Pak. J. Bot., 54(5): 1663-1673, 2022. DOI: http://dx.doi.org/10.30848/PJB2022-5(4)

EVALUATION OF THE RESPONSE OF INDIGENOUS COTTON CULTIVARS TO LOW POTASSIUM STRESS IN HYDROPONICS SYSTEM

MUHAMMAD NAEEM AKHTAR[1,3*], TANVEER-UL-HAQ[1] AND FIAZ AHMAD[2]

[1]*Department of Soil & Environmental Sciences, MNS- University of Agriculture, Multan- Pakistan*
[2]*Plant Physiology/Chemistry Section, Central Cotton Research Institute, Multan- Pakistan*
[3]*Pesticide Quality Control Laboratory, Multan-Pakistan*
**Corresponding author's: muhammaduam01@gmail.com*

Abstract

The quantity and availability of potassium (K) are declining in soils of the world and becoming a serious issue for successful cotton production. Considerable variation for K acquisition has been reported in cotton germplasm. Therefore, exploiting the genotypic variation for K uptake and utilization could be useful for the development of K efficient cultivars. Nine pre-selected cotton cultivars were evaluated for their potassium use efficiency (KUE) and growth response under low (0.26 mM) and adequate (3.33 mM) K levels. Cultivars were grown for six weeks in a hydroponics system supplying with half-strength Hoagland's solution with the above-mentioned levels of K.Cultivars showed variable response for biomass production, shoot tissue K concentration, K uptake, KUE at low and adequate K levels. Leaves, stalk and root biomass productions were significantly reduced due to low K stress. A significant positive correlation ($R^2 = 0.95^{**}$, $p<0.01$) was found between shoot dry matter (SDM) and KUE at a low K supply level in cotton cultivars. Overall reduction of net photosynthetic rate (P_N) in cultivars due to low K stress was 38.7% compared with adequate K level. Furthermore, the correlations of K utilization index and KUEwith the net photosynthetic rate (P_N) were positive and highly significant ($R^2 = 0.95^{**}$, $R^2 = 0.85^{**}$, $p<0.01$), respectively, at a low K level. Therefore, the potassium utilization efficiency (KUTE) trait can be used as a criterion for the selection of K-efficient cotton cultivars. The results exhibit significant variability for K uptake and KUEin the indigenous cotton cultivars which can be exploited to develop promising cultivars for low K input environments.

Key words: Gossypium hirsutum cultivars, Genetic variation, K uptake and use efficiency, gas exchanges characteristics.

Introduction

Most of the world's soils are exhausted in the supply of micronutrients including potassium due to the use of hybrid varieties and intensive cropping (Zorb *et al.*, 2014). Cotton crop is generally more sensitive to low potassium (K) availability in soils with poor fertility (Hussain *et al.*, 2021; Gilani *et al.*, 2020). In Pakistan, about 43% of agricultural soils are K deficient (K<80 ppm), mainly due to high cropping intensity, monoculture cropping patterns, low soil organic matter and shortage of canal irrigation water (Hassan *et al.*, 2008). Therefore, less K availability in soils severely affects the growth and yield of cotton. However, K uptake in plants is under genetic control and considerable variation has been found in many crop plants for potassium use efficiency (KUE) by many scientists (Aamir *et al.*, 2014).

Cotton is an important fiber crop of Pakistan. The total area of the world under cotton cultivation is 33.2 million hectares with an average annual production of 18.9 million tons. In Pakistan, cotton is grown on an area of 2.54 million hectares with an average seed cotton yield of 830 kg ha^{-1} (Anon., 2020). Globally, Pakistan ranked 4th largest among seed cotton-producing countries during the year 2016-17. It provides the raw material for the local textile industry and contributed 1.4%to the country's GDP (Ahmad *et al.*, 2021). The area and production of cotton are declining in Pakistan due to many challenges including low yielding varieties, low nutrient use efficiency, heavy insect pest attacks, changing climate, and environmental stresses, particular, heat and drought stress, all widening the gap between the actual and potential yield of cotton cultivars.

The selection and development of efficient cotton cultivars for low-K-input environments may improve crop yield and reduce the demand for K fertilizers. Potassium is a quality nutrient and plays a vital role in crop production. The slow release from minerals and fixation under certain conditions also reduce K uptake in crops (Gill *et al.*, 2005). The intermittent response of crops for K uptake is one of the major factors responsible for low K fertilization by the farmers. Therefore, alternate approaches must be explored to increase K use efficiency in agriculture. The selection and development of efficient K cultivars are particularly important for developing countries with inadequate potassium reserves. Under the current situation, farmers need K-efficient cotton genotypes that perform better than others with the same K inputs (Nawaz *et al.*, 2006; Hassan *et al.*, 2011; Irfan *et al.*, 2020). Crop plants have developed physiological, biochemical, and molecular adaptive mechanisms to manage low K stress. The improved plants met their K demand through uptake by an efficient transport system from the soil and translocation into other plant parts. The transport of K across membranes is mediated by K channels and transporters. Potassium transporters in plants are generally, classified into three families of membrane proteins: the K^+ uptake permeases (KT/HAK/KUP), the K^+ transporters (Trk/HKT) family and the cation proton antiporters (CPA) (Maser *et al.*, 2001).

Potassium is one of the dynamic nutrients for the plant kingdom. It constitutes about 10% of the total plant biomass (Azeem *et al.*, 2021), and is involved in various physiological and morphological processes including water relations, enzyme activation, and quality of produce. Considerable genetic variability has been reported among cotton cultivars for K uptake and K utilization efficiency (Mahmood *et al.*, 2001; Aamir *et al.*, 2014). The variable capacity forK acquisition in cotton cultivars, in turn, improves the efficiency of the photosynthetic system and root development. Plants use adaptive mechanisms such as alteration of root architecture to explore more soil volume, increased carboxylate exudation containing phosphatases, the release of nucleases and various organic acids to tolerate low K stress. Plants utilize these strategies to extract more K from exchangeable pools in the soil. Therefore, the selection and development of cultivars with improved K use efficiency could be an alternate strategy to overcome problems of low K availability in soils (Hassan *et al.*, 2010). Zhang *et al.*, (2007) also reported that improved plant growth under low K availability inefficient plants is attributed to the enlarged root system, efficient physiological and transport mechanisms. Cotton cultivars with enhanced K-use efficiency may be helpful in the development of high-yielding cotton cultivars in national breeding programs. The selection and development of cultivars with the potential to grow under low K conditions can improve cotton yield. Therefore, a hydroponics experiment was performed to evaluate the indigenous cotton cultivars for KUE and other growth traits under low K environment.

Materials and Methods

Experimental site, treatments and design: The hydroponic culture experiment was conducted in the glasshouse at Central Cotton Research Institute, (CCRI) Multan-Pakistan during the growing season 2018-19. The treatments plan included two levels of K (adequate and low) and nine cultivars. The experiment was laid out in CRD with two factorial arrangements with 3 replications. Based on results from the preliminary sand culture experiment, nine cotton cultivars with variable K efficiency were selected to further test their response at low K (0.26 mM) and adequate (3.33mM) levels.

Set up of hydroponic system and management: Nursery of cotton cultivars was grown in iron trays filled with washed river sand. At the two-leaf stage, the uniform-sized seedlings of cotton were transplanted into holes of the thermopore sheets floating on half-strength Hoagland's solution (Hoagland & Arnon, 1950) amended with desired potassium (K) levels in the iron tubs lined with the polythene sheet. The hydroponic system was comprised of six iron tubs (1.5 × 1.5 × 0.5 ft) of 50 L capacity. Three tubs were kept as adequate K levels and the other three as low K levels. Twenty-seven plants were maintained in each tub randomly repeating three plants of each cultivar in equally spaced numbered holes, moreover, every plant was properly tagged. Aeration was provided with the help of aeration pumps. The pH of the Hoagland's solution was maintained at 6.5±0.2 daily with the help of pH meter (Hanna, Japan) by using 1.0 M NaOH or 1.0 M HCl. Harvesting was done after six weeks of transplanting.

Data collection and K analysis: Agronomic data were taken about growth parameters i.e. shoot- root dry matter and root: shoot ratio while gas exchange characteristics were recorded by using a handheld portable photosynthesis system (CL-340 CID, USA) at the age of 40 days after transplanting. Harvested plants were washed with distilled water and dried with the help of blotting paper. Leaf, stalk and roots were separated and immediately stored in the paper bags before air drying in the laboratory. Later, plant material was dried at 70°C for 48 hours in a drying oven and the oven-dry weights were recorded and finally ground to get the fine powder. From ground plant samples, K concentration was determined by using the ion extraction method on flame photometer Jenway PFP-7 (Munns *et al.,* 2010).

Estimation of potassium use efficiency indices: K use efficiency indices were calculated using the following formulas:

NUE indices	Formula	References
Potassium uptake	$= \text{K concentration (mg)} \times \text{Dry matter (g)}$	Hassan *et al.*, (2011)
Potassium use efficiency (KUE)	$= \dfrac{\text{Shoot dry weight at adq. K} - \text{Shoot dry weight at low K}}{\text{Shoot K uptake at adq. K} - \text{Shoot K uptake at low K}}$	Fageria*et al.*, (2001)
Relative K accumulation (RKA)	$= \dfrac{\text{K uptake in shoot at low K}}{\text{K uptake in shoot at adequate K}} \times 100$	Yang *et al.*, (2003)
K efficiency ratio (KER)	$= \dfrac{\text{Value at low K}}{\text{Value at adequate K}} \times 100$	Hassan *et al.*, (2011) Gunes *et al.*, (2006)
Potassium stress factor (K	$= \dfrac{\text{Shoot dry weight at adq.K} - \text{Shoot dry weight at low K}}{\text{Shoot dry weight at adequate K}} \times 100$	Irfan *et al.*, (2020)
K utilization efficiency (KUTE)	$= \dfrac{\text{Total fresh biomass at low K}}{\text{Total fresh biomass at adequate K}} \times 100$	Irfan *et al.*, (2020)
K utilization index (KUI)	$= \dfrac{\text{Dry matter yield index}}{\text{Potassium use efficiency}} \times 100$	Aamir *et al.*, (2014)
Dry matter yield index (DMYI)	$= \dfrac{\text{Total dry biomass at low K}}{\text{Mean of cultivars}} \times \dfrac{\text{Total dry biomass at adequate K}}{\text{Mean of cultivars}}$	Fageria *et al.*, (2010) Fageria *et al.*, (2010

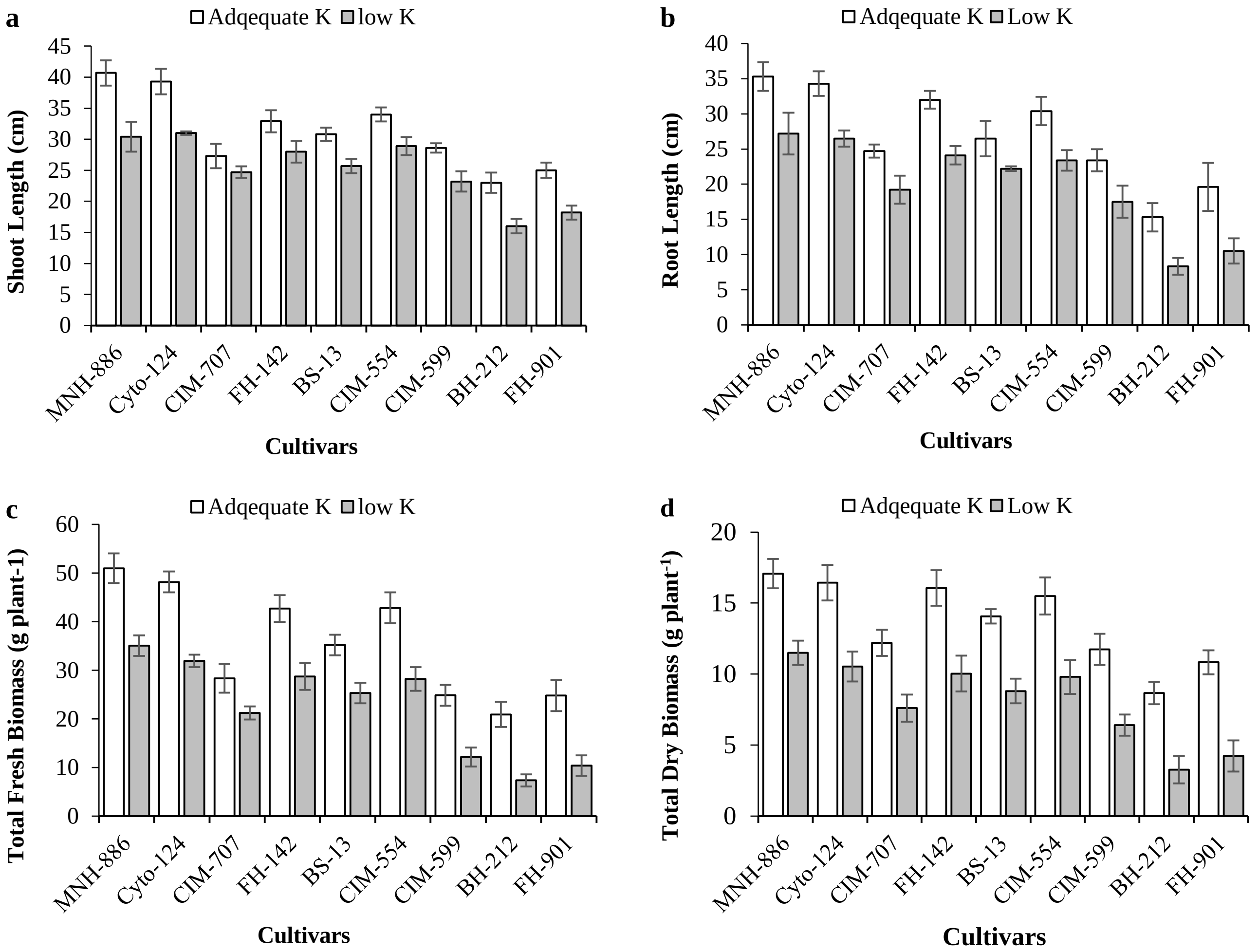

Fig. 1. Shoot length (a), root length (b), total fresh biomass (c) and total dry biomass (d) of nine cotton cultivars at two K levels under hydroponic conditions. Values are means of three replicates (n = 6) and presented with standard error.

Statistical analysis

The recorded data were subjected to statistical analysis and the treatment means were compared by using the least significant difference test (LSD) at a significance level of $p<0.05$. Two tail correlations and curve fittings were carried out with SPSSsav (version 16.0) and MS Excel software using the Statistical Analysis ToolPak (Microsoft Co.).

Results

Comparison of cotton cultivars for shoot length, root elongation and total fresh biomass: Low K supply caused a reduction in both shoot and root elongation of cotton cultivars as compared with adequate K treatment (Fig. 1 a & b), however, the effect was more pronounced on a shoot than on root length. A highly significant variation ($p\leq0.05$) was observed among treatments, cultivars and their interaction for the shoot and root lengths as well as for total fresh biomass under adequate and low K supplies levels.

At the low K level, shoot length was ranged from 16.0 cm for cultivar BH-212 to 31.0 cm for Cyto-124 with a mean value of 25.1 cm (Fig. 1a), whereas, at adequate K level, shoot length was ranged from 23.0 to 40.7cm in BH-212 and MNH-886, with a mean shoot length of 31.3 cm, respectively. Low K supply caused a 19.9% reduction in overall shoot length compared to control. The relative shoot length was ≥75% in seven cultivars including, CIM-707 (90.5%), FH-142 (85.1%), CIM-554 (85.0%), IUB-2013 (83.4%), CIM-599 (81.1%), Cyto-124 (78.9%) and MNH-886 (74.7%), respectively. The root length of cotton cultivars was increased at a low K level relative to adequate K, which might be an adaptive strategy of the cultivars to thrive in K starving conditions. At the low K level, root length was ranged from 8.3 cm for cultivar BH-212 to 27.2 cm for MNH-886 with a mean value of 19.9 cm (Fig. 1b), whereas, at adequate K level, root length was ranged from 15.3 to 35.3 cm with a mean root length of 26.8 cm, respectively. At low K supply treatment, the overall reduction in root length of cotton cultivars was 19.7% compared with adequate K supply level. The mean total plant length (root and shoot) was 45.0 cm at the low K level compared with adequate K level, resulting in the reduction of 22.6%. Similarly, at the low K level, total fresh biomass was ranged from 7.3g for cultivar BH-212 to 35.1g for MNH-886 (Fig. 1c), whereas, at adequate K level, it was ranged from 20.9 to 51.0g in BH-212 and MNH-886, respectively. Low K supply caused a 37.2% reduction in overall total fresh biomass compared with control.

Table 1. Plant dry biomass of nine cotton cultivars at two K supply levels in hydroponic culture.

Cotton cultivars	Dry matter production (g plant^{-1})								
	Leaves			Stalk			Root		
	Adequate K	Low K	KER %	Adequate K	Low K	KER %	Adequate K	Low K	KER %
MNH-886	8.90 ± 0.37	6.00 ± 1.04	67.4	3.63 ± 0.07	2.00 ± 0.04	55.1	4.53 ± 0.45	3.50 ± 0.28	77.3
Cyto-124	8.23 ± 0.52	5.17 ± 0.27	62.8	3.97 ± 0.08	2.17 ± 0.04	54.7	4.23 ± 0.28	3.20 ± 0.17	75.7
CIM-707	5.37 ± 0.87	3.10 ± 0.25	57.7	3.17 ± 0.06	1.20 ± 0.02	37.9	3.67 ± 0.07	2.23 ± 0.45	60.8
FH-142	7.00 ± 0.31	5.03 ± 0.19	71.9	4.63 ± 0.09	1.70 ± 0.03	36.7	4.43 ± 0.38	3.30 ± 0.34	74.5
BS-13	6.00 ± 0.36	4.43 ± 0.35	73.8	4.03 ± 0.08	1.73 ± 0.03	42.9	4.03 ± 0.10	2.63 ± 0.12	65.3
CIM-554	7.03 ± 1.34	4.67 ± 0.19	66.4	4.30 ± 0.08	2.00 ± 0.04	46.5	4.17 ± 0.28	3.13 ± 0.12	75.1
CIM-599	5.27 ± 0.61	3.27 ± 0.10	62.0	2.93 ± 0.06	1.13 ± 0.01	38.6	3.53 ± 0.14	2.20 ± 0.47	62.3
BH-212	3.93 ± 0.18	1.80 ± 0.28	45.8	1.67 ± 0.03	0.70 ± 0.01	41.9	3.07 ± 0.03	1.47 ± 0.26	47.9
FH-901	4.57 ± 0.29	2.23 ± 0.20	48.8	2.83 ± 0.05	0.50 ± 0.01	17.7	3.43 ± 0.44	1.55 ± 0.22	45.2
Mean	**6.26**	**3.97**	**61.9**	**3.46**	**1.46**	**41.3**	**3.90**	**2.58**	**64.9**
F test:									
Cultivars (C)		**37.02****			**24.69****			**58.74****	
K levels (K)		**7.57****			**1.39****			**5.77****	
C × K interaction		**0.22ns**			**0.31ns**			**0.21ns**	
LSD – value									
Cultivars (C)		**1.56**			**1.74**			**0.72**	
K levels (K)		**0.73**			**0.82**			**0.34**	

Data are shown as means of three replication along with standard error with six plants for each replication. Means of cultivars, K levels and K × C are presented by using the F test. **; significant and ns; non-significant at $p<0.05$ whereas KER is the potassium efficiency ratio

Comparison of cotton cultivars for plant dry matter accumulation in leaf, stalk, root and total dry matter (g plant^{-1}): The exposure to low K level caused a reduction in the production of leaves dry matter (LDM), however, a significant variation for LDM ($p \leq 0.05$) was observed among cotton cultivars (Table 1). The overall reduction in LDM of cotton cultivars was 36.6% when K supply was decreased from adequate (3.33 mM) to low K level (0.26 mM KCl). Leaves dry matter at low K supply level ranged from 1.80 to 5.17 g plant^{-1} in cultivar BH-212 and Cyto-124, respectively, with a mean LDM value of 3.97 g plant^{-1}. The comparison made based on relative LDM shows that at low K level, out of 9 cultivars, six cultivars viz: MNH-886, Cyto-124, CIM-554, FH-142, IUB-2013 and CIM-599 were ≥60% of their respective controls in decreasing order. The cultivars which were below 59% of control included CIM-707, BH-212 and FH-901 in decreasing order, respectively. At low K level, the production of stalk dry matter (SDM) cultivars ranged from 0.50g plant^{-1} in BH-212 to 2.17g plant^{-1} for MNH-886 with a mean value of 1.46g plant^{-1} for the cultivars. On exposure to low K level the minimum reduction in the SDM was recorded in cultivar MNH-886 (44.9%) followed by Cyto-124 (45.3%), CIM-554 (53.5%), IUB-2013 (57.1%), and BS-212 (58.1%), respectively, whereas, reduction in SDM was highest (82.3%) in FH-901. Compared with adequate K control treatment the overall reduction in SDM of cotton cultivars was 57.9% at low K level (Table 1).

The production of root dry matter (RDM) of cotton cultivars at low K level ranged from 1.47g plant^{-1} in BH-212 to 3.50g plant^{-1} for MNH-886 with a mean value of 2.58 g plant^{-1} (Table 1). The reduction in RDM was minimum in cultivar MNH-886 (22.7%) followed by Cyto-124 (24.4%), CIM-707 (24.9%), IUB-2013 (25.5%), BH-212 (34.7%), CIM-554 (37.9%) and CIM-599 (39.2%), respectively, whereas, it was highest in FH-901 (54.8%) and FH-142 (52.1%), respectively. There was a 64.8% reduction in overall RDM in cultivars at a low K level when compared with adequate K treatment. At low K level, the total plant dry matter (PDM) (root, stalk and leaves) of cotton cultivars ranged from 3.97g plant^{-1} in BH-212 to 17.50g plant^{-1} in MNH-886, with a mean value of 8.0 g plant^{-1} (Fig. 1d). The minimum reduction in plant dry matter was in cultivar MNH-886 (32.6%) followed by Cyto-124 (35.6%), CIM-599 (36.8%), CIM-707 (37.5%), IUB-2013 (37.6%), CIM-554 (43.7%) andFH-142 (54.2%), respectively,whereas, it was highest in FH-901 (60.5%).Overall, MNH-886, Cyto-124, FH-142 and CIM-554 produced higher PDM than BH-212. The variety FH-901 produced less PDM at low K level accounting 57.2% reduction when compared with adequate K level.

Comparison of cotton cultivars for K concentration and tissue-specific distribution in leaves, stalk, root and total K concentration (mg g^{-1}dw): The statistical analysis explained that the variance for K concentration in leaves, stalk, root and total concentration is significantly varied among treatments, cultivars and treatment × cultivar interaction ($p \leq 0.05$) (Table 2). Generally, the K concentration was higher in the leaves followed by stalks and roots at both low and adequate K supply levels.

The data indicate that the K concentration of leaves (14.5 mg g-^{1}dw) at a low K level was significantly decreased (30.7%) compared with concentration (21.0 mg g^{-1}dw) at an adequate K supply level. The K concentration was ranged from 5.4 to 18.8 mg g^{-1}dw in cultivars BH-212 and CIM-554, with a mean concentration of 14.5 mg g^{-1} dw at low K level, whereas, it was ranged from 16.3 to 23.0 mg g^{-1} dw in BH-212 and MNH-886, with a mean value of 21.0 mg g^{-1}dw at adequate K level (Table 2). The comparison of cotton cultivars based onKER for K concentration indicates that five cultivars including CIM-554 (84.3%), Cyto-124 (81.5%), FH-142 (81.6%), MNH-886 (81.3%), and IUB-2013 (78.6%) were more than 75% of their respective controls, whereas, rest of the four cultivars CIM-599 (69.5%), CIM-707 (59.1%), FH-901 (38.5%), and BH-212 (33.1%) were ≤70% of control, respectively. There is 29.2% decrease in K concentration of stalk tissue at a low K supply level compared to adequate K level in cotton cultivars. At low K level, the stalk K concentration was ranged between 3.9 to 13.4 mg g^{-1}dwin cultivars BH-212 and MNH-886, with a mean value of 10.8 mg g^{-1}, respectively. The seven cultivars which maintained more than 70% of their KER for stalk K concentration, at low K supply level include Cyto-124, CIM-544, FH-142, MNH-886, CIM-707, IUB-2013 and CIM-599, respectively. Generally, the K concentration in the shoot was higher than stalk and root at both adequate and low K levels. The root K concentration was ranged between 1.2 to 9.3 mg g^{-1}dw in cultivars with a mean concentration value of 6.8 mg g^{-1}dw, at a low K level. There was a 33% decrease in K concentration of root at low K supply level compared to adequate K level in cotton cultivars. The seven cultivars which sustained more than 60% of their KER for K concentration, at low K level include Cyto-124, CIM-544, FH-142, MNH-886, IUB-2013, CIM-707 and CIM-599, respectively (Table 2).

The low K supply to cotton cultivars caused a 30.7% reduction in K concentration when compared with adequate K level, however, the response of cultivars was variable. At low K level, the total K concentration was ranged from 10.5 to 41.4 mg g^{-1}dw in BH-212 and MNH-886, with the mean value of 32.1 mg g^{-1} dw. At adequate K level, the total K concentration was recorded from 34.9 to 52.4 mg g^{-1}dwin cultivars, with a mean value of 46.3 mg g^{-1} dw. The comparison of cotton cultivars on the basis of KER for the total K concentration shows that seven cultivars including CIM-544 (80.8%), FH-142 (79.5%), Cyto-124 (79.3%), MNH-886 (79.0%), IUB-2013 (77.2%), CIM-599 (74.8%) and CIM-707 (68.2%) were more than 65% of their respective controls. The cultivar BH-212 experienced maximum reduction (69.1%) in total K concentration under low K supply treatment.

Comparison of cotton cultivars for tissue K uptake and specific distribution in leaves, stalk, root and total K uptake (mg plant^{-} dw^{1}): The cultivars varied significantly ($p \le 0.05$) in K uptake in different plant parts when grown under adequate and low K levels (Table 3). Generally, the K uptake was higher in the leaves followed by stalk and root at both low and adequate K supply levels. A total of 55.7% overall reduction in plant K uptake was observed at low K level than an adequate K level.

The data regarding K uptake of leaves at low K level depicts that there was a decrease of 52.3% compared with K uptake at adequate K supply level. At low K level, the K uptake of leaves in cotton cultivars was ranged from 10.0 to 112 mg plant^{-1}dw in cultivars BH-212 and MNH-886, with a mean K uptake of 63.9 mg plant^{-1} dw, whereas, it was ranged from 64.0 to 205.0 mg plant^{-1} dw, with a mean value of 134.0 mg plant^{-1}dw at adequate K level. The comparison of cultivars based onKER for K uptake in leaves indicated that five cultivars including, FH-142 (58.3%), IUB-2013 (58.3%), CIM-554 (56.1%), MNH-886 (54.6%) and Cyto-124 (51.3%) were more than 50% of their respective controls, whereas, four cultivars CIM-599 (43.0%), CIM-707 (33.9%), FH-901 (19.3%), and BH-212 (15.6%) were ≤ 45% of control, respectively (Table 3).

There is a 68.0% decrease in K uptake of stalks at low K supply level compared to adequate K level in nine cotton cultivars. The stalk K uptake was ranged from 2.2 to 28.8 mg plant^{-1}dwin cultivars (FH-901 and Cyto-124) with a mean value of 17.5 mg plant^{-1} dw, respectively. At low K level, only six cultivars maintained more than 30% of their KER for K uptake in stalks includes Cyto-124, CIM-544, MNH-886, CIM-707, IUB-2013 and CIM-599, respectively. On an overall basis at a low K level, there was 51% less K uptake in roots compared with adequate K level. The root K uptake was ranged from 1.8 to 32.6 mg plant^{-1} dw in cultivars BH-212 and MNH-886, with a mean uptake value of 19.6 mg plant^{-1} dw, respectively at low K level. The seven cotton cultivars which maintained more than 40% of their relative K uptake at low K level include Cyto-124, CIM-544, FH-142, MNH-886, CIM-707, CIM-599 and IUB-2013, respectively (Table 3).

Table 2. K concentration in different plant organs of nine cotton cultivars at K supply levels in hydroponic culture.

Cotton cultivars	K concentration (mg/g)								
	Leaves			Stalk			Root		
	Adequate K	Low K	KER %	Adequate K	Low K	KER %	Adequate K	Low K	KER %
MNH-886	23.0 ± 0.47	18.7 ± 1.19	81.3	18.0 ± 0.34	13.4 ± 0.26	74.4	11.4 ± 0.22	9.3 ± 0.18	81.6
Cyto-124	22.7 ± 0.98	18.5 ± 0.24	81.5	17.8 ± 0.34	13.3 ± 0.25	74.7	11.2 ± 0.19	9.2 ± 0.16	82.1
CIM-707	21.5 ± 0.85	12.7 ± 0.98	59.1	13.3 ± 0.25	11.2 ± 0.21	84.2	9.9 ± 0.19	6.6 ± 0.13	66.7
FH-142	22.3 ± 0.72	18.2 ± 1.16	81.6	17.7 ± 0.34	13.1 ± 0.25	74.0	11.1 ± 0.21	9.3 ± 0.15	83.8
BS-13	22.0 ± 0.47	17.3 ± 0.98	78.6	17.2 ± 0.33	12.8 ± 0.24	74.4	10.9 ± 0.20	8.6 ± 0.13	78.9
CIM-554	22.3 ± 0.72	18.8 ± 1.06	84.3	17.5 ± 0.33	13.2 ± 0.25	75.4	11.2 ± 0.21	9.2 ± 0.18	82.1
CIM-599	20.3 ± 0.98	14.1 ± 1.87	69.5	13.0 ± 0.25	11.6 ± 0.22	89.2	9.5 ± 0.18	6.3 ± 0.12	66.3
BH-212	16.3 ± 0.72	5.4 ± 0.28	33.1	11.0 ± 0.21	3.9 ± 0.07	35.5	7.6 ± 0.14	1.2 ± 0.02	15.8
FH-901	18.2 ± 0.59	7.0 ± 1.93	38.5	11.3 ± 0.22	4.4 ± 0.08	38.9	8.2 ± 0.16	1.3 ± 0.03	15.9
Mean	**21.0**	**14.5**	**67.5**	**15.2**	**10.8**	**69.0**	**10.1**	**6.8**	**63.7**
F test:									
Cultivars (C)	**17.27****			**96.25****			**110.06****		
K levels (K)	**116.89****			**384.77****			**511.78****		
C × K interaction	**2.93****			**7.65****			**17.40****		
LSD-value									
Cultivars (C)	**2.56**			**0.96**			**0.63**		
K levels (K)	**1.21**			**0.45**			**0.30**		

Data are shown as means of three replication along with standard error with six plants for each replication. Means of cultivars, K levels and K × C are presented by using the F test. **; significant and ns; non-significant at $p<0.05$ whereas KER is the potassium efficiency ratio

Table 3. K uptake in different plant organs of nine cotton cultivars at K supply levelsin hydroponic culture.

Cotton cultivars	K uptake (mg plant^{-1})								
	Leaves			Stalk			Root		
	Adequate K	Low K	KER %	Adequate K	Low K	KER %	Adequate K	Low K	KER %
MNH-886	205 ± 20.03	112 ± 25.8	54.6	65.4 ± 1.94	26.8 ± 0.80	41.0	51.7 ± 4.70	32.6 ± 2.87	63.1
Cyto-124	187 ± 11.37	96 ± 5.20	51.3	70.6 ± 2.10	28.8 ± 0.86	40.8	47.4 ± 3.22	29.4 ± 2.15	62.0
CIM-707	115 ± 22.75	39 ± 5.27	33.9	42.1 ± 1.25	13.4 ± 0.40	31.8	36.3 ± 0.06	14.7 ± 3.03	40.5
FH-142	156 ± 4.67	91 ± 6.97	58.3	82.0 ± 2.44	22.3 ± 0.66	27.2	49.2 ± 4.89	30.7 ± 3.71	62.4
BS-13	132 ± 9.99	77 ± 10.2	58.3	69.4 ± 2.06	22.2 ± 0.78	32.0	44.0 ± 1.78	22.6 ± 1.47	51.4
CIM-554	157 ± 26.6	88 ± 2.18	56.1	75.3 ± 2.23	26.4 ± 0.21	35.1	46.7 ± 2.31	28.8 ± 0.94	61.7
CIM-599	107 ± 17.25	46 ± 4.87	43.0	38.1 ± 1.13	13.1 ± 0.08	34.4	33.6 ± 0.76	13.9 ± 2.74	41.4
BH-212	64 ± 5.46	10 ± 1.77	15.6	18.3 ± 0.54	2.7 ± 0.06	14.8	23.3 ± 0.26	1.8 ± 031	7.70
FH-901	83 ± 5.29	16 ± 5.82	19.3	32.0 ± 0.95	2.2 ± 0.66	6.9	28.2 ± 4.18	2.0 ± 0.36	7.11
Mean	**134.0**	**63.9**	**43.4**	**54.8**	**17.5**	**29.3**	**40.0**	**19.6**	**44.1**
F test:									
Cultivars (C)	**13.48****			**3.18****			**23.57****		
K levels (K)	**87.62****			**51.26****			**183.79****		
C × K interaction	**0.49ns**			**0.99ns**			**0.29ns**		
LSD- value									
Cultivars (C)	**32.21**			**23.75**			**6.50**		
K levels (K)	**15.18**			**11.19**			**3.06**		

Data are shown as means of three replication along with standard error with six plants for each replication. Means of cultivars, K levels and K × C are presented by using the F test. **; significant and ns; non-significant at $p<0.05$ whereas KER is the potassium efficiency ratio

The low K supply to cultivars caused a 55.8% reduction in total K uptake as compared with an adequate K level. Total K uptake was ranged from 14.5 mg plant^{-1}dw in BH-212 to 171.4 mg plant^{-1}dw in MNH-886, with a mean value of 101 mg plant^{-1}dw at low K level, whereas, at adequate K level the total plant K uptake was recorded from 105 to 322 mg plant^{-1} in cultivars BH-212 and MNH-886, with a mean value of 228 mg plant^{-1} dw, respectively. The comparison of cultivars based on KER for total K uptake shows that five cultivars including MNH-886 (53.2%), CIM-554 (51.3%), Cyto-124 (50.6%), FH-142 (50.1%) and CIM-599 (40.9%) were more than 50% of their respective controls at low K level.

Comparison of cotton cultivars for photosynthetic rate and gas exchange characteristics: The reduction of K in the solution results in lowering of net photosynthetic rate in the cotton cultivars, however, cultivars differed significantly ($p<0.01$) for net photosynthetic rate (P_N) at both K supply levels (Table 4). At low K level, P_N ranged from 11.0 to 23.3 µmol (CO_2) m^{-2}S^{-1}in cultivars with a mean value of 19.4 µmol (CO_2) m^{-2}S^{-1}. However, interestingly cultivar MNH-886 retained higher P_N than the other cultivars at low K level. At adequate K level, it was ranged from 22.3 to 38.6 µmol (CO_2) m^{-2}S^{-1} with a mean value of 31.6 µmol (CO_2) m^{-2}s^{-1}. Overall reduction in P_N among cultivars due to low K stress is 38.7% compared with the adequate control level. The transpiration rate (E) of nine cotton cultivars was also significantly and negatively affected by low K level. There is 48% reduction in transpiration rate due to low supply of K compared to an adequate K level. At low K level, the E ranged from 1.27 to 2.70 mmol H_2O m^{-2} s^{-1} with a mean E value of 2.1 mmol H_2O m^{-2} s^{-1} in cotton cultivars. At low K level the minimum reduction in transpiration rate of 42.1 mmol H_2O m^{-2} s^{-1} was recorded in cultivar CIM-554, followed by IUB-2013 (43.8), FH-142 (46.0), MNH-886 (46.7), CIM-599 (47.2), Cyto-124 (48.4), CIM-707 (49.4) and FH-901 (53.3), whereas, the maximum reduction of 59.3% was noted in BH-212, respectively. The limited supply of K caused 19.1% reduction in the rate of stomatal conductance (gs) in nine cotton cultivars. However, there was significant variation among cultivars for gs and it ranged from 38.1 to 71.3mmol H_2O m^{-2} s^{-1} with the mean value of 60.5mmol H_2O m^{-2} s^{-1} at a low K level. The comparison of cultivars based on KER values of stomatal conductance indicated that the cultivars Cyto-124 and MNH-886 maintained a higher rate of gs (84% of control) than the rest of the cultivars (Table 4).

Comparison of cotton cultivars for K use efficiency indices: Potassium use efficiency (KUE) is expressed asK utilization efficiency (KUTE), potassium efficiency ratio (KER), relative K accumulation (RKA), potassium utilization index (KUI) and potassium stress factor (KSF). The cotton cultivars also showed variations for K use efficiency indices at both K supply levels (Fig. 2 a & b).

KUE is a quantity of biomass production per unit of tissue K concentration. This parameter can help classify the cultivars that can thrive under a low concentration of a particular nutrient supply. The KUE ranged from 5.1 to 21.6 g SDWmg g^{-1} K uptake at low and adequate K supply levels, respectively (Fig. 2 a). The overall KER in cultivar Cyto-124 showed the maximum (80.5%) followed by MNH-886 (80.4%), CIM-554 (83.7%), CIM-599 (75.9%) and CIM-707 (66.5%), respectively, whereas, FH-901 and BH-212 showed 42.9 and 34.6 % KER, respectively at low K supply.

Plants take up K by roots and then translocate in other plant parts for various key physiological processes, particularly for adaptation to low K environments. Therefore, the KUTEtrait is an important marker to evaluate potential under low K supply. It is found that the

KUTEvaries from 42 to 70% in cotton cultivars with a mean value of 64.8% (Fig. 2b). The cultivar MNH-886 accumulated 68% higher KUTE than cultivar BH-212. Similarly, relative K accumulation (RKA) in cultivars was ranged from 15.4 to 51.3% (Fig. 2b). The MNH-886 showed more RKA, followed by Cyto-124 ≤ IUB-2013 ≤ CIM-554 ≤ FH-142, CIM-707 ≤ FH-901and BH-212. The increase in the K stress factor caused a decrease in RKA (%) of cotton cultivars.

The potassium utilization index designates the relative reduction in the KUE as the K concentration in the growth medium is reduced from adequate to low K level. Data regarding KUI (Table 5) presented that MNH-886 shows the maximum KUI (5.2%) value, therefore seemed to have high plasticity in adjusting to a K stress environment. Whereas BH-212 and FH-901 showed low values (0.7 and 0.9) of KUI at adequate and low K levels, respectively.

Table 4. Gas exchange characteristics of nine cotton cultivars at K supply levelsin hydroponic culture.

Cotto cultivars	**Net photosynthetic rate P_N (µmol CO_2 $m^{-2}s^{-1}$)**			**Transpiration rate (E) E(mmol H_2O $m^{-2}s^{-1}$)**			**Stomatal conductance C(mmol CO_2 $m^{-2}s^{-1}$)**		
	Adequate K	**Low K**	**KER %**	**Adequate K**	**Low K**	**KER %**	**Adequate K**	**Low K**	**KER %**
MNH-886	38.67 ± 1.76	23.33 ± 0.88	60.3	5.07 ± 0.32	2.70 ± 0.26	53.3	84.7 ± 3.61	71.4 ± 3.26	84.3
Cyto-124	35.33 ± 1.72	21.67 ± 1.45	61.3	4.50 ± 0.40	2.32 ± 0.45	51.6	76.9 ± 5.67	66.4 ± 3.67	86.4
CIM-707	31.67 ± 1.86	20.33 ± 1.76	64.2	3.87 ± 0.39	1.96 ± 0.29	50.6	73.3 ± 5.42	58.0 ± 4.87	79.1
FH-142	36.67 ± 1.76	22.33 ± 0.88	60.9	4.63 ± 0.32	2.50 ± 0.35	54.0	88.0 ± 3.49	73.4 ± 4.71	83.4
BS-13	32.67 ± 1.20	20.67 ± 1.45	63.3	4.00 ± 0.38	2.25 ± 0.54	56.3	78.4 ± 3.29	64.6 ± 4.85	82.4
CIM-554	34.33 ± 1.45	21.67 ± 0.88	63.1	4.20 ± 0.21	2.43 ± 0.84	57.9	82.5 ± 6.95	69.0 ± 2.46	83.6
CIM-599	28.33 ± 0.88	19.67 ± 0.87	69.4	3.60 ± 0.29	1.90 ± 0.35	52.8	67.9 ± 3.12	48.6 ± 4.06	71.7
BH-212	22.33 ± 1.20	11.00 ± 0.58	49.3	3.12 ± 0.09	1.27 ± 0.17	40.7	59.1 ± 3.26	38.2 ± 3.61	64.6
FH-901	24.33 ± 1.20	13.67 ± 0.89	56.2	3.17 ± 0.03	1.48 ± 0.08	46.7	62.3 ± 4.15	41.5 ± 2.98	66.6
Mean	**31.6**	**19.4**	**60.9**	**4.02**	**2.09**	**51.5**	**74.8**	**59.0**	**78.0**
F test:									
Cultivars (C)		**26.92****			**5.90****			**13.55****	
K levels (K)		**389.91****			**155.17****			**56.51****	
C × K interaction		**6.21****			**0.27ns**			**0.34ns**	
LSD- value									
Cultivars (C)		**2.66**			**0.66**			**9.04**	
K levels (K)		**1.25**			**0.31**			**4.26**	

Data are shown as means of three replication along with standard error with six plants for each replication. Means of cultivars, K levels and K × C are presented by using the F test. **; significant and ns; non-significant at $p<0.05$ whereas KER is the potassium efficiency ratio

Table 5. Potassium utilization index of nine cotton cultivars at K supply levelsin hydroponic culture.

Cotton cultivars	**Potassium utilization index (KUI %)**
MNH-886	5.21
Cyto-124	4.72
CIM-707	2.10
FH-142	3.75
BS-13	2.99
CIM-554	3.53
CIM-599	1.57
BH-212	0.58
FH-901	0.88
Mean	**2.81**
F test:	
Cultivars (C)	**8.10****
LSD for cultivars (C) = **1.6746**	

Means of cultivars are presented by using the F test. **; significant and ns; non-significant at $p<0.05$

Discussion

K takes part in the various morpho-physiological process throughout plant life. The quantity and availability of nutrients including K is declining in soils of the world and becoming a serious issue for cotton production (Tan *et al.*, 2005). The K deficiency results in poor root development, reduced seed cotton yield and low quality produce. However, it has been found that K uptake is under genetic control and considerable variation has been reported in cotton cultivars (Aamir *et al.*, 2014). An adequate supply of K significantly ($p≤0.05$) affected morphological and physiological characteristics of cotton seedlings compared to control. The findings explored that low K supply caused a reduction in length (~23%) and biomass (~37%) of cotton seedlings than control treatment (Fig. 1, Table 1). The possible reason for the reduction in length and biomass in low K supply seedlings might be a hindrance in the physiological role of K (Tan *et al.*, 2005). Zhang *et al.*, (2007) and Azeem *et al.*, (2021) witnessed the variations in plant growth under low K availability. However, variations in growth parameters occurred (Fig. 1 a, b, c & d) that might be due to genetic variations as reported earlier that plant response to K uptake and K utilization efficiency varied with the type of cultivars (Mahmood *et al.*, 2001; Aamir *et al.*, 2014). Considerable variations in LDM, SDM, RDM and PDM were found associated with the type of cultivar even at the same K supply (Table 1). Such variations are also highlighted by different researchers because K uptake is under genetic control (Aamir *et al.*, 2014). The findings were further supported by leaf K contents in cultivars (Table 2). The higher but variable K contents in cultivars CIM-554, Cyto-124, FH-142, MNH-886, and IUB-2013 compared to their respective controls might be due to K physiological role in uptake under strict control of genetic makeup. These findings are in line with the findings of Fageria *et al.*, (2001). Significant higher dry mass and K contents were observed in plants having adequate K supply (Tables 1, 2). Like agronomic parameters, a significant reduction in K uptake and use efficiency were also recorded due to Low K supply (Tables 1, 2 & 3), quite in line with findings of Zhang *et al.*, (2007), Hassan *et al.*, (2010) and Irfan *et al.*, (2020). Thus, the existence of genetic variation in cotton germplasm is important for the development of varieties with high nutrient use efficiency and these traits can be used in future breeding programs as screening markers. The selection and development of cultivars efficient in K uptake and use efficiency at low K input is one of the key strategies to sustain cotton production. Therefore, improving K uptake and use efficiency in cotton is a major target of breeders in the development of promising cotton cultivars.

According to Fageria *et al*., (2001) and Abbadi (2017), KUE is closely linked to the dry matter yield index because the same species differ extensively in their capacity to remove the nutrient under deficient environments. The contents of Tables 3 & 4 also explored the same findings. Our findings suggest that cultivars with less reduction in biomass under low K stress are supposed to be more K-efficient. This is because under a low nutrient environment plants either adapt to compatible nutrients or use some efficient transport mechanisms to extract that particular nutrient from the soil (Fageria *et al*., 2003; Zhang *et al*., 2007). There are several ways to express KUE like KUI, KUTE, RKA, and KER (Fig. 2 a & b), however, both acquisition and utilization are imperative. We focused on acquisition because it is more important in situations where the nutrient application is very low and the risk of fixation is high (Irfan *et al*., 2020). The K-efficiency relations of cotton cultivars are affected at both low and adequate K supply levels in the current study. Potassium utilization efficiency (KUI) is a key tool to measure the plasticity of a cultivar to adjust to a low K environment. Our findings also reveal how KUI varied within cultivars (Table 5). The K efficient cultivars i.e., MNH-886, CIM-554, Cyto-124, FH-142, CIM-707 and IUB-2013 had up to four-folds higher KUI than K inefficient cultivars i.e. BH-212 and FH-901 (Table 5), indicating that K efficient cultivars inherited greater plasticity in adjusting to a low K stress environments (Aamir *et al*., 2014; Abbadi 2017). Higher KUTE and RKA found in K efficient cultivars (Fig. 2 a, b) are also in line with the findings of Aamir *et al*., (2014). We also reported higher PDM, KUTE, and RKA in cultivar MNH-886 (K-efficient) compared to cultivar BH-212 (K-inefficient) (Table 6). Yang *et al*., (2004) and Irfan *et al*., (2020) proposed that the above-mentioned traits are associated with the efficiency of K acquisition and internal utilization and could be useful for the development of K efficient genotypes with improved K uptake ability under soils with low fertility. These variations in KUE might be due to differential response from K uptake membrane transporters and variable partitioning patterns within the plants as also reported by Fageria *et al*., (2010) in upland rice.

The role of K in gas exchange is one of the crucial phenomena. A close link between gas exchange characteristics and KUE was also observed in the current study (Table 6) which might be due to the improved regulation of K^+ ionic concentration in guard cells. A similar relationship was also reported by Zhang *et al*., (2007). A similar response was also documented by Zhao *et al*., (2001); Perviz *et al*., (2004) and Wang *et al*., (2012).

It was observed that K efficient cultivars responded well to low K supply compared to K inefficient cultivars (Tables 1 & 6). The possible reasons might be plant make-up as plants take up K from the soil through root epidermal and cortical cells and then transported to shoot via xylem uploading (Nawaz *et al*., 2006; Zhang *et al*., 2007; Hassan *et al*., 2011). Under a low K environment, the uptake and distribution pattern of K in the plant is mediated through different transport proteins and K channels (Wang *et al*., 2013). The transport proteins can be classified into two main groups as high- affinity transporters, which are active at low concentrations of external K, and low-affinity transport systems which operate at higher external K concentration (≥ 0.3 mM K) (Wang *et al*., 2013). Generally, K concentration in the soil solution is relatively low and ranged from only 0.1 to 5.0 mM K. Therefore, usually plants are exposed to low K stress during most of the growth periods. The first reported Ktransporter involved in nutrient uptake was the *Shaker*-like, voltage-gated and K^+- selective cation channel AKT1 (Hirsch *et al*., 1998). However, AtAKT1 and AtHAK5 are two main transporters that contribute to K^+ uptake in roots. Another trait of interest is the K stress factor (KSF) which can be used to evaluate the relative tolerance of crop cultivars to low K stress. Cultivars with higher KSF values have low potential to grow under K limiting conditions while cultivars with low KSF values are thought to be more adaptable for low input sustainable agricultural systems (Fig. 2b). Therefore, KSF showed a negative relationship with KUE ($R^2 = -0.95^{**}$) among cotton cultivars at low K supply level (Table 6). Furthermore, a scatter diagram and liner fit regression model was found good in the classification of cultivars for high K efficient and low K efficient cultivars based on KUE, KSF, KUI and dry matter yield index (DMYI) (Figs. 3a & b). These results are in agreement with Gill *et al*., (2005) and Fageria *et al*., (2008). Biomass partitioning is also an important approach under low K in which plants tend to invest more in active plant organs including young leaves, stalks and roots. A positive correlation ($R^2 = 0.99^{**}$) between total K uptake and total plant dry matter (Table 6) was also reported by Nawaz *et al*., (2006), Zhang *et al*., (2007) and Hassan *et al*., (2011). Similarly, a positive correlation between KUE and SDW was also observed ($R^2 = 0.95^{**}$) at a low K level. A linear fit regression model showed a strong relationship ($R^2 = 0.98^{**}$) between DMYI and KUIindifferent cotton cultivars (Fig. 3a) which is supported by many researchers (Yang *et al*., 2003; Fageria *et al*., 2010; Hassan *et al*., 2011; Irfan *et al*., 2020) who documented that high yielding cultivars produced more dry matter due to existence of efficient ion transport system controlled by many genes. The root traits such as root elongation, density and root surface area play a key role in water and nutrients extraction and in turn, affect K uptake efficiency in plants. However, the taproot system in cotton is reported to be less efficient in K uptake, which makes it sensitive to low K availability (Dong *et al*., 2004; Tian *et al., 2*008; Yang *et al*., 2011).

The results revealed the existence of genetic variation in cotton cultivars for biomass production, K uptake, K partitioning and KUE at a low K level. The cotton cultivars MNH-886, FH-142, CIM-554, Cyto-142, and IUB-2013 produced greater biomass at low and adequate K levels. These cultivars may thrive in low K environments without compromising the seed cotton yield. The variation in K uptake and K utilization efficiency in cotton cultivars is also found in previous studies (Gill *et al*., 1997; Sabir *et al*., 2003; Makhdum *et al*., 2007; Zhang *et al*., 2007; Hassan *et al*., 2011; Aamir *et al*., 2014).

Table 6. Relationship (Pearson correlation coefficient) of different plant traits in cotton cultivars at low K supply level.

P. Traits	SL	RL	TFW	SDW	RDW	TDW	SKC	RKC	TKC	SKU	RKU	TKU	P_N	E	g_s	KUE	KUTE	RKA	KUI
SL	1																		
RL	0.99**	1																	
TFW	0.95**	0.96**	1																
SDW	0.97**	0.98**	0.97**	1															
RDW	0.96**	0.97**	0.96**	0.98**	1														
TDW	0.97**	0.98**	0.97**	0.99**	0.99**	1													
SKC	0.96**	0.97**	0.89**	0.94**	0.93**	0.94**	1												
RKC	0.96**	0.98**	0.91**	0.95**	0.94**	0.95**	0.99**	1											
TKC	0.96**	0.97**	0.89**	0.94**	0.93**	0.94**	1.0**	0.99**	1										
SKU	0.97**	0.974**	0.96**	0.99**	0.99**	0.99**	0.94**	0.95**	0.95**	1									
RKU	0.97**	0.98**	0.96**	0.99**	0.99**	0.99**	0.96**	0.97**	0.96**	0.99**	1								
TKU	0.97**	0.98**	0.96**	0.99**	0.99**	0.99**	0.95**	0.95**	0.95**	1.0**	0.99**	1							
P_N	0.95**	0.96**	0.88**	0.90**	0.90**	0.91**	0.98**	0.97**	0.98**	0.90**	0.93**	0.91**	1						
E	0.95**	0.97**	0.95**	0.97**	0.97**	0.97**	0.96**	0.96**	0.96**	0.99**	0.98**	0.97**	0.96**	1					
g_s	0.94**	0.96**	0.96**	0.95**	0.96**	0.96**	0.94**	0.96**	0.94**	0.95**	0.97**	0.96**	0.92**	0.98**	1				
KUE	0.96**	0.98**	0.95**	0.95**	0.94**	0.95**	0.99**	0.99**	0.99**	0.96**	0.98**	0.96**	0.97**	0.97**	0.94**	1			
KUTE	0.86**	0.89**	0.76*	0.83**	0.82**	0.83**	0.96**	0.94**	0.96**	0.84**	0.86**	0.84**	0.95**	0.88**	0.85**	0.95**	1		
RKA	0.94**	0.96**	0.87**	0.94**	0.92**	0.94**	0.99**	0.98**	0.99**	0.94**	0.95**	0.95**	0.95**	0.95**	0.92**	0.99**	0.95**	1	
KUI	0.94**	0.95**	0.97**	0.98**	0.98**	0.99**	0.87**	0.88**	0.87**	0.98**	0.96**	0.97**	0.85**	0.94**	0.92**	0.89**	0.74*	0.87**	1
KSF	-0.86**	-0.89**	-0.76*	-0.83**	-0.82**	-0.83**	-0.96**	-0.94**	-0.96**	-0.84**	-0.86**	-0.85**	-0.95**	-0.88**	-0.85**	-0.95**	-1.00**	-0.95**	-0.74*

Correlation is significant at the 0.01 level *. Correlation is significant at the 0.05 level.

Shoot length: SL
Root length: RL
Total fresh weight: TFW:
Shoot dry weight: SDW
Root dry weight: RDW
Shoot Potassium concentration: SKC
Root potassium concentration: RKC
Total potassium concentration: TKC
Shoot potassium uptake: SKU
Total dry weight: TDW
Root potassium uptake: RKU
Total potassium uptake: TKU
Net photosynthesis rate: P_N
Transpiration rate: E
Stomatal conductance: G_s
Potassium use efficiency: KUE
Potassium utilization efficiency: KUTE
Relative potassium accumulation: RKA
Potassium utilization index: KUI
Potassium stress factor: KSF

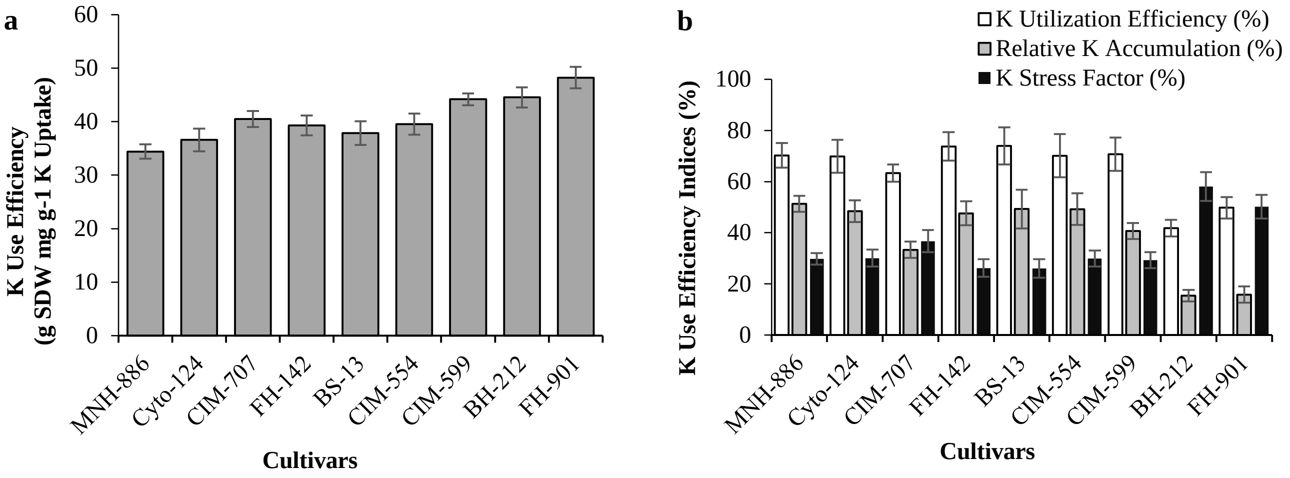

Fig. 2. (a) Potassium use efficiency of nine cultivars (lowest value of cultivars showed high KUE), (b) Relationship among K utilization efficiency, relative K accumulation and K stress factor of nine cotton cultivars. All values are means of three replicates (n = 6) and presented with standard error.

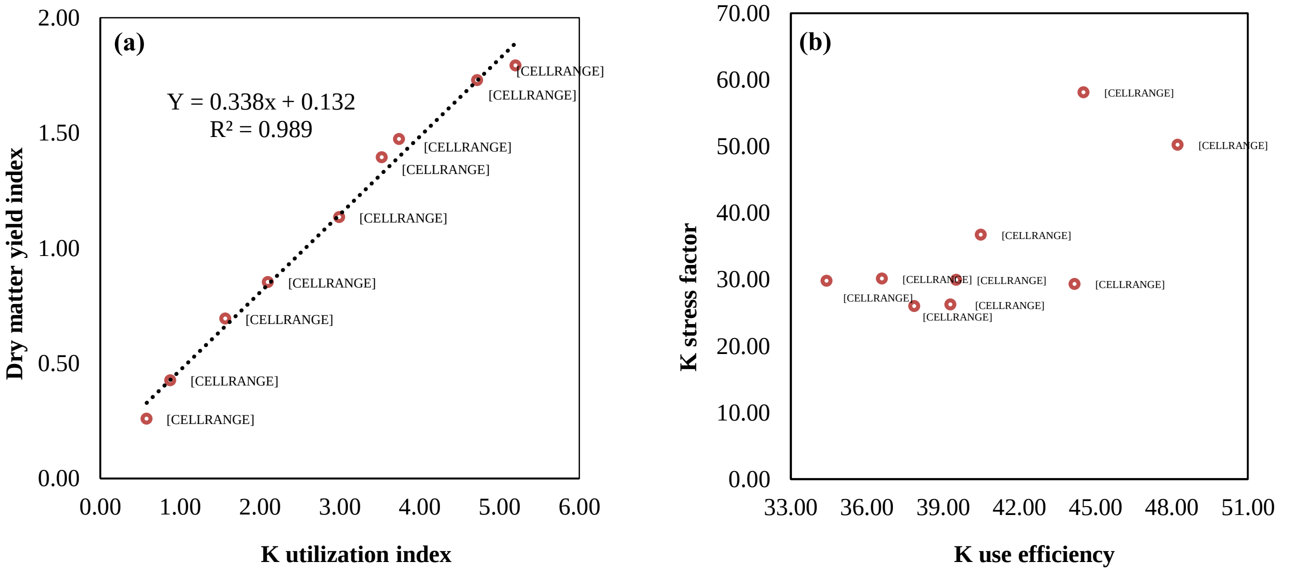

Fig. 3(a). Relationship among cultivars for K utilization index and dry matter yield index by using the linear fit regression model. (b) Performance of cultivars for K efficiency by using scatter plot (lowest values of both KUE and KSF showed high K use efficiency among cultivars). All values are the means of three replicates (n = 6).

Conclusion

It is concluded that cotton cultivars showed variable responses in biomass production and allocation at low and adequate K levels in the nutrient solution. The increased growth at low K levels in some cultivars might be attributed to K uptake by the high-efficiency K transport system. The tolerant cultivars exhibited higher KUTE at low K supply level. Therefore, KUTE in cotton is a promising trait to select promising cotton cultivars at early growth. The cultivars MNH-886, Cyto -124, FH-142, CIM-554, IUB-2013, and CIM-707 were classified as K efficient group due to production of higher dry matter, enhanced K uptake, greater relative K accumulation, more KUI, and improved gas exchange characteristics at low K level. These cultivars have the potential to grow under low K soils with little yield reduction. These findings also provide baseline information on the variability of K acquisition and utilization in indigenous cotton germplasm for its use as donors in breeding programs for cotton improvement.

References

Aamir, M., M.F. Sabir and M.A. Sadiq. 2014. Exploiting genotypic variability among cotton cultivars for potassium use efficiency. *Develop. Country Stud.*, 4: 7-12.

Ahmad, S., W. Huifang, S. Akhtar, S. Imran, H. Yousaf, C. Wang and M. Sohail Akhtar. 2021. Impact assessment of better management practices of cotton: a sociological study of southern punjab, Pakistan. *Pak. J. Agric. Sci.*, 58: 291-300.

Anonymous. 2020. Economic survey of Pakistan. 2020-2021. Government of Pakistan. Finance. Division Advisory Wing, Islamabad.

Azeem, F., M. Hussain, S. Hussain, M. Zubair, H. Nadeem, M. A. Ali, M. Afzal and M.H. Siddique. 2021. Genome-wide analysis and expression profiling of potassium transport related genes in *Solanum tuberosum*. *Pak. J. Agric. Sci.*, 58: 81-94.

Gunes, A., A. Inal, M. Alpaslan and I. Cakmak. 2006. Genotypic variation in phosphorus efficiency between wheat cultivars grown under greenhouse and field conditions. *Soil Sci. Plant Nutr.,* 52: 470-478.

Dong, H., Z.L.W. Tang and D. Zhang. 2004. On potassium deficiency in cotton disorder,cause, and tissue diagnosis. *Agri. Consp. Sci.*, 67: 77-85.

Fageria, N.K., A.B. Dos Santos and M.F. De Moraes. 2010. Yield, potassium uptake and use efficiency in upland rice genotypes. *Comm. Soil Sci. Plant Anal.*, 41: 2676-2684.

Fageria, N.K., V.C. Baligar and Y.C. Li. 2008. The Role of nutrient efficient plants in improving crop yields in the twenty frst century. *J. Plant Nutr.,* 31: 1121-1157.

Fageria, N.K. and V.C. Baligar. 2003. Methodology for evaluation of lowland rice genotypes for nitrogen use efficiency. *J. Plant Nutr.,* 26: 1315-1333.

Fageria N.K., M.P. Barbosa Filho and J.G.C. da Costa. 2001. Potassium use efficiency in common bean genotypes. *J. Plant Nutr.*, 24: 1937-1945.

Gilani, M., S. Danish, N. Ahmed, A.A. Rahi, A. Akrem, U. Younis, I. Irshad and R.K. Iqbal. 2020. Mitigation of drought stress in spinach using individual and combined applications of salicylic acid and potassium. *Pak. J. Bot.*, 52: 1505-1513.

Gill, M.A., M.I. Ahmed and M. Yaseen. 1997. Potassium-deficiency stress tolerance and potassium utilization efficiency in wheat genotypes. pp. 321-322 In*: Plant Nutrition for Sustainable Food Production and Environment*. Springer, Dordrecht.

Gill, M.A., M.A. Tahir and A. Yousaf. 2005. Genotypic variation of chickpea (*Cicer arietinum* L.) grown under adequate and k deficient stress in hydroponics culture. *Pak. J. Agric. Sci.*, 42: 22-26.

Hoagland, D.R. and D.I. Arnon. 1950. The water-culture method for growing plants without soil. *Cir. Calif. Agric. Exp. Stn.*, 2: 347-349.

Hassan, Z.U. and M. Arshad. 2010. Cotton growth under potassium deficiency stress is influenced by photosynthetic apparatus and root system. *Pak. J. Bot.*, 42: 917-925.

Hassan, Z.U., M. Arshad and A. Khalid. 2011. Evaluating potassium-use-efficient cotton genotypes using different ranking methods. *J. Plant Nutr.,* 34: 1957-1972.

Hassan Z.U., K.S. Memon,. M. Memon and M. Arshad. 2008. Quantifying the effect of temperature on ammonium bicarbonate diethylene triamine penta-acetic acid extractable potassium and developing a novel correction factor to express the data. *Comm. Soil Sci. Plant Anal.,* 39: 3047-3056.

Hussain, Shabir, H. Ali and S.T.R. Gardezi. 2021. Soil applied potassium improves productivity and fiber quality of cotton cultivars grown on potassium deficient soils. *PloS One,* 16:e0250713.

Hirsch, R.E., B.D. Lewis., E.P. Spalding and M.R. Sussman. 1998. A role for the AKT1 potassium channel in plant. *Sci.,* 280: 918-921.

Irfan, M., T. Aziz., M.A. Maqsood, H.M. Bilal., K.H.M. Siddique and M. Xu. 2020. Phosphorus use efficiency in rice is linked to tissue-specific biomass and P allocation patterns. *Sci. Rep.*, 10: 1-14.

Abbadi, J. 2017. Potassium use efficiency of safflower and sunflower grown in different soils. *World J. Agric. Res.,* 5: 244-257.

Maser, P., S. Thomine., J.I. Schroeder, J.M. Ward., K. Hirschi., H. Sze and J.F. Harper. 2001. Phylogenetic relationships within cation transporter families of Arabidopsis. *Plant Physiol.,* 126: 1646-1667.

Mahmood, T., M.A. Gill., A.M. Ranjha., Z. Ahmad and A.H. Rehman. 2001. Potassium deficiency stress tolerance and potassium utilization efficiency in wheat genotypes. *Int. J. Agric. Bio.,* 3: 113-116.

Munns, R., P.A. Wallace., N.L. Teakle and T.D. Colmer. 2010. Measuring soluble ion concentrations (Na^+, K^+, Cl^-) in salt-treated plants. pp. 371-382. In: *Plant Stress Tolerance*. Humana Press.

Nawaz, I., Hassan, A.M. Ranjha and M. Arshad. 2006. Exploiting genotypic variation among fifteen maize genotypes of Pakistan for potassium uptake and use efficiency in solution culture. *Pak. J. Bot.*, 38: 1689-1696.

Perviz, H., M. Ashraf and M.I. Makhdum. 2004. Influence of potassium nutrition on gas exchange characteristics and water relations in cotton (*Gossypium hirsutum* L.). *Photosynthetica,* 42: 251-255.

Sabir, M., M.A. Gill., T. Aziz and M.A. Maqsood. 2003. Differences among rice cultivars in potassium uptake and its utilization. *Pak. J. Agric. Sci.,* 40: 119-121.

Tian, X.L., G.W. Wang, R. Zhu., P.Z. Yang, L.S. Duan and L.H. Zhao. 2008. Conditions and indicators for screening cotton (*Gossypium hirsutum* L.) varieties tolerant to low potassium. *Acta Agro. Sinica,* 34: 1435-1443.

Tan, Z.X., R. Lal and K.D. Wiebe. 2005. Global soil nutrient depletion and yield reduction. *J. Sustain. Agric.,* 26: 123-146.

Wang, L. and F. Chen. 2012. Genotypic variation of potassium uptake and use efficiency in cotton (*Gossypium hirsutum* L). *J. Plant Nutr. Soil Sci.,* 175: 303-308.

Wang, Y. and W.H. Wu. 2013. Potassium transport and signaling in higher plants. *Ann. Rev. Plant Biol.*, 64: 451-476.

Yang, X.E., J.X. Liv., W.M. Wang., H. Li., A.C. Lno., Z.Q. Ye and Y. Yang. 2003. Genotypic differences and some associated plant traits in potassium internal use efficiency of lowland rice (*Oryza sativa* L.)., 67: 272-283.

Yang, X.E., J.X. Liu, W.M. Wang, Z.Q. Ye and A.C. Luo. 2004. Potassium internal use efficiency relative to growth vigor, potassium distribution, and carbohydrate allocation in rice genotypes. *J. Plant Nutr.*, 27: 837-852.

Yang, F., G. Wang., Z. Zhang, A.E. Eneji., L. Duan., Z. Li and X. Tian. 2011. Genotypic variations in potassium uptake and utilization in cotton. *J. Plant Nutr.*, 34: 83-97.

Zhang, Z., X. Tian, L. Duan, B. Wang, Z. He and Z. Li. 2007. Differential responses of conventional and Bt-transgenic cotton to potassium deficiency. *J. Plant Nutr.*, 30: 659-670.

Zhao, D., D.M. Oosterhuis and C.W. Bednarz. 2001. Influence of potassium deficiency on photosynthesis, chlorophyll content, and chloroplast ultrastructure of cotton plants. *Photosynthetica,* 39: 103-109.

Zorb, C., M. Senbayram and E. Peiter. 2014. Potassium in agriculture status and perspectives. *J. Plant Physiol.*, 171: 656-669.

(Received for publication 15 April 2021)