m wide, and 4 m long. Plots were demarcated, and treatments were assigned using a randomized complete block design (RCBD) with split-split plots. The main plot factor was irrigation level (normal or reduced), the sub-plot factor was potassium application (0 kg ha^{-1} K_2O or 50 kg ha^{-1} K_2O), and the sub-sub-plot factor was cotton cultivar (five cultivars mentioned above). Each treatment combination was replicated four times.

The recommended doses of nitrogen (150 kg ha^{-1}) and phosphorus (60 kg ha^{-1}) were applied to all plots. Potassium fertilizer was applied according to the treatment plan (0 kg ha^{-1} K_2O or 50 kg ha^{-1} K_2O) at sowing time (Ahmad *et al.,* 2013). Nitrogen application was split into three doses throughout the growing season. Meanwhile, phosphorous was applied at the time of sowing.

Cotton seeds were sown using the dibbling method, and thinning was done 15 days later to maintain a plant spacing of 25 cm x 75 cm. Standard weeding and insect pest control practices were employed. Soil moisture content was monitored regularly using a moisture meter (TDR-200) to determine irrigation needs. Plots under normal irrigation received the full recommended water amount, while reduced irrigation plots received only half. Cutthroat flumes were used to measure irrigation water application. Irrigation was discontinued during the second week of September in both growing seasons. Weather data, including temperature (maximum and minimum), rainfall, and relative humidity, were also recorded and presented in (Fig. 1). Average humidity in the 1st and 2nd growing season was 30 and 32%, respectively. Average temperature was 36.5 and 36.8ºC, respectively.

Data collection

Measurement of water relations and biochemical attributes: The leaf area of three randomly selected leaves (top, middle, and bottom) from five plants per replicate was measured using a leaf area measurement system (Delta-T-Devices LTD, Sunwell Cambridge, England). The leaf area index (LAI) was calculated using the following equation:

$$\text{Leaf area index} = \frac{\text{Leaf area}}{\text{Ground area}}$$

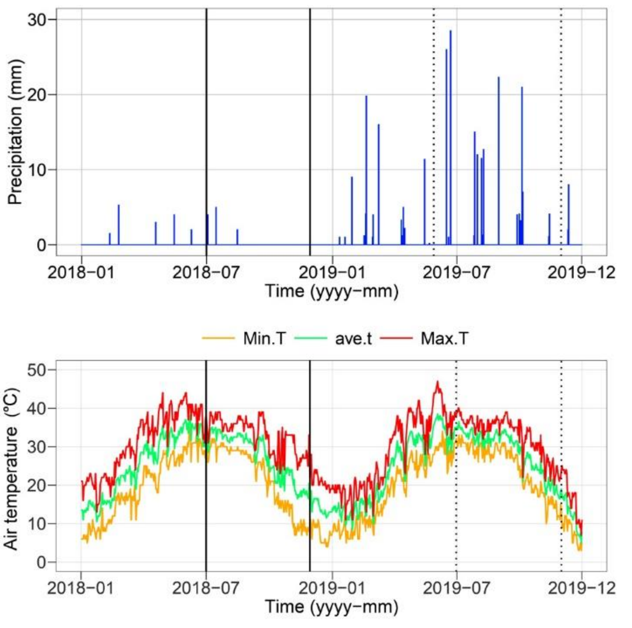

Fig. 1. Daily precipitation and mean, minimum, and average temperature during 2018 and 2019 in the experimental site. The vertical lines show the experiment duration.

Proline content was determined spectrophotometrically following the ninhydrin method described by (Bates *et al.,* 1973). Briefly, fresh leaf material (0.5 g of the leaf material used for the other parameters) was homogenized in 10 ml of 3% sulfosalicylic acid, and the homogenate was filtered. The filtrate (2.0 ml) was reacted with 2.0 ml of acid ninhydrin and 2.0 ml of glacial acetic acid at 100°C for one hour. The reaction mixture was extracted with 4 ml of toluene, and the absorbance was read at 520 nm. Total free amino acids were determined following the procedure of (Hamilton & Van Slyke, 1943), for which one ml of each sample extracted for soluble protein determinations was treated with 1 ml of 10% pyridine and 1 ml of 20% ninhydrin solution. The optical densities of the solutions were read at 570 nm using the spectrophotometer (Hitachi U-2000, Japan).

For measuring the leaf water potential (ΨW), osmotic potential (Ψs), and pressure potential (Ψp), a fully expanded youngest leaf (should be fourth from the top) was excised from each plant at 11:00 AM by using a pressure bomb apparatus (Chas W. Cook Division, Birmingham, England). The chlorophyll contents were measured using a chlorophyll meter (SPAD-502, Minolta Japan). Leaf relative water contents (LRWC) were determined by collecting fresh leaves from every treatment. The sampled fresh leaves were weighed, soaked in water overnight, and dried at 70°C for 24 h, or until constant weight. Finally, LRWC was calculated using the formula given below:

$$\text{LRWC (\%)} = \frac{\text{FW} - \text{DW}}{(\text{TW} - \text{DW})} \times 100$$

Similarly, the membrane stability integrity/membrane leakage was determined using the method described by (Ashraf *et al.,* 1994; Yan *et al.,* 1996). The fully expanded fourth leaf was taken from the top of each plant and from each treatment at the peak flowering stage. After weighing the fresh leaves, the material was poured into a glass beaker and kept for three hours at room temperature. The electrical conductivity of the solution was measured with the help of an EC meter (HI 8633, Hanna Instruments Co. Ltd). The solution in the glass beaker was autoclaved for 10 minutes to release all electrolytes from the leaf tissue and cooled at room temperature. The following formula computed the electrolyte leakage.

$$\text{Electrolyte leakage (\%)} = \frac{\text{C1}}{\text{C2}} \times 100$$

Where, C1 is the electrolyte conductivity before boiling, and C2 is the electrolyte conductivity after boiling.

After harvesting, the total crude fat, crude protein, crude fiber, and ash from cotton seed were estimated according to AOAC method (Bellaloui *et al.,* 2015; He *et al.,* 2013). About 0.5 g of seed powder was taken in a 250 ml flask. Then, 50 ml of 1.25% H_2SO_4 was added and boiled for 30 minutes. Samples were cooled and filtered. The procedure was repeated three times. Again, the filtrate was taken, and 50 ml of 1.25% NaOH was added and boiled on a hot plate for 30 minutes. Samples were again cooled, and the residue was filtered. The procedure was repeated thrice. The residue was finally air-dried and weighed. The filtrate was burned in a high-temperature muffle furnace at 600°C. The ash was weighed, and equations were given to calculate the ash (%) and crude fiber.

$$\text{Ash (\%)} = \frac{\text{Weight of ash}}{\text{Weight of original sample}} \times 100$$

$$\text{Crude fiber (\%)} = \frac{\text{Weight of residue} - \text{Weight ash}}{\text{Weight of sample}} \times 100$$

Plant analysis, K uptake, and potassium use efficiency indices: The leaf, fruit, lint, and seed samples were air-dried and grounded in a coffee grinder. The wet digestions of these samples were carried out. The readings for K concentration in leaf, fruit, lint, and seed were recorded using a Flame Photometer. The K uptake in leaf, stalk, and fruit was determined by multiplying the K content of plants by their dry biomass weight, and the values were represented as kg ha^{-1}. Different forms of the K use efficiencies were calculated using the formulae as reported by (Arif *et al.,* 2018).

$$\text{Apparent recovery efficiency (\%)} = \frac{\text{K uptake in treated} - \text{K uptake in control}}{\text{Nutrient applied}} \times 100$$

$$\text{Agronomic use efficiency (g/g)} = \frac{\text{Seed cotton yield in K treated} - \text{Seed cotton yield in control}}{\text{Nutrient applied}}$$

$$\text{Physiological use efficiency (g/g)} = \frac{\text{Seed cotton yield in K treated} - \text{Seed cotton yield in control}}{\text{Nutrient uptake}}$$

Statistical analysis: The data regarding cotton characteristics were examined using a linear model using the “lm” package in R (R Core Team, 2019). A separate study was carried out for the years 2018 and 2019. The mean separation of the cultivars within the irrigation level and the potassium levels was done at $p<0.05$ using the least square mean and modified Tukey Multiple Test comparison methods using the “means” package in R (Lenth, 2018).

Results

Effect of applied potassium on leaf area and leaf area index of cotton cultivars under varied irrigation levels: The main effect of K levels, irrigation levels, and cultivars was significant on the leaf area and leaf area index in both growing seasons at $p<0.05$ (Table 1). The reduced irrigation caused a reduction in leaf area compared with regular/normal irrigation. However, K application at the rate of 50 kg ha^{-1} increased the leaf area compared with without K application. The K application at the rate of 50 kg ha^{-1} under the reduced irrigation in both growing seasons, as compared without K, increased leaf area by 8.43, 4.08, 2.37, 2.71, and 5.18% in BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142, respectively (Table 1). Similarly, overall, the leaf area index was higher in the cotton-growing season of 2018 than in the cotton-growing season of 2019. The decrease in leaf area index was found by 1.1, 3.6, 1.28, 2.2, and 2.8% in BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142 under reduced irrigation with K application at the rate of 50 kg ha^{-1}. Among cotton cultivars, the FH-142 performs better in terms of leaf area and leaf area index with K application under reduced irrigation (Table 1).

Effect of applied potassium on leaf water potential and osmotic potential of cotton cultivars under varied irrigation levels: The principal and interactive effects of K levels, irrigation levels, and cultivars were significant on the leaf water and osmotic potential at $p<0.05$ in both growing seasons (Table 2). The K application at the rate of 50 kg ha^{-1} increased the leaf water potential compared with without the K application. The K application under normal irrigation conditions has increased the leaf water potential by 17.7, 10.1, 7.4, 13.2, and 10.4% in BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142, respectively (Table 2). Similarly, the leaf osmotic potential was increased by 7.3, 10.5, 15.5, 14.3, and 16.2% in BH-212, IUB-2013, CIM-544, CYTO-124, and FH-142, respectively, under reduced irritation with K application as compared with no K application. Whereas the increase in leaf osmotic potential was 13.1, 26.6, 16.9, 17.1, and 18.6% in BH-212, IUB-2013, CIM-544, CYTO-124, and FH-142, respectively, under normal irrigation with K applied as compared with without K application (Table 2).

Effect of applied potassium on leaf turgor potential and proline under varied irrigation levels: The K application @ 50 kg ha^{-1} increased the leaf turgor potential compared without the K application. The K application under normal irrigation conditions increased the leaf turgor potential by 10.7, 16.1, 55.7, 51.7, and 56.4% in cultivars BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142, respectively, during both growing seasons (Table 3). Similarly, the main effect of irrigation levels, K levels, and cultivars was also significant on the proline contents in both growing seasons at $p<0.05$ (Table 3). The BH-212 showed higher proline contents than other cultivars like IUB-2013, CIM-554, CYTO-124, and FH-142, which were 8.7, 42.4, 35.4, and 23.7%, respectively, under normal irrigation conditions with K application at the rate of 50 kg ha^{-1} in both cotton-growing seasons (Table 3).

Effect of applied potassium on membrane electrolyte leakage of cotton cultivars under varied irrigation levels: Fig. 2 shows that all cultivars behave statistically dissimilar for membrane electrolyte leakage under both potassium and irrigation levels. Upon comparison among the cotton cultivars, the cultivar BH-212 has shown a 14.2 % higher membrane leakage % as compared with CYTO-124 (6.0%), IUB-2013 (5.0%), CIM-554 (3.0%), and FH-142 (9.0%) under the reduced irrigation condition with the application of K at the rate of 50 kg ha^{-1} on an average basis across both the growing season (Fig. 2). But overall, the performance of CIM-554 cultivar was better under reduced irrigation as compared with rest of all the cultivars.

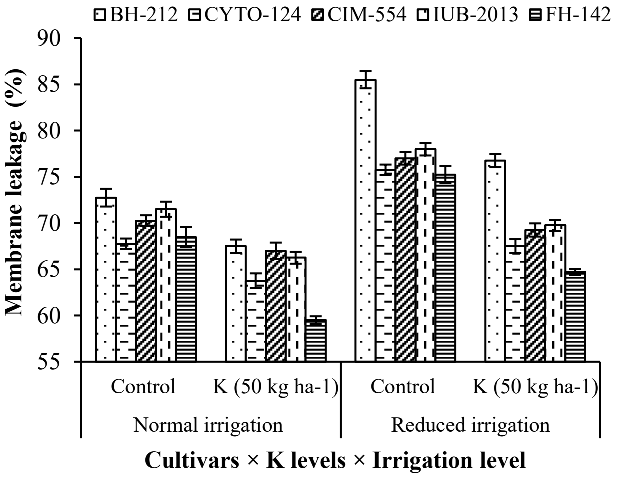

Fig. 2. The impact of irrigation and potassium levels on the electrolyte leakage in the leaf (data is the average of two years). The cultivars with the same letter (s) are statistically non-significant with potassium rate and irrigation level. Error bars indicate the standard deviation of four replications.

Effect of applied potassium total soluble amino acid and chlorophyll contents of cotton cultivars under varied irrigation levels: The main and interactive effects of irrigation levels, K levels, and cultivars on the total soluble amino acids in both growing seasons was statistically alike at $p<0.05$. The total soluble amino acids level increased by 8.7, 2.8, 3.3, 2.1, and 2.6% in BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142, respectively, as compared under reduced irrigation with K application at the rate of 50 kg ha^{-1} (Table 4). The main effect of irrigation level, K level, and cultivars was significant on leaf chlorophyll contents in both growing seasons at <0.05. The K application under reduced and normal irrigation in both growing seasons increased the chlorophyll contents. The K application vs without potassium application increased chlorophyll contents by 7.2, 3.6, 8.3, 7.1, and 3.3% in cultivars BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142 under reduced irrigation conditions during both kinds of the cotton growing seasons.

Effect of applied potassium seed crude fiber and seed crude protein of cotton cultivars under varied irrigation levels: The main effect of irrigation and K levels was statistically alike on the seed crude fiber in both growing seasons at $p<0.05$. The K application at the rate of 50 kg ha^{-1} in normal irrigation conditions during both the cotton growing season increased the seed crude fiber by 35.4, 19.9, 11.8, 23.8, and 26.5% in BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142, respectively, as compared with without K application (Table 5). The impact of water level, K level, and cultivars was significant on the seed crude protein in both cotton growing seasons at $p<0.05$ (Table 5). The cultivar CYTO-124 showed a higher seed crude protein than other cultivars (BH-212, IUB-2013, CIM-554, and FH-142). The CYTO-124 increased the seed crude protein by 30.0, 13.3, 25.0, and 8.6% in BH-212, IUB-2013, CIM-554, and FH-142, respectively, with the application of K at the rate of 50 kg ha^{-1} under normal irrigation conditions in both growing seasons (Table 5).

Table 1. Impact of reduced irrigation and potassium levels on leaf area and leaf area index in two cotton growing seasons 2018 and 2019.

Cotton cultivars	Leaf area /(cm^{-2})				Leaf area index			
	Reduced Irrigation		Normal Irrigation		Reduced Irrigation		Normal Irrigation	
	K level ($0\ kg\ ha^{-1}$)	K level ($50\ kg\ ha^{-1}$)	K level ($0\ kg\ ha^{-1}$)	K level ($50\ kg\ ha^{-1}$)	K level ($0\ kg\ ha^{-1}$)	K level ($50\ kg\ ha^{-1}$)	K level ($0\ kg\ ha^{-1}$)	K level ($50\ kg\ ha^{-1}$)
	Cotton growing season (2018)							
BH-212	77.5 ± 3.66a	84.0 ± 4.02a	83.0 ± 4.14a	93.0 ± 3.76a	2.19 ± 0.17a	2.79 ± 0.13a	2.58 ± 0.02a	2.99 ± 0.05a
IUB-2013	105.0 ± 1.68b	109.0 ± 2.65b	108.0 ± 2.35b	115.0 ± 1.78b	2.45 ±0.19ab	3.06 ± 0.03ab	2.95 ± 0.07b	3.24 ± 0.17b
CIM-554	109.0 ± 3.29b	113.0 ± 1.41b	114.0 ± 1.83bc	127.0 ± 1.58b	2.72 ± 0.05b	3.13 ± 0.04b	3.02 ± 0.09b	3.34 ± 0.08b
CYTO-124	113.3 ± 1.93b	116.0 ± 1.47b	118.0 ± 1.58c	128.8 ± 3.86b	2.87 ± 0.09b	3.18 ± 0.14b	3.08 ± 0.10b	3.38 ± 0.19b
FH-142	107.0 ± 2.20b	115.0 ± 1.22b	113.0 ± 1.29bc	131.0 ± 13.65b	2.81 ± 0.10b	3.17 ± 0.06b	3.09 ± 0.19b	3.34 ± 0.17b
	Cotton growing season (2019)							
BH-212	74.0 ± 2.35a	82.0 ± 5.31a	81.25 ± 4.71a	92.0 ± 5.45a	2.08 ± 0.16a	2.76 ± 0.09a	2.49 ± 0.06a	2.92 ± 0.05a
IUB-2013	101.0 ± 3.03b	103.0 ± 2.12b	103.0 ± 3.03b	113.0 ± 3.03b	2.39±0.13b	2.95 ± 0.05ab	2.88 ± 0.04b	3.17 ± 0.05b
CIM-554	107.0 ±2.35bc	111.0 ± 2.97bc	112.0 ± 2.20b	125.0 ± 2.08c	2.60 ± 0.02bc	3.09 ± 0.06b	2.9 ± 0.15b	3.28 ± 0.11b
CYTO-124	111.0 ± 1.96c	114.0 ± 2.20c	116.3 ± 1.55c	132.0 ± 2.48d	2.84 ± 0.10c	3.11 ± 0.07b	2.99 ± 0.16b	3.34 ± 0.12b
FH-142	104.0 ± 2.58c	113.0 ± 3.72c	109.7 ± 1.25bc	116.0 ± 2.48bc	2.71 ± 0.05bc	3.08 ± 0.05b	3.01 ± 0.29b	3.18 ± 0.12b

The values mean ± standard deviation of four replications. The values with same letter (s) within irrigation level and potassium rate are statistically non-significant at $p<0.05$

Table 2. Impact of reduced irrigation and potassium level on leaf water potential and leaf osmotic potential in five cotton cultivars.

Cotton cultivars	Leaf water potential / (-MPa)				Leaf osmotic potential / (-MPa)			
	Reduced Irrigation		Normal Irrigation		Reduced Irrigation		Normal Irrigation	
	K level ($0\ kg\ ha^{-1}$)	K level ($50\ kg\ ha^{-1}$)	K level ($0\ kg\ ha^{-1}$)	K level ($50\ kg\ ha^{-1}$)	K level ($0\ kg\ ha^{-1}$)	K level ($50\ kg\ ha^{-1}$)	K level ($0\ kg\ ha^{-1}$)	K level ($50\ kg\ ha^{-1}$)
	Cotton growing season (2018)							
BH-212	65.28 ± 3.01a	72.52 ± 6.53a	72.35 ± 4.74a	85.17 ± 4.4a	2.06 ± 0.01a	2.21 ± 0.06a	2.29 ± 0.01a	2.59 ± 0.04a
IUB-2013	72.33 ± 3.29b	83.75 ± 4.75b	82.45 ± 3.46b	90.78 ± 2.08b	2.19 ± 0.11ab	2.42 ± 0.03b	2.44 ± 0.02b	3.09 ± 0.06b
CIM-554	74.7 ± 2.68b	84.25 ± 3.74b	85.88 ± 4.27b	92.2 ± 1.74b	2.32 ± 0.05b	2.68 ± 0.02b	2.72 ± 0.03b	3.18 ± 0.04b
CYTO-124	75.85 ± 3.61b	86.3 ± 3.10b	83.55 ± 4.47b	94.55 ± 0.95b	2.37 ± 0.05b	2.71 ± 0.04b	2.75 ± 0.04b	3.22 ± 0.07b
FH-142	72.9 ± 4.22b	85.62 ± 3.22b	84.75 ± 2.46b	93.57 ± 1.74b	2.29 ± 0.03b	2.66 ± 0.05b	2.69 ± 0.02b	3.19 ± 0.04b
	Cotton growing season (2019)							
BH-212	62.95 ± 3.04a	74.17 ± 6.24a	71.62 ± 3.47a	84.28 ± 3.69a	2.03 ± 0.01a	2.03 ± 0.06a	2.09 ± 0.01a	2.55 ± 0.04a
IUB-2013	71.55 ± 3.04b	84.35 ± 4.90b	81.4 ± 3.46b	90.3 ± 2.46b	2.33 ± 0.05b	2.33 ± 0.04b	2.37 ± 0.02b	3.05 ± 0.03b
CIM-554	74.35 ± 2.84b	85.67 ± 3.24b	87.67 ± 4.80b	93.5 ± 1.27b	2.59 ± 0.03b	2.59 ± 0.03b	2.64 ± 0.06b	3.14 ± 0.04b
CYTO-124	71.35 ± 2.94b	85.17 ± 3.16b	87.2 ± 4.12b	93.5 ± 0.67b	2.63 ± 0.03b	2.63 ± 0.04b	2.68 ± 0.09b	3.17 ± 0.01b
FH-142	71.8 ± 4.23b	87.35 ± 3.33b	84.47 ± 2.65b	93.4 ± 1.73b	2.62 ± 0.04b	2.62 ± 0.03b	2.65 ± 0.04b	3.15 ± 0.03b

The values mean ± standard deviation of four replications. The values with same letter (s) within irrigation level and potassium rate are statistically non-significant at $p<0.05$

Table 3. Impact of reduced irrigation and potassium level on leaf turgor potential and proline contents in five cotton cultivars.

Cotton cultivars	Leaf turgor potential / (MPa)				Proline / (µg g^{-1})			
	Reduced Irrigation		Normal Irrigation		Reduced Irrigation		Normal Irrigation	
	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})
	Cotton growing season (2018)							
BH-212	0.44 ± 0.02a	0.48 ± 0.02a	0.45 ± 0.04a	0.48 ± 0.02a	20.11 ± 4.2c	16.12 ± 3.22a	14.9 ± 3.25b	11.25 ± 2.8a
IUB-2013	0.45 ± 0.01a	0.51 ± 0.04ab	0.46 ± 0.03a	0.90 ± 0.05b	15.93 ± 3.86b	13.22 ± 2.98a	11.61 ± 2.78ab	10.93 ± 2.79a
CIM-554	0.47 ± 0.05a	0.75 ± 0.04b	0.68 ± 0.04b	0.89 ± 0.04b	14.18 ± 1.9ab	12.62 ± 3.59a	9.87 ± 0.95a	7.72 ± 2.05a
CYTO-124	0.48 ± 0.01a	0.73 ± 0.03b	0.72 ± 0.01b	0.91 ± 0.03b	11.65 ± 2.9a	11.88 ± 3.53a	10.35 ± 0.49ab	8.10 ± 2.27a
FH-142	0.48 ± 0.03a	0.73 ± 0.04b	0.67 ± 0.01b	0.92 ± 0.05b	14.3 ± 4.88ab	11.12 ± 2.09a	12.53 ±2.63ab	9.93 ± 1.93a
	Cotton growing season (2019)							
BH-212	0.40 ± 0.01a	0.50 ± 0.02a	0.51 ± 0.04a	0.47 ± 0.03a	19.25 ± 2.16b	17.05 ± 3.16 a	15.57 ± 1.69c	12.25 ± 1.48 a
IUB-2013	0.42 ± 0.02a	0.50 ± 0.03a	0.55 ± 0.01b	0.93 ± 0.04b	16.35 ± 2.82ab	14.28 ± 2.18a	12.68 ± 2.0b	11.27 ± 2.07a
CIM-554	0.48 ± 0.07b	0.73 ± 0.05b	0.70 ± 0.02b	0.91 ± 0.06b	15.18 ± 1.58ab	12.82 ± 2.72a	10.22 ± 1.13a	8.60 ± 1.66a
CYTO-124	0.48 ± 0.04b	0.72 ± 0.06b	0.73 ± 0.02b	0.90 ± 0.08b	14.17 ± 1.86a	12.35 ± 2.44a	10.45 ± 1.21a	9.05 ± 1.86a
FH-142	0.46 ± 0.04ab	0.74 ± 0.02b	0.71 ± 0.03b	0.90 ± 0.06b	14.57 ± 4.21a	12.35 ± 1.67a	11.8 ± 1.25ab	9.90 ± 2.62a

The values mean ± standard deviation of four replications. The values with same letter (s) within irrigation level and potassium rate are statistically non-significant at $p<0.05$

Table 4. Impact of reduced irrigation and potassium level on amino acid and chlorophyll contents index in five cotton cultivars.

Cotton cultivars	Total soluble amino acid / (µg g^{-1})				Chlorophyll contents / (SPAD value)			
	Reduced Irrigation		Normal Irrigation		Reduced Irrigation		Normal Irrigation	
	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})
	Cotton growing season (2018)							
BH-212	93.5 ± 2.06a	103.4 ± 2.30a	85.3 ± 3.18a	94.2 ± 2.10a	39.8 ± 2.55a	43.3 ±3.59a	45.1 ± 3.58a	48.4 ± 3.33a
IUB-2013	97.3 ± 2.93ab	108.0 ± 1.91ab	92.4 ± 4.95ab	103.6 ± 2.38ab	42.2 ± 3.14a	49.2 ± 3.81ab	51.8 ± 3.28ab	53.8 ± 2.80ab
CIM-554	105.0 ± 2.85b	115.8 ± 2.72bc	101.6 ± 1.60b	107.9 ± 2.53b	44.2 ± 2.20ab	50.9 ± 3.17ab	53.3 ± 3.01ab	57.7 ± 1.25ab
CYTO-124	107.3 ± 2.53b	116.8 ± 2.02c	103.5 ± 2.13b	109.8 ± 1.65b	46.7 ± 0.94ab	54.7 ± 2.37ab	55.1 ± 2.68ab	59.5 ± 2.29ab
FH-142	103.4 ± 3.49ab	116.0 ± 1.41bc	98.3 ± 3.91ab	106.3 ± 1.83ab	48.3 ± 2.75b	55.9 ± 2.66b	59.7 ± 2.45b	61.6 ± 1.69b
	Cotton growing season (2019)							
BH-212	89.4 ± 1.64a	97.4 ± 1.68ab	82.5 ± 3.20a	90.6 ± 2.13a	35.5± 2.47a	40.2 ± 3.88a	44.5 ±4.42a	46.5 ± 3.00a
IUB-2013	94.5 ± 3.7ab	95.5 ± 2.77a	89.8 ± 4.88ab	99.0 ± 2.01ab	39.2 ± 2.50ab	43.5 ± 3.03a	46.0 ± 3.40ab	48.5 ± 2.68ab
CIM-554	98.6 ± 1.96ab	110.8 ± 4.15c	98.4 ± 1.34b	103.8 ± 2.44b	42.7 ± 1.89ab	49.7 ± 2.72ab	52.7 ± 2.84ab	56.7 ± 1.04ab
CYTO-124	102.8 ± 2.49b	111.5 ± 3.20c	101.8 ± 2.48b	105.0 ± 2.48b	42.9 ± 0.84ab	55.5 ± 1.39b	55.8 ± 1.92ab	58.9 ± 2.55ab
FH-142	98.4 ± 3.12ab	108.7 ± 3.20bc	95.8 ± 4.07ab	100.9 ± 1.98ab	46.4 ± 2.38b	52.2 ± 2.85ab	56.5 ± 1.65b	59.9 ± 1.86b

The values mean ± standard deviation of four replications. The values with same letter (s) within irrigation level and potassium rate are statistically non-significant at $p<0.05$

Table 5. Impact of reduced irrigation and potassium levels on seed crude fiber and seed crude protein index in five cotton cultivars.

Cotton cultivars	Seed crude fiber (%)				Seed crude protein (%)			
	Reduced Irrigation		Normal Irrigation		Reduced Irrigation		Normal Irrigation	
	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})
	Cotton growing season (2018)							
BH-212	13.38 ± 2.34a	17.08 ± 2.85a	13.46 ± 1.74a	18.23 ± 2.72a	13.25 ± 2.53a	19.45 ± 2.9a	15.22 ± 2.54a	21.45 ± 2.51a
IUB-2013	16.73 ± 1.76b	19.38 ± 3.61b	16.85 ± 1.97b	20.2 ± 3.5b	16.55 ± 2.18b	22.4 ± 2.5b	17.27 ± 3.14b	24.55 ± 2.79bc
CIM-554	15.72 ± 2.33b	21.35 ± 2.78bc	17.62 ± 2.58b	19.7 ± 3.41b	15.3 ± 1.46 b	20.15 ± 3.09b	17.38 ± 3.01b	22.05 ± 1.68b
CYTO-124	16.25 ± 2.43b	20.7 ± 5.96b	17.29 ± 2.54b	21.4 ± 3.55b	16.5 ± 2.33b	23.25 ± 3.05b	18.4 ± 3.39b	27.5 ± 3.78c
FH-142	17.1 ± 2.06bc	20.4 ± 3.76b	17.45 ± 2.11b	22.08 ± 3.29b	17.22 ± 3.61bc	21.62 ± 3.52bc	18.23 ± 2.08bc	25.5 ± 2.17bc
	Cotton growing season (2019)							
BH-212	12.47 ± 2.65a	16.68 ± 3.15a	12.43 ± 1.56a	17.15 ± 2.91a	12.38 ± 2.47a	18.5 ± 2.94a	14.35 ± 2.53a	20.48 ± 2.54a
IUB-2013	15.73 ± 1.76b	18.35 ± 3.55b	15.82 ± 1.29a	19.39 ± 3.53b	15.7 ± 2.08b	21.31 ± 2.54b	16.42 ± 3.24b	23.5 ± 2.91b
CIM-554	14.8 ± 2.07b	20.2 ± 3.03bc	16.88 ± 2.55a	18.9 ± 2.88b	14.45 ± 1.25b	19.23 ± 3.13b	16.3 ± 3.01b	21.3 ± 1.69ab
CYTO-124	15.4 ± 2.57b	19.45 ± 3.05b	16.75 ± 3.35a	20.95 ± 3.08bc	15.69 ± 2.57b	22.52 ± 3.19bc	17.38 ± 3.5bc	26.62 ± 3.67c
FH-142	16.25 ± 2.19b	19.52 ± 3.58b	16.7 ± 2.26a	20.73 ± 4.25bc	16.68 ± 3.35b	20.7 ± 3.43bc	17.5 ± 2.16bc	24.52 ± 1.96bc

The values mean ± standard deviation of four replications. The values with same letter (s) within irrigation level and potassium rate are statistically non-significant at $p<0.05$

Table 6. Impact of reduced irrigation and potassium levels on seed ash and leaf potassium uptake index in five cotton cultivars.

Cotton cultivars	Seed ash / %				Leaf potassium uptake / (kg ha^{-1})			
	Reduced Irrigation		Normal Irrigation		Reduced Irrigation		Normal Irrigation	
	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})
	Cotton growing season (2018)							
BH-212	2.83 ± 0.38a	3.78 ± 1.17a	3.13 ± 0.88a	4.44 ± 0.7a	15.8 ± 1.57a	22.5 ± 1.26a	21.0 ± 1.56a	26.2 ± 1.11a
IUB-2013	3.95 ± 0.6b	4.45 ± 0.96b	4.16 ± 0.76b	4.96 ± 1.09b	22.8 ± 1.59b	30.4 ± 1.05b	27.3 ± 2.77b	36.7 ± 1.18b
CIM-554	3.91 ± 0.31bc	4.8 ± 0.70b	4.23 ± 1.33bc	5.33 ± 1.3bc	24.7 ± 1.07c	33.0 ± 1.07bc	29.5 ± 1.22b	39.3 ± 2.69bc
CYTO-124	3.82 ± 1.3b	4.36 ± 1.04b	4.13 ± 1.45b	5.08 ± 1.36b	26.1 ± 1.05c	34.9 ± 1.17c	30.9 ± 1.24b	45.2 ± 2.40c
FH-142	3.79 ± 1.33b	4.53 ± 1.3b	4.45 ± 0.79b	5.39 ± 1.32b	25.5 ± 2.21c	32.6 ± 1.31bc	28.9 ± 1.68b	41.4 ± 1.18bc
	Cotton growing season (2019)							
BH-212	2.72 ± 0.4a	3.35 ± 0.86a	3.07 ± 0.81a	4.11 ± 0.21a	11.6 ± 1.18a	16.8 ± 1.11a	18.8 ± 1.94a	24.6 ± 1.67a
IUB-2013	3.57 ± 0.46 b	4.04 ± 0.87 b	4.06 ± 0.73b	4.28 ± 0.83b	22.3 ± 1.02b	30.1 ± 2.63b	26.1 ± 1.98b	34.6 ± 2.67b
CIM-554	3.66 ± 0.42bc	4.42 ± 0.93 bc	4.04 ± 1.39b	5.09 ± 1.25bc	23.9 ± 1.14bc	32.4 ± 1.12b	28.8 ± 1.13bc	39.0 ± 1.68bc
CYTO-124	3.33 ± 0.94 b	4.18 ± 1.16b	3.94 ± 1.49b	4.93 ± 1.29b	25.1 ± 1.88c	34.1 ± 1.69b	29.5 ± 1.13c	43.8 ± 1.17c
FH-142	3.46 ± 0.78b	4.23 ± 1.24 b	4.25 ± 0.73 b	5.21 ± 1.11 b	24.6 ± 1.81bc	31.8 ± 1.30b	27.6 ± 1.20bc	40.2 ± 1.81bc

The values mean ± standard deviation of four replications. The values with same letter (s) within irrigation level and potassium rate are statistically non-significant at $p<0.05$

Table 7. Impact of reduced irrigation and potassium levels on stalk and fruit potassium uptake index in five cotton cultivars.

Cotton cultivars	Stalk Potassium uptake / (kg ha^{-1})				Fruit Potassium Uptake / (kg ha^{-1})			
	Reduced Irrigation		Normal Irrigation		Reduced Irrigation		Normal Irrigation	
	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})	K level (0 kg ha^{-1})	K level (50 kg ha^{-1})
Cotton growing season (2018)								
BH-212	12.4 ± 1.75a	21.4 ± 1.79a	16.2 ± 1.62a	24.7 ± 1.98a	57.6 ± 1.85a	84.7 ± 1.37a	65.4 ± 1.38a	87.3 ± 2.38a
IUB-2013	16.6 ± 1.23b	29.0 ± 1.55b	20.8 ± 1.2b	34.1 ± 1.30bc	80.7 ± 2.81b	125.8 ± 2.71b	105.4 ± 2.31b	150.6 ± 2.68b
CIM-554	18.7 ± 1.90bc	31.0 ± 1.67c	21.7 ± 1.34b	35.2 ± 1.65bc	84.5 ±2.20b	133.2 ± 2.44bc	118.3 ± 2.73c	164.1 ± 2.97bc
CYTO-124	20.6 ± 1.93c	33.1 ± 1.37d	22.8 ± 1.05b	36.9 ± 1.82c	97.5 ± 2.58c	141.1 ± 3.38cd	124.8 ± 2.65c	165.3 ± 2.67c
FH-142	19.5 ± 1.09bc	34.0 ± 1.21d	22.5 ± 1.84b	35.8 ± 1.51b	92.0 ± 2.65bc	145.5 ± 2.26d	119.3 ± 2.52c	172.7 ± 3.16bc
Cotton growing season (2019)								
BH-212	11.3 ± 1.43a	24.0 ± 1.20a	15.2 ± 2.10a	21.5 ± 2.88a	52.5 ± 1.10a	83.8 ± 2.42a	62.5 ± 2.67a	86.6 ± 2.28 a
IUB-2013	15.5 ± 1.79b	33.8 ± 2.55b	19.8 ± 1.85b	28.7 ± 1.63b	78.8 ± 2.75b	123.7 ± 2.12b	99.1 ± 2.21b	144.7 ± 1.48b
CIM-554	17.6 ± 1.87bc	34.5 ± 1.73b	21.1 ± 1.30b	31.3 ± 1.59bc	81.3 ± 1.09bc	134.3 ±2.97bc	112.3 ± 2.84c	155.7 ± 2.28bc
CYTO-124	19.6 ± 1.61c	36.8 ± 1.79b	22.0 ± 1.88b	33.3 ± 1.33c	92.3 ± 2.08d	140.9 ± 2.74c	118.9 ± 3.41c	166.2 ± 3.29c
FH-142	18.6 ± 1.98c	34.6 ± 1.84b	21.3 ± 1.71b	34.1 ± 1.43c	86.3 ± 2.32cd	143.0 ± 3.85c	115.7 ± 2.78c	159.9 ± 3.91c

The values mean ± standard deviation of four replications. The values with same letter (s) within irrigation level and potassium rate are statistically non-significant at $p<0.05$

Effect of applied potassium on seed ash and leaf potassium uptake of cotton cultivars under varied irrigation levels: The main effect of irrigation levels, K levels, and cultivars was significant on seed ash and the leaf K uptake in both growing seasons at $p<0.05$. The seed ash contents increased by 17.5, 11.5, 10.4, 16.5, and 19.0% under normal irrigation, as compared with reduced irrigation with K application at the rate of 50 kg ha^{-1} during the cotton growing season. Similarly, the K uptake was higher where normal irrigation was given to the crop in both cotton growing seasons compared with the reduced irrigation conditions (50% less water). The leaf K uptake was increased among the cultivars by 15.0, 20.7, 18.9, 29.4, and 26.0% in BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142 under normal irrigation conditions over the reduced irrigation conditions with K application at the rate of 50 kg ha^{-1} during both the cotton growing season(Table 6).

Effect of applied potassium on stalk and fruit potassium uptake of cotton cultivars under varied irrigation levels: The main and interactive effects of K levels, irrigation levels, and cultivars were statistically alike on the stalk K uptake in both growing seasons at $p<0.05$. The interaction of water level × potassium level, water level × cultivars, potassium level × cultivar, and water level × potassium level × cultivars in both cotton growing seasons 2018 and 2019 was significant at $p<0.05$. The K application increased stalk potassium uptake by 33.2, 39.4, 42.6, 45.8, and 50.8% in BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142, respectively, compared with without potassium application under normal irrigation condition in both cotton-growing seasons (Table 7). The main effect of water levels, potassium levels, and cultivars on the fruit potassium uptake in both growing seasons was statistically significant at $p<0.05$. The normal irrigation with K application increased by 50 kg ha^{-1} increased fruit potassium uptake by 5.3, 18.1, 18.5, 19.3, and 11.5% in BH-212, IUB-2013, CIM-554, CYTO-124, and FH-142 over the reduced irrigation condition in the cotton-growing seasons 2018 and 2019 (Table 7).

Effect of applied potassium on potassium recovery efficiency (KRE) of cotton cultivars under varied irrigation levels: The main effect of potassium level and cultivars was statistically alike on potassium recovery efficiency (KRE) (leaves + stalks + fruits) in both growing seasons at $p<0.05$ (Fig. 3). The KRE among cultivars increased under normal irrigation conditions compared with the reduced irrigation conditions. The cultivar FH-142 showed a higher KRE over other cultivars under the reduced irrigation levels. CYTO-124 showed a higher KRE than other cultivars under normal irrigation levels. The cultivar FH-142 showed an increase in KRE by 39.7, 14.2, 11.9, and 5.3% as compared with BH-212, IUB-2013, CYTO-124, and CIM-544 cultivars, respectively, under the reduced irrigation conditions during both cotton growing seasons (Fig. 3). Whereas, the cultivar CYTO-124 showed an increase in the KRE by 47.8, 14.1, 7.8, and 1.73% as compared with BH-212, IUB-2013, CIM-554, and FH-142 cultivars, respectively, under normal irrigation conditions during both cotton growing seasons (Fig. 3).

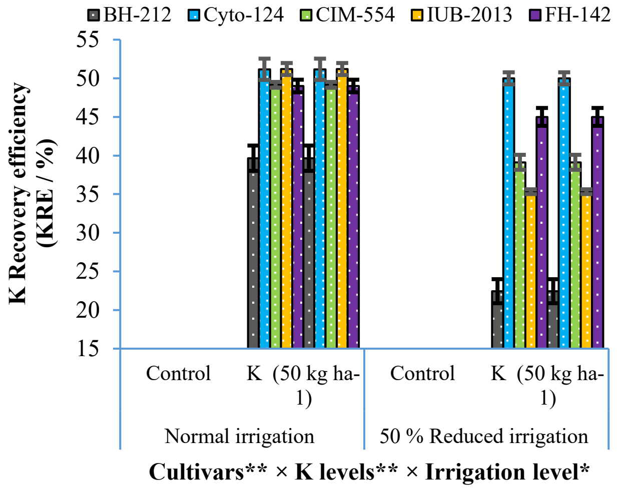

Fig. 3. The impact of irrigation and potassium levels on the potassium recovery efficiency in cotton cultivars under reduced (R) and normal (N) irrigation levels during both the growing season. (Average of two-year data). Error bars indicate the standard deviation of four replications.

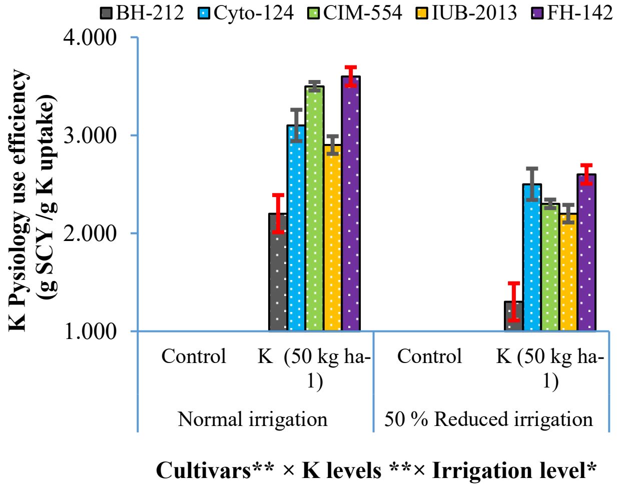

Fig. 4. The impact of irrigation (normal (Ns) and reduced (R) irrigation) and potassium levels on the physiological efficiency in cotton cultivars in both the growing season. (Average of two-year data). Error bars indicate the standard deviation of four replications.

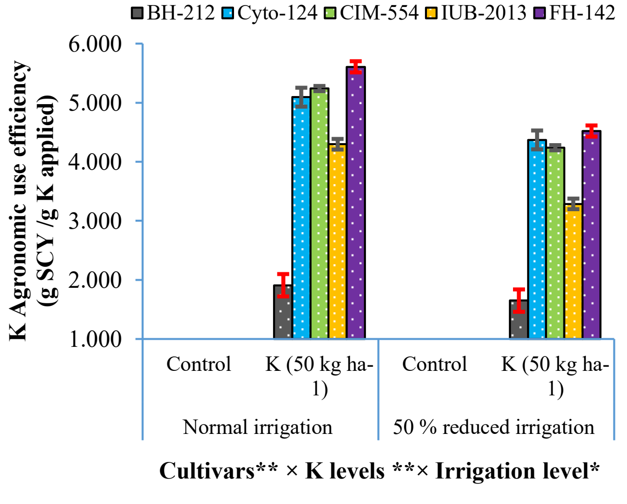

Fig. 5. The impact of irrigation and potassium levels on the agronomical use efficiency in cotton cultivars under reduced (R) and normal (N) irrigation levels during both the growing season. (Average of two-year data). Error bars indicate the standard deviation of four replications.

Effect of applied potassium on physiology efficiency (PE) of cotton cultivars under varied irrigation levels: The main effect of potassium level and cultivars was noteworthy on physiological efficiency (PE) (leaves+ stalks+ fruits) in both growing seasons at $p<0.05$ (Fig. 4). The PE among cultivars increased under the reduced irrigation conditions compared with the normal irrigation level. The cultivar FH-142 showed a higher PE over other cultivars under reduced irrigation. CIM-544 showed a higher PE over other cultivars under normal irrigation levels. The cultivar FH-142 showed an increase in PE by 62.5, 27.9, 35.9, and 19.5% as compared with BH-212, IUB-2013, CYTO-124, and CIM-544 cultivars, respectively, under the reduced irrigation level during both cotton growing seasons (Fig. 4). Whereas, the cultivar CIM-544 showed an increase in PE by 35.5, 12.7, 8.4, and 6.1% compared with BH-212, CYTO-124, IUB-2013, and FH-142 cultivars, respectively, under normal irrigation conditions during both cotton growing seasons (Fig. 4).

Effect of applied potassium on agronomic use efficiency (AUE) of cotton cultivars under varied irrigation levels: The main effect of potassium level and cultivars was statistically alike on AUE in both growing seasons at $p<0.05$. The interaction of irrigation level, potassium level, and potassium level × cultivars on AUE was also significant during both cotton growing seasons at $p<0.05$ (Fig. 5). The AUE among cultivars increased under reduced irrigation conditions compared with normal irrigation conditions. The cultivar FH-142 showed a higher AUE over other cultivars under both irrigation levels. The cultivar FH-142 showed an increase in the AUE by 67.3, 26.0, 24.3, and 10.1% compared with BH-212, IUB-2013, CIM-554, and CYTO-124 cultivars, respectively, under the reduced irrigation conditions during both cotton growing seasons (Fig. 5). Whereas, the cultivar FH-142 showed an increase in the AUE under the normal irrigation levels during both growing seasons by 65.3, 22.6, 8.7, and 5.9% compared with BH-212, IUB-2013, CIM-554, and CYTO-124 cultivars, respectively (Fig. 5).

Correlation between potassium uptake and water use efficiency: The Fig. 6 shows a positive relationship between potassium uptake and water use efficiency. When the potassium uptake increases, water use efficiency also increases among cotton cultivars. Because potassium is vital in plant water relations and improved water use efficiency under stress.

Discussion

The study confirms that water stress significantly reduces cotton growth and physiological parameters in all cultivars compared with optimal irrigation conditions (Tables 2-4). This aligns with previous research demonstrating that water scarcity hinders cellular expansion, leaf development, and floral bud formation, ultimately leading to restricted stem and root growth (Nelissen *et al.,* 2018). These findings are further supported (Deeba *et al.,* 2012; Wang *et al.,* 2014; Hejnák *et al.,* 2015; Niu *et al.,* 2018), who reported similar reductions in physiological and biochemical characteristics under water stress conditions.

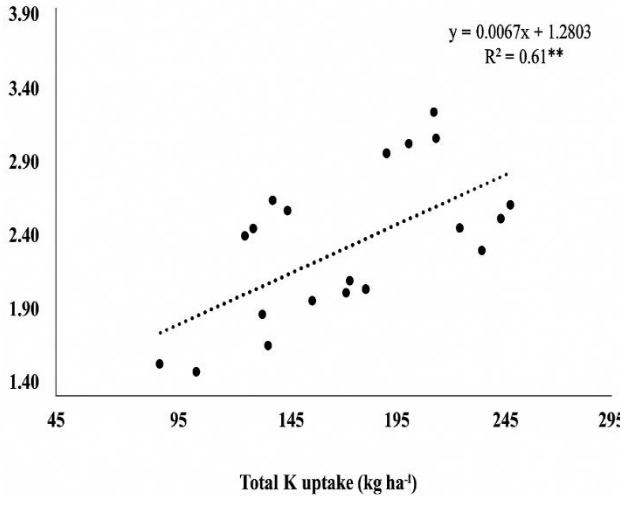

Fig. 6. The correlation between total potassium uptake and water use efficiency in cotton growing season.

However, the study demonstrates a crucial mitigating effect of potassium application on these negative impacts. Potassium application under reduced irrigation significantly improved leaf area, leaf area index, and various biochemical attributes compared with no potassium application (Tables 2-4). This suggests that potassium is vital in promoting drought tolerance and maintaining cellular functions under water stress.

Makhdum *et al.,* (2006) reported varying potassium uptake responses among different cotton cultivars. This study supports these findings, as cultivars displayed diverse potassium uptake abilities (Tables 6-7). Cultivars with a larger root surface area (Pettigrew *et al.,* 1996; Wang and Chen, 2012; Yang *et al.,* 2014) may have a greater advantage in potassium acquisition, leading to increased K transport throughout the plant. This efficient potassium absorption helps maintain optimal cytosolic K^+ concentration, which is crucial for various physiological processes (Wang & Chen, 2012; Wang *et al.,* 2014; Khan *et al.,* 2017; Zahoor *et al.,* 2017).

Therefore, selecting cultivars with high potassium uptake efficiency can be a valuable strategy to enhance plant growth, yield, and yield attributes under limited potassium conditions (Table 5). This approach aligns with the concept of sustainable cotton production by minimizing potassium fertilizer application and environmental impact. Furthermore, identifying cultivars with superior nutrient-use efficiency can reduce chemical fertilizers' economic and environmental costs (Baligar *et al.,* 2001). This aligns with the findings of Hassan *et al.,* (2014), who reported increased shoot and root biomass and cotton yield with adequate potassium application across four cultivars (Hassan *et al.,* 2014).

Interestingly, Makhdum *et al.,* (2006) observed higher sensitivity to potassium deficiency in Bt cotton cultivars compared with non-Bt cultivars. This finding highlights the potential importance of potassium management strategies with the growing adoption of Bt cotton varieties. Cultivar selection for superior nutrient absorption and utilization, as emphasized by (Akhtar *et al.,* 2022b; Pettigrew *et al.,* 1996) could be crucial for optimizing cotton production in soils with limited potassium availability. The positive correlation observed between total potassium uptake and water use efficiency (WUE) in this study (Fig. 6) further underscores potassium's role in enhancing cotton crop water utilization.

Cultivars demonstrating higher potassium uptake and potassium use efficiency also accumulated greater biomass (Tables 6-7 and Fig. 5). This finding aligns with the observation that cultivars exhibit varying responses in potassium uptake and translocation throughout the plant due to the high mobility of potassium within plant tissues (Rengel & Damon, 2008). Similar results were obtained in the current study; cultivars with higher K uptake showed higher biomass and yield (Tables 6-7 and Fig. 5). Bt-transgenic cotton cultivars seem more sensitive to modern K deficiency than conventional cultivars, resulting in increased interest in K fertilizers with the increased use of transgenic cotton, as described by (Dong *et al.,* 2004).

Genetic variability in potassium uptake efficiency was also observed among the five cultivars (Yang *et al.,* 2011). They also reported that potassium-efficient cultivars displayed a significant advantage in terms of dry mass production per unit of potassium accumulated and per unit of potassium fixation compared with potassium-inefficient cultivars. These findings suggest that potassium-efficient cultivars could achieve higher yields under potassium-deficient soil conditions. However, even with potassium application, these cultivars might still exhibit deficiency symptoms during critical stages like flowering and boll development.

The study also revealed a positive impact of potassium application on proline, leaf water potential, seed amino acid content, seed crude fiber content, and seed crude protein content under reduced irrigation conditions (Tables 3-4). This is likely due to increased potassium uptake facilitated by its adequate availability in the soil (Zahoor *et al.,* 2017). Notably, the cultivar CYTO-124 displayed the highest proline, amino acid, and crude protein content, while CIM-554 exhibited the highest crude protein content under stress conditions with potassium application. The stress-induced increase in proline content observed in this study aligns with the findings of (Zhang *et al.,* 2014), who reported proline accumulation as a response to drought stress. Overall, the higher levels of proline, amino acids, and crude protein observed with potassium application under reduced irrigation suggest that potassium can be instrumental in maximizing yield and seed quality under drought conditions (Onyango *et al.,* 2008).

Further research could explore the intricate physiological mechanisms through which potassium application influences stress resilience and various physiological functions in cotton plants. Additionally, studying how potassium interacts with other agricultural practices across diverse environmental contexts would yield valuable insights for enhancing cotton production in different field settings. With this knowledge, farmers can make informed choices about sustainable and high-quality cotton cultivation strategies.

Conclusions

This study explored how potassium application and irrigation levels influence cotton growth, physiology, and potassium use efficiency. The key findings highlight the importance of potassium for mitigating the negative effects of water stress on cotton plants. Several cultivars, including FH-142, CIM-554, CYTO-124, and IUB-2013, demonstrated superior performance under both irrigation levels with and without potassium application, suggesting their potassium-efficient nature. FH-142 exhibited exceptional potassium recovery efficiency under water stress with potassium application. These findings offer valuable insights for both farmers and breeders. Farmers can benefit by selecting potassium-efficient cultivars to maintain cotton growth and quality under water stress, particularly on potassium-deficient soils. Breeders can leverage the observed genetic variation in potassium use efficiency to develop even more efficient cotton varieties. Both parties can contribute to more sustainable and productive cotton production by adopting these strategies.

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