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CHARACTERIZATION OF DIVERSE COTTON CULTIVARS FOR POTASSIUM ACQUISITION BASED ON MORPHOLOGICAL AND PHYSIOLOGICAL TRAITS AT EARLY GROWTH STAGE

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Abstract

Categorization of cotton cultivars on the basis of their growth performance under nutrient deficient conditions is an essential for the development of K efficient cultivars in any crop. Soil all over the world is exhausting for the supply of adequate potassium (K) nutrition due to intensive systems of crop cultivation. The exploitation of genetic variability underlying efficient K transport system is a viable cost-effective strategy to increase cotton productivity in low input production system. The aim of this study was to characterize 46 diverse cotton cultivars for enhanced K acquisition and utilization efficiency at low (0.26 mM K) and adequate (3.33mM K) potassium levels in a sand culture experiment. Our data revealed that at low K level, the shoot dry matter weight of cotton cultivars ranged from 1.19 to 3.16 g plant^{-1}, whereas K content in shoot tissue varied from 5.5-11.8 (mg g^{-1}dw). Similarly, at low K level, shoot K uptake in cotton cultivars ranged from 6.90 to 37.4 (mg plant^{-1}dw), whereas it was ranged from 30.3 to 67.5 (mg plant^{-1}dw) at adequate K level. An overall 67.6% reduction in total K uptake was noticed in cotton cultivars at low K level when compared with adequate K level. The cotton cultivars were classified into highly, moderately, and poorly K efficient groups based on K use efficiency, dry matter yield index, and morphological and physiological traits. The highly K efficient group includes cultivars e.g., MNH-886, CYTO-124, FH-142, CIM-554, CIM-707 and IUB-2013, whereas the cultivars BH-212 and FH-901 were represented as poorly K efficient cultivars. The moderately K efficient group includes CIM-599, N-444, CIM-534, FH-Lalazar, CIM-443, VH-369, CIM-663, CYTO-515, and BH-184. We concluded that genetic diversity is existed among indigenous cotton cultivars for K utilization efficiency. The K- efficient cultivars can be used as donor of key K acquisition traits in breeding programs to develop cotton varieties with enhanced K uptake and utilization along with high yields.

Key words: Cotton, Genetic variability; K uptake; K utilization index; K use efficiency, K Classification methods.

Introduction

Cotton (*Gossypium hirsutum* L.) is an important fiber crop in arid and semiarid regions of the world, including 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 yield of 830 kg ha^{-1} (Anon., 2020-21).

However, this crop is under threat due to many challenges. Cotton, which is grown by old-fashioned ways, put away a lot of resources, impairment the environment, and constructs many communal complications, which is a muted threat to the sustainability of the cotton crop. The unnecessary utilization of groundwater, and fertilizers, the augmented vulnerability of cotton to insect and pest attacks, decline of natural assets (Ahmad *et al.*, 2021).

Potassium (K) levels in soils of the developing countries are continuously depleting due to poor soil management and intensive cropping (Zorb *et al*., 2014). Cotton is found to be more sensitive to low K and often shows deficiency symptoms in soils with marginal K availability (Gulick *et al.*, 1989). About 43% of soils in Pakistan are reported to be K deficient (K< 80 ppm), mainly due to low organic matter, use of mono-cropping system, scarcity of canal irrigation water and limited use of potassium fertilizers (Hassan *et al.*, 2008). Conclusively, low K availability in soil severely affects the growth and yield of cotton. However, the selection and development of cotton cultivars efficient in K uptake and use efficiency at low K input are one of the key strategies to improve cotton production and reduce demand for K fertilizers. This would decrease the input cost of K-fertilizers and sustain its resources for future use (Hassan & Arshad, 2010).

Mineral nutrition plays a critical role in cotton production: The K is a key macronutrient and governs the health and quality attributes of the cotton crop. It is the most abundant cation in plants and contributed up to 10% in dry biomass production (Leigh & Wyn Jones, 1984). The K content below 10 mg Kg^{-1} dry weight leads to the appearance of K deficiency symptoms in most plant species (Marschner, 1995; Epstein & Bloom, 2005). It activates enzymes (>60 enzymes), maintains plant turgidity, transports sugar and starch, helps in protein biosynthesis, and control diseases and insect attacks (Wang *et al*., 2013). The production of plant biomass and boll development are affected due to K deficiency in leaves of cotton crop. Under low K, the accumulation of sugars and starch affects the reproductive stage due to lack of metabolites formation (Sawan, 2016). Therefore, K is described as the quality element in agriculture and its short supply results in growth disrupted and poor in quality.

A considerable genetic variability has been reported in cotton cultivars for growth, K uptake, and K utilization efficiency (Mahmood *et al*., 2001; Aamer *et al.*, 2014). Cultivars have variable capacity for enhanced K acquisition to improve the efficiency of the photosynthetic system and root development in plants. This approach is more useful for developing countries having limited K resources. Many crops have evolved adaptive mechanisms to cope with low K stress, such as alteration of root architecture to explore more soil volume, enhanced carboxylate exudation containing phosphatases, nucleases, and organic acids. Plants use these strategies to extract more K from the soil solution and exchangeable pools, in turn translocate it to young organs and reprioritize metabolic K utilization. Cultivars with improved K use efficiency (KUE) could be an alternate approach to have good crop production on soil with low K availability (Hassan & Arshad, 2010).

K utilization efficiency is the capacity of a cultivar to transform acquired K into biomass or grain yield. The efficient K user genotypes produce greater yields even at low K tissue levels which show their higher KUE. These plants have ability to acquire more K under low K availability in growth medium and improve plant growth is attributed to the extended root system and efficient transport and physiological mechanisms (Zhang *et al*., 2007). Some of the plant species frequently translocate K from the mature leaves to growing regions during vegetative growth in response to low K supply from the soil. The remobilization can also occur during the reproductive phase when new sinks are emerged while K take up through roots is reduced. KUE is the ability of plant species to produce relatively more biomass or yield under low K supply compared with non-efficient genotypes (Zhang *et al*., 2007). Cotton cultivars with enhanced KUE can be successfully exploited in yield improvement programs. Similarly, trait of improved internal K-utilization efficiency is also important and required to better transform accumulated K into biomass and yield to develop K-efficient cotton cultivars (Fageria *et al*., 2001).

The growth and yield traits such as shoot dry weight, dry matter yield index, shoot nutrient uptake, and nutrient use efficiency have been successfully used to classify crop cultivars under low nutrient stress conditions (Fageria *et al*., 2003; 2010; Hassan *et al*., 2011; Bilal *et al*., 2018). It was reported that dry matter production is associated with crop yield because of its effect on dry matter yield index (DMYI). Modern cotton cultivars showed higher DMYI as compared to traditional cultivars for major traits. Therefore, DMYI can be used as key indicator for the classification of crop cultivars into performance groups (Fageria *et al.*, 2010).

Regardless of significant physiognomies of K, its use in our farming system is very partial. Nitrogen and phosphorus are the only nutrients applied with the thoughtful that our soils contain sufficient quantity of K. The fundamental knowledge of plant traits linked with K use efficiency is vital for the identification and classification of K efficient cotton cultivars. Therefore, keeping in the view the significance of K and little information on genetic variation for KUE in indigenous cotton germplasm, the present study was carried out to evaluate the 46 cotton cultivars for KUE and other associated traits by using the different ranking methods. This will help us in determining the association between growth traits and potassium utilization index and assist in selection of K efficient cultivars. This would also provide baseline information and donor material for incorporation of key K transport traits in breeding lines for the development of efficient cotton cultivars, ultimately reduce input cost and increase cotton production.

Materials and Methods

A sand culture experiment was conducted in rain-protected wire-house at Central Cotton Research Institute (CCRI), Multan-Pakistan in year 2017-18. The experiment was laid out by CRD with three replications in a factorial arrangement. The experimental treatments were comprised of 46 diverse cotton cultivars including both *Bt* and non-*Bt* exposed with two levels of K i.e. low K (0.26 mM KCl) and adequate K (3.33 mM KCl). The seed of cotton cultivars were obtained from different cotton research institutes/ stations in Pakistan (Table A). Five delinted seeds of each cotton cultivar were sown in the polythene bags of 15×25 cm size having one kg coarse river sand (thoroughly washed with 1.0 M HCl). A total of six small holes were made on the base of bags to provide adequate drainage. The sand-filled polythene bags were placed in iron tubs according to the treatment plan. All the essential nutrients other than K were supplied by using modified half strength Hoagland solution and K was supplied according to treatments calculation using KCl salt. After saturation of the sand-filled bags, the excess solution was collected in respective storage containers. The pH of the nutrient solutions was maintained at 6.5 by using 1.0 M NaOH or 1.0 M HCl. The nutrient solution was renewed twice a week, and deionized water was added to compensate for daily evapotranspiration. The Hoagland solution was supplied to plants for the period of four weeks after germination.

Composition of hoagland solution (Hoagland & Arnon, 1950).

Sr. No.	Salts	Stock ($g L^{-1}$)	mL stock solution for 1 L
	Macronutrients		
1.	NH4H2PO4	115.03	0.5 ml
2.	KCL	74.5	2.5 ml
3.	Ca (NO3)2 4H2O	236	2.5 ml
4.	MgSO4.7H2O	246	1.0 ml
	Micronutrients		
1.	H3BO3	2.86	1.0 ml
2.	MnCl2.4H2O	1.81	1.0 ml
3.	ZnSO4.7H2O	0.22	1.0 ml
4.	CuSO4.5H2O	0.08	1.0 ml
5.	H2MoO4.H2O	0.02	1.0 ml
6.	Fe-EDTA	37.33	1.0 ml

Table (A). Seed sources of different cotton cultivars used in the experiment.

Sr. No.	Cultivar name	Institute / Station	Sr. No.	Cultivar name	Institute / Station
1.	NIAB-777	NIAB, FSD	24.	CIM-663	CCRI, Multan
2.	NIAB-111	NIAB, FSD	25.	CIM-534	CCRI, Multan
3.	VH-289	CRS-Vehari	26.	CIM-443	CCRI, Multan
4.	FH-901	CRS- FSD	27.	SLH-19	CRS, Sehiwal
5.	CIM-482	CCRI, Multan	28.	SLH-381	CRS, Sehiwal
6.	SLH-377	CRS, Sehiwal	29.	BH-160	CRS-Bhawalpur
7.	N-1042	NIAB FSD	30.	VH-189	CRS-Vehari
8.	VH-383	CRS-Vehari	31.	VH-305	CRS-Vehari
9.	SLH-317	CRS,Sehiwal	32.	MNH-93	CRI, Multan
10.	N-444	NIAB, FSD	33.	CIM-496	CCRI, Multan
11.	MNH-1016	CRI, Multan	34.	CYTO-124	CCRI, Multan
12.	N-1048	NIAB, FSD	35.	VH-327	CRS-Vehari
13.	SLH-33	CRS, Sehiwal	36.	VH-369	CRS-Vehari
14.	MNH-886	CRS-Multan	37.	CIM-446	CCRI, Multan
15.	CYTO-515	CCRI, Multan	38.	CIM-544	CCRI, Multan
16.	CIM-707	CCRI, Multan	39.	BH-212	CRS-Bhawalpur
17.	IUB-2013	IUB,Bahwalpur	40.	CRS-M-38	CRS-Multan
18.	MNH-988	CRS-Multan	41.	CYTO-313	CCRI, Multan
19.	VH-363	CRS-Vehari	42.	FH-142	CRI, FSD
20.	F. H-Lalahazar	CCRI, FSD	43.	BZU-5	BZU, Multan
21.	BH-184	CRS-Bhawalpur	44.	CIM-573	CCRI, Multan
22.	CIM-599	CCRI, Multan	45.	CIM-506	CCRI, Multan
23.	NIAB-78	NIAB, FSD	46.	CIM-473	CCRI, Multan

CCRI = Central Cotton Research Institute, Multan
CRI = Cotton Research Institute, Multan
NIAB = Nulcear Institute of Agriculture and Biotechnology, Faisalabad
BH = Cotton Research Bahwalpur
VH = Cotton Research Station, Vehari
SLH = Cotton Resarch station, Sehiwal
BZU = Bahodin Zakaria University, Multan
IUB = Islamiya University Bahwalpue

The harvested plants were washed with distilled water and wiped with the help of a blotting paper. Leaf, stalk, and roots were separated and immediately put in the paper bags before air drying in the laboratory. Later, these were 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 as described by Munns *et al*., (2010).

Following formula were used to calculate K uptake and K use efficiency indices:

$$\text{Potassium uptake} = \text{K concentration} \times \text{Dry matter}$$ Hassan *et al*., (2011)

$$\text{Potassium use efficiency (KUE)} = \frac{\text{Shoot dry weight at adq.K} - \text{Shoot dry weight at low K}}{\text{Shoot K uptake at adq.K} - \text{Shoot K uptake at low K}}$$ Fageria *et al*., (2001)

$$\text{K efficiency ratio (KER)} = \frac{\text{Value at low K}}{\text{Value at adq.K}} \times 100$$ Gunes *et al*., (2006); Hassan *et al*., (2011)

$$\text{Dry matter yield index (DMYI)} = \frac{\text{Dry matter yield at low K}}{\text{Aerage DMY of 46 cultivars}} \times \frac{\text{dry matter yield at adq.K}}{\text{Aerage DMY of 46 cultivars}}$$ Fageria *et al*., (2010) Fageria *et al*., (2001)

$$\text{Potassium stress factor (KSF)} = \frac{\text{Shoot dry weight at adq.K} - \text{Shoot dry weight at low K}}{\text{Shoot dry weight at adequate K}} \times 100$$ Irfan *et al*., (2020)

For classification of cotton cultivars; four methods were employed. In the first method the cotton cultivars were grouped based on K efficiency against each parameter as efficient (E) if the KE values were over the mean and as inefficient (IE), if the KE values were below the mean as the method described by Gunes *et al*., (2006) and Hassan *et al*., (2011). In the second method by using averaged K use efficiency and average plant dry weight under adequate and deficient K application, the 46 cotton cultivars were placed in four groups as given below:

	If Cultivar PDW	Cultivar KUE
Efficient and responsive (ER)	> mean population PDW	> mean population KUE
Efficient but non-responsive (ENR)		< mean population KUE
In-efficient but responsive (IR)	< mean population PDW	> mean population KUE
In-efficient and non-responsive (INR)		< mean population KUE

A scatter diagram is plotted between KUE (x-axis) and plant dry matter weight (y-axis). This categorization divides cultivars into four categories i.e., efficient and responsive (ER), in-efficient and responsive (IR), efficient and non-responsive (ENR), and in-efficient and non-responsive (INR). This classification of cotton cultivars was done by the method described by Fageria *et al*., (2008) and Bilal *et al.*, (2018).

In the third method the cotton cultivar was declared as a high K efficient (HKE), if its PDMYI and KUE were >µ+STD, a low K efficient (LKE), if its PDMYI and KUE were <µ-STD and if PDMYI and KUE of a cultivar were fall between µ+STD and µ-STD it was declared as a medium K efficient (MKE), where µ indicates the mean PDMYI of all tested cultivars while STD is the standard deviation of µ. A scatter diagram is plotted between K uptake (x-axis) and dry matter yield index (y-axis). Each axis is divided into three portions (i.e low, medium and high). This categorization method divides cultivars into nine categories i.e., LKE: Low Potassium Efficient, MKE: Medium Potassium Efficient, HKE: High K efficient, LDMYI: Low Dry Matter Yield Index, MDMYI: Medium Dry Matter Yield Index, HDMYI: High Dry Matter Yield Index). This classification of cotton cultivars was according to Fageria *et al*., (2010); Hassan *et al*., (2011) and Bilal *et al.*, (2018). In the last method the hierarchical cluster analysis was also performed to classify cotton cultivars for K use efficiency. In this method 46 cotton cultivars were categorized into three groups, viz; HE: Highly Efficient, ME: Medium Efficient and LE: Low Efficient based on morphological and physiological traits at low and adequate K levels. The cluster analysis was performed by using the complete and average linkage method to calculate the Euclidean squared distance metrix in R software and the Wards Linkage Method in SPSS (Haq *et al.*, 2014).

The computer software STATISTIX 8.1 (Analytical Software, Inc. Tallahassee, FL, USA) was used to perform statistical analysis following the methods of Steel *et al*., (1997). Complete Randomized Design (CRD) with factorial arrangement was employed and the results were compared by two-way ANOVA technique. The graphical presentation of data was performed using Microsoft Office (Redmond, WA, USA).

Results

Comparison of cotton cultivars for growth [plant dry matter (g plant^{-1})]: The exposure of 46 cotton cultivars to low K level caused a reduction in the production of shoot dry matter (SDM) and there was significant variation for shoot dry matter among treatments (K), cultivars (C), and their interaction (K×C) at $p\leq 0.05/0.01$ (Table 1). Shoot dry matter of cotton cultivars at low K supply level was ranged from 1.19 to 3.16 g plant^{-1} in cultivar FH-901 and CYTO-124, respectively, with a mean SDM value of 1.89g plant^{-1}. At adequate K level, the SDM varied between 3.16 to 4.53 g plant^{-1} in BH-212 and CIM-544, respectively, with a mean value of 3.72g. The performance of cotton cultivars for SDM was 50.9% at deficient relative to adequate K level (Fig. 1). The comparison of cultivars based on K efficiency ratio (KER), showed that out of 46 cultivars, nine cultivars were ≥70% of relative KER in decreasing order (CIM-443, CIM-663, CYTO-515, CYTO-124, N-444, BH-184, IUB-2013, MNH-886, and CIM-707). The cotton cultivars which were below 40% of control included; MNH-93, SLH-33, CRS-M-38, SLH-377, BH-212, VH-305, CIM-506, MNH-1016, FH-901, VH-327, SLH-381 and SLH-19 in decreasing order, respectively. In the rest of 25 cotton cultivars, the relative KER was ranged from 40 to 69%, respectively.

At low K level, the root dry matter (RDM) of cotton cultivars was ranged from 0.93g plant^{-1} in NIAB-78 to 1.94g plant^{-1} for CIM-554 with a mean value of 1.20g among all cultivars, whereas, at adequate K level the RDM was ranged from 1.96g plant^{-1} in NIAB-78 to 3.18g plant^{-1} in CIM-554 with a mean weight of 2.27g. The relative value for RDW was 52.9% at a low K level, causing an overall reduction of 47.1% as compared with adequate K level (Fig. 1). Under low K level, the total plant dry Matter (TPDM) (shoot + root) of cotton cultivars ranged from 2.21g plant^{-1} in FH-901 to 5.09g plant^{-1} in CYTO-124, with a mean value of 3.09g, whereas, at adequate K level it was fluctuated from 5.21g plant^{-1} in FH-901 to 7.71g plant^{-1} in CIM-554, with a mean of 5.99g plant^{-1} (Table 1). The performance of cotton cultivars for TPDM was 51.7% at deficient relative to adequate K level (Fig. 1).

Comparison of cotton cultivars for potassium accumulation (mg g^{-1} dw): The data shows that K accumulation in the shoot and root of cotton cultivars was reduced at low K level compared with adequate K level (Table 2). The overall reduction in shoot K was 32.4% at low K level compared to adequate K supply with a relative value of 35.9% (Fig. 1). A significant variation was found for the shoot, root and total K accumulation among treatments, cultivars, and treatments × cultivars interaction at $p<0.05/0.01$ (Table 2). At low K level the shoot K was ranged from 5.48-11.84 (mg g^{-1} dw) in cotton cultivars with a mean of 7.73 mg g^{-1} dw, whereas, at adequate K level, it was ranged from 9.58 – 14.92 mg g^{-1} dw, with a mean of 11.43 mg g^{-1} dw. The KER of shoot K was ≥74% in six cultivars including, CYTO-124 (79.7%), CIM-663 (74.8%), FH-142 (74.6%), CIM-496 (74.2%), CIM-544 (74.0%), and CYTO-313 (74.0%), respectively. The K accumulation in the shoot was 66.6% greater than root at low and adequate K levels, respectively. At low K level, the root K was ranged from 1.82- 3.69 (mg g^{-1} dw) in cotton cultivars, with a mean of 2.54 (mg g^{-1} dw), whereas, at adequate level it was ranged from 3.12 mg g^{-1} dw in FH-901 to 4.97 mg g^{-1} dw in CIM-544, with a mean weight of 3.18 mg g^{-1} dw. When cotton cultivars were compared based on KER, following six cultivars, CYTO-124, CYTO-313, FH-162, CIM-663, CIM-544 and CIM-496 were higher than other cultivars. The total K concentration in cultivars was ranged from 7.30-15.8 (mg g^{-1} dw), with a mean value of 10.30 (mg g^{-1} dw). There was 32.3% reduction in total shoot and root K concentration at low K level compared with an adequate K level with a 36.0 relative value (Fig. 1). At adequate K level the highest total K accumulation was 19.9 (mg g^{-1} dw) recorded in CIM-554 and a minimum of 12.7 (mg g^{-1} dw) in cultivar BH-212. The cultivars which exhibited a total K accumulation of more than 74% (KER) include CYTO-124, CYTO-313, FH-142, CIM-663, CIM-496 and CIM-544, respectively (Table 2).

Comparison of cotton cultivars for K uptake and tissue-specific distribution (mg plant^{-1}): The data about K uptake in shoot and root of the 46 diverse cotton cultivars at low and adequate K levels are presented in Table 3. The statistical analysis explained that the variation for the shoot, root and total K uptake was significantly among treatments, cultivars and treatment× cultivar interaction (p≤0.05/0.01). Generally, the K uptake was higher in the shoot than root at both low and adequate K supply levels.

At low K level, the K uptake of the shoot (15.3 mg plant^{-1}) was significantly reduced (67.6 %) compared with K uptake (42.9 mg plant^{-1}) at adequate K supply level (Fig.1). At low K level, the shoot K uptake in cotton cultivars was ranged between 6.90 to 37.4 (mg plant^{-1} dw) in cultivars BH-212 and CYTO-124, with a mean uptake of 15.3 (mg plant^{-1}). At adequate K level Shoot K uptake was ranged from 30.3 mg plant^{-1} (BH-212) to 67.5 mg plant^{-1} (CIM-554), with a mean value of 82.8 mg plant^{-1} (Table 3). The comparison of cotton cultivars on the basis of KER showed that eight cultivars including CYTO-124 (58.7%), CIM-663 (57.4%), CYTO-515 (54.1%), BH-184 (52.7%), N-444 (52.1%), FH-142 (51.7%), CIM-443 (51.6%) and MNH-886 (50.6%) were higher than 50% of their respective control. The eleven cultivars (VH-363, CIM-506, CRS-M-38, FH-901, MNH-1016, MNH-93, SLH-317, CIM-573, BH-212, SLH-3811, SLH-19) were ≤ 10%, respectively. The rest of the 27 cultivars showed an intermediate response in the uptake of K at a low K level compared with adequate K, having mean KER value of 34.3%. There was 63.5% reduction in K uptake of the root in cotton cultivars at a low K supply level compared with an adequate K level. The root K uptake was ranged between 2.0 to 7.6 mg plant^{-1} in cultivars - BH-212 and CYTO-124, with a mean K uptake value of 3.18 mg plant^{-1}, respectively at low K level (Table 3). The eight cotton cultivars which maintained more than 40% of KER, at low K level, includes CYTO-124, CIM-544, FH-142, MNH-886, CIM-707, CIM-663, IUB-2013 and VH-305, respectively. At low K level, 67.6% reduction in total K uptake were noticed in cotton cultivars as compared with adequate K level (Fig. 1). The total K uptake was ranged from 8.8 mg plant^{-1} in BH-212 to 44.9 mg plant^{-1} in CYTO-124, with a mean value of 18.5 mg plant^{-1} at low K level. But at adequate K level, the total K uptake was recorded from 36.8 mg plant^{-1} to 83.3 mg plant^{-1} in cultivars BH-212 and CIM-544, with a mean value of 51.6 mg plant^{-1}, respectively. The comparison of cotton cultivars based on KER showed that five cultivars including CYTO-124 (56.5%), CIM-663 (54.7%), CYTO-515 (51.2%) and BH-184 (50.3%) were greater than 50% from their respective controls.

Comparison of cotton cultivars for Potassium use efficiency indexes: The Potassium use efficiency (KUE) was ranged from 36.7-84.2 (g dw mg^{-1} K) with a mean value of 65.8 g dw mg^{-1} K (Table 4). Out of 46 the 11 cultivars showed less than 50 (g dw mg^{-1} K) of KUE value as compared to other cultivars. Cotton cultivars that showed the lowest KUE mean having a higher dry matter yield index with more K utilization index because of higher K uptake capacity. These cultivars include IUB-13 (36.7) < CIM-443 (40.6) < CIM-707 (41.7) < CYTO-124 (42.7) < MNH-886 (43.0) < CIM-554 (45.7) < FH-142 (45.9) < CIM-663 (46.8) < CYTO-515 (47.1), respectively. The K utilization index (KUI) varies from 0.74 % in cultivar FH-901 to 5.3% in IUB-2013, with a mean value of 1.81%. The six cultivars which recorded the highest KUI are IUB-2013 (5.33%), CYTO-124 (4.81%), CIM-707 (4.55%), CIM-554 (4.45%), FH-142 (3.95%), and MNH-886 (3.88%), respectively. Similarly, the dry matter yield index (DMYI) of the cotton cultivars ranged from 0.62 – 1.96 with a mean value of 1.33 (Table 4). The minimum DMYI of 0.62 was recorded in FH-901 and the maximum of 2.06 in CYTO-124. The cultivars which showed more than 1.60 of the DMYI include CYTO-124 (2.06), CIM-554(2.03), IUB-2013(1.96), CIM-707(1.89), FH-142(1.81), and MNH-886 (1.67), respectively. Generally, there were less effects of low K treatment on K efficient cultivars as indicated by low potassium stress factor (KSF %). The values of KSF of cultivars under low and adequate K levels ranged between 23.0-68.8% with a mean value of 49.6%. The cultivars CIM-443, CIM-663, CYTO-515, CYTO-124, N-444, BH-184, IUB-2013, MNH-886, CIM-707, and FH-142 showed relative KSF values less than 30% in decreasing order, respectively (Table 4).

Correlation among various morphological and physiological traits: The various morpho-physiological traits like shoot dry weight, root dry weight, total plant dry weight, shoot K concentration and uptake, root K concentration and uptake, total K uptake and K use efficiency exhibited a positive correlation (Table 5). At low K level shoot dry weight showed a highly significant positive correlation with total plant dry weight (0.98**), shoot K concentration (0.82**), shoot K uptake (0.97**), total K uptake (0.95**) and K utilization index (0.94**). The root dry weight also showed a highly positive strong correlation with shoot dry weight (0.86**) and K concentration (0.86**), root K uptake (0.98**), DMYI (0.92**) and K utilization index (0.91**), respectively (Table 5).

Table 1. Plant dry biomass of 46 cotton cultivars at adequate and low K supply levels at early growth stage.

Cotton cultivars	dry matter yield (g plant^{-1})								
	Shoot			Root			Total		
	Adq.K	Low K	KER	Adq.K	Low K	KER	Adq.K	Low K	KER
NIAB-777	3.56	1.51	42.4 IE	2.05	1.09	53.0 E	5.61	2.60	46.3 IE
NIAB-111	3.48	1.39	40.0 IE	2.07	1.10	53.3 E	5.55	2.49	45.0 IE
VH-289	3.44	1.70	49.6 IE	2.08	1.09	52.4 E	5.52	2.79	50.6 E
FH-901	3.19	1.19	37.3 IE	2.02	1.02	50.7 E	5.21	2.21	42.5IE
CIM-482	3.55	1.49	42.1 IE	2.06	1.05	51.1 E	5.61	2.55	45.4 IE
SLH-377	3.25	1.29	39.6 IE	2.13	1.09	51.0 E	5.37	2.37	44.1 IE
N-1042	3.59	1.49	41.5 IE	2.12	1.10	51.8 E	5.71	2.59	45.3 IE
VH-383	3.49	1.48	42.3 IE	2.13	1.09	51.0 E	5.62	2.56	45.6 IE
SLH-317	3.41	1.39	40.9 IE	2.14	1.01	47.1 IE	5.55	2.40	43.3 IE
N-444	3.58	2.61	72.9 E	2.15	1.10	51.4 E	5.73	3.71	64.8 E
MNH-1016	3.22	1.21	37.5 IE	2.13	1.02	48.2 E	5.35	2.23	41.7 IE
N-1048	3.58	1.57	43.9 IE	2.35	1.09	46.2 IE	5.93	2.66	44.8 IE
SLH-33	3.31	1.32	39.8 IE	2.02	1.10	54.2 E	5.33	2.41	45.3 IE
MNH-886	4.19	2.95	70.3 E	2.60	1.58	60.7 E	6.80	4.53	66.6 E
CYTO-515	3.79	2.83	74.8 E	2.54	1.36	53.7 E	6.33	4.19	66.3 E
CIM-707	4.24	2.97	70.0 E	3.02	1.85	61.3 E	7.26	4.82	66.4 E
IUB-2013	4.38	3.12	71.3 E	2.92	1.82	62.4 E	7.30	4.95	67.7 E
MNH-988	3.75	1.55	41.4 IE	2.08	1.11	53.2 E	5.83	2.66	45.6 IE
VH-363	3.67	1.55	42.2 IE	2.08	1.12	53.8 E	5.75	2.67	46.4 IE
FH-Lalazar	3.90	2.64	67.5 E	2.09	1.17	56.1 E	5.99	3.81	63.6 E
BH-184	3.82	2.74	71.7 E	2.19	1.13	51.6 E	6.00	3.86	64.4 E
CIM-599	3.95	2.68	67.8 E	2.23	1.11	50.0 E	6.18	3.79	61.4 E
NIAB-78	3.52	1.46	41.5 IE	1.96	0.93	47.2 IE	5.49	2.39	43.6 IE
CIM-663	3.69	2.83	76.8 E	2.28	1.25	54.8 E	5.97	4.08	68.4 E
CIM-534	4.03	2.72	67.5 E	2.31	1.21	52.5 E	6.35	3.94	62.0 E
CIM-443	3.73	2.87	77.0 E	2.44	1.28	52.5 E	6.17	4.15	67.3 E
SLH-19	3.98	1.24	28.5 IE	2.13	1.10	51.4 E	6.11	2.34	36.0 IE
SLH-381	4.04	1.31	30.1 IE	2.03	1.09	53.8 E	6.07	2.40	37.6 IE
BH-160	3.62	1.56	43.1 IE	2.02	1.04	51.6 E	5.64	2.60	46.2 IE
VH-189	3.78	1.59	42.2 IE	2.07	1.07	51.5 E	5.85	2.66	45.5 IE
VH-305	3.37	1.33	39.4 IE	2.39	1.37	57.1 E	5.77	2.70	46.7 IE
MNH-93	3.43	1.37	39.8 IE	2.09	1.06	50.6 E	5.52	2.42	43.9 IE
CIM-496	3.60	1.53	42.5 IE	2.04	1.07	52.5 E	5.64	2.60	46.1 IE
CYTO-124	4.30	3.16	73.5 E	3.16	1.93	61.0 E	7.46	5.09	68.2 E
VH-327	3.97	1.53	36.5 IE	2.14	1.16	54.4 E	6.11	2.70	42.5IE
VH-369	3.98	2.55	64.0 E	2.29	1.26	55.3 E	6.27	3.81	60.8 E
CIM-446	3.63	1.61	44.2 IE	2.14	1.05	49.0 E	5.77	2.66	46.0 IE
CIM-544	4.53	2.92	64.5 E	3.18	1.94	61.1 E	7.71	4.86	63.1 E
BH-212	3.16	1.25	39.5 IE	2.06	1.07	51.8 E	5.23	2.32	44.4 IE
CRS-M-38	3.98	1.58	39.7 IE	2.14	1.05	49.2 E	6.12	2.64	43.1 E
CYTO-313	3.37	1.35	40.1 IE	2.32	1.10	47.5 IE	5.69	2.46	43.1 IE
FH-142	4.36	3.02	69.2 E	2.81	1.65	58.6 E	7.17	4.67	65.0 E
BZU-5	3.57	1.47	41.1 IE	2.12	1.08	50.8 E	5.69	2.55	44.7IE
CIM-573	3.39	1.36	40.3 IE	2.26	1.11	48.9 E	5.65	2.47	43.7IE
CIM-506	3.30	1.28	38.7 IE	2.36	1.08	45.6 IE	5.66	2.35	41.6 IE
CIM-473	3.67	1.57	42.9 IE	2.31	1.05	45.5 IE	5.97	2.62	43.9 IE
Mean	**3.72**	**1.89**	**46.2**	**2.27**	**1.20**	**48.4**	**5.99**	**3.09**	**46.9**

F-ratio for analysis of variance:						
K-level (K)	878.34**		61.32*		11.45NS	
Cultivars (C)	15.55**		55.71**		4.20**	
K x C	1.23NS		2.27**		0.91NS	
LSD- Value	0.05 = *	0.01 = **	0.05 = *	0.01 = **	0.05 = *	0.01 = **
K-level (K)	0.09	0.2076	0.0247	0.057	0.0915	0.2111
Cultivars (C)	0.269	0.3549	0.1064	0.1404	0.2942	0.3881
(K x C)	0.3804	0.5019	0.1505	0.1986	0.416	0.5489

KER is potassium efficiency ratio for each trait. Cultivars means followed by similar letter for KER are alike in performance.
Means of cultivars, K levels and their interaction were compared by F ratio analysis coupled with LSD test.
*, ** Significant at $p<0.05$ and <0.01, respectively.

Table 2. Shoot, root and total K concentration of 46 cultivars at adequate and low K levels at early growth stage.

Cotton cultivars	Shoot K concentration (mg g^{-1} dw)			Root K concentration (mg g^{-1} dw)			Total K concentration (mg g^{-1} dw)		
	Adq. K	Low K	KER	Adq. K	Low K	KER	Adq. K	Low K	KER
NIAB-777	11.12	6.83	61.4 IE	3.71	2.28	61.5 IE	14.8	9.1	61.5 IE
NIAB-111	11.22	7.37	65.7 IE	3.74	2.45	65.6 IE	15.0	9.8	65.7 IE
VH-289	10.38	7.50	72.2 E	3.46	2.51	72.4 E	13.8	10.0	72.3 E
FH-901	9.92	6.46	65.1 IE	3.12	2.15	69.0 E	13.0	8.6	66.0 IE
CIM-482	10.86	6.72	61.8 IE	3.62	2.23	61.5 IE	14.5	8.9	61.8 IE
SLH-377	11.18	7.32	65.5 IE	3.73	2.42	65.0 IE	14.9	9.7	65.4 IE
N-1042	11.10	7.33	66.1 IE	3.70	2.44	66.1 IE	14.8	9.8	66.1 IE
VH-383	11.11	7.51	67.6 E	3.70	2.48	66.9 IE	14.8	10.0	67.4 IE
SLH-317	11.40	6.69	58.6 IE	3.80	2.19	57.6 IE	15.2	8.9	58.4 IE
N-444	11.84	8.46	71.4 E	3.95	2.81	71.1 E	15.8	11.3	71.4 E
MNH-1016	11.18	7.23	64.7 IE	3.73	2.45	65.8 IE	14.9	9.7	64.9 IE
N-1048	11.25	7.25	64.5 IE	3.75	2.38	63.5 IE	15.0	9.6	64.2 IE
SLH-33	11.32	7.47	65.9 IE	3.77	2.50	66.3 IE	15.1	10.0	66.0 IE
MNH-886	13.96	10.05	72.0 E	4.65	3.34	71.8 E	18.6	13.4	71.9 E
CYTO-515	11.62	8.41	72.4 E	3.87	2.79	72.1 E	15.5	11.2	72.3 E
CIM-707	13.90	9.60	69.0 E	4.63	3.19	68.9 E	18.5	12.8	69.0 E
IUB-2013	14.58	9.44	64.7 IE	4.86	3.16	65.1 IE	19.4	12.6	64.8 IE
MNH-988	11.30	7.63	67.5 E	3.77	2.52	66.9 IE	15.1	10.1	67.4 IE
VH-363	10.99	6.46	58.8 IE	3.97	2.63	66.3 IE	15.0	9.1	60.8 IE
FH-Lalahazar	11.57	8.10	70.0 E	3.86	2.68	69.4 E	15.4	10.8	69.8 E
BH-184	12.18	8.94	73.4 E	4.06	2.96	72.8 E	16.2	11.9	73.3 E
CIM-599	11.54	8.28	71.7 E	3.85	2.80	72.9 E	15.4	11.1	72.0 E
NIAB-78	10.70	7.15	66.8 IE	3.57	2.41	67.4 IE	14.3	9.6	67.0 IE
CIM-663	11.73	8.77	74.8 E	3.91	2.94	75.1 E	15.6	11.7	74.9 E
CIM-534	11.44	7.78	68.0 E	3.81	2.59	68.0 E	15.3	10.4	68.0 E
CIM-443	11.64	7.80	67.0 IE	3.88	2.59	66.7 E	15.5	10.4	66.9 IE
SLH-19	11.05	7.46	67.5 E	3.68	2.50	67.8 E	14.7	10.0	67.6 E
SLH-381	10.96	7.49	68.4 E	3.65	2.51	68.7 E	14.6	10.0	68.5 E
BH-160	10.33	6.84	66.2 IE	3.44	2.24	65.0 IE	13.8	9.1	65.9 IE
VH-189	10.41	6.84	65.7 IE	3.47	2.27	65.4 IE	13.9	9.1	65.6 IE
VH-305	10.23	7.30	71.4 E	3.41	2.42	70.8 E	13.6	9.7	71.2 E
MNH-93	11.11	6.76	60.8 IE	3.70	2.27	61.3 IE	14.8	9.0	61.0 IE
CIM-496	9.98	7.41	74.2 E	3.33	2.47	74.2 E	13.3	9.9	74.2 E
CYTO-124	14.84	11.84	79.7 E	4.95	3.92	79.2 E	19.8	15.8	79.6 E
VH-327	10.58	7.28	68.8 E	3.53	2.49	70.5 E	14.1	9.8	69.2 E
VH-369	11.47	7.61	66.4 IE	3.82	2.40	62.9 IE	15.3	10.0	65.5 IE
CIM-446	10.63	7.43	69.9 E	3.54	2.47	69.7 E	14.2	9.9	69.8 IE
CIM-544	14.92	11.05	74.0 E	4.97	3.69	74.2 E	19.9	14.7	74.1 E
BH-212	9.58	5.48	57.2 IE	3.16	1.82	57.8 IE	12.7	7.3	57.3 IE
CRS-M-38	9.98	6.23	62.4 IE	3.21	2.06	64.2 IE	13.2	8.3	62.8 IE
CYTO-313	10.17	7.52	74.0 E	3.17	2.49	78.5 E	13.3	10.0	75.1 E
FH-142	14.11	10.53	74.6 E	4.70	3.57	75.9 E	18.8	14.1	74.9 E
BZU-5	11.13	7.03	63.2 IE	3.71	2.28	61.6 IE	14.8	9.3	62.8 IE
CIM-573	10.97	6.23	56.8 IE	3.66	2.08	56.8 IE	14.6	8.3	56.8 IE
CIM-506	11.17	7.14	63.9IE	3.72	2.35	63.2 IE	14.9	9.5	63.7 IE
CIM-473	11.26	7.44	66.1 IE	3.75	2.47	65.8 IE	15.0	9.9	66.0 IE
Mean	**11.43**	**7.73**	**67.35**	**3.81**	**2.58**	**67.60**	**15.2**	**10.3**	**67.5**

F-ratio for analysis of variance:						
K-level (K)	7648.94**		34561.8**		18530.7**	
Cultivars (C)	24.97**		51.80**		46.12**	
K x C	7.34**		1.61*		5.69**	
LSD- Value	0.05 = *	0.01 = **	0.05 = *	0.01 = **	0.05 = *	0.01 = **
K-level (K)	0.5586	1.2885	0.1931	0.4453	0.7500	1.7300
Cultivars (C)	0.3113	0.4107	0.1272	0.1678	0.4234	0.5586
(K x C)	0.4403	0.5809	0.1799	0.2373	0.5987	0.7899

KER = potassium efficiency ratio for each trait.

Mean values of KER followed by similar letter are statistically alike in performance.

Means of cultivars, K levels and their interaction were compared by F-Ratio analysis coupled with LSD.

*, ** Significant at p<0.05 and <0.01, respectively.

Table 3. Shoot, root and total K uptake of 46 cotton cultivars at adequate and low K supply level at early growth stage.

Cotton cultivars	Shoot K uptake (mg plant^{-1})			Root K uptake (mg plant^{-1})			Total K uptake (mg plant^{-1})		
	Adq. K	Low K	KER	Adq. K	Low K	KER	Adq. K	Low K	KER
NIAB-777	39.7	10.3	26.0 IE	7.6	2.5	32.6 IE	47.3	12.8	27.1 IE
NIAB-111	39.0	10.3	26.3 IE	7.7	2.7	34.9 IE	46.7	13.0	27.7 IE
VH-289	35.7	12.8	35.8 E	7.2	2.7	37.9 E	42.9	15.5	36.2 E
FH-901	31.7	7.7	24.3 IE	6.3	2.2	35.0 IE	38.0	9.9	26.1 IE
CIM-482	38.5	10.1	26.2 IE	7.5	2.4	31.6 IE	46.0	12.4	27.0 IE
SLH-377	36.3	9.4	25.9 IE	7.9	2.6	33.2 IE	44.2	12.0	27.2 IE
N-1042	39.8	10.9	27.5 IE	7.8	2.7	34.2 IE	47.7	13.6	28.6 IE
VH-383	38.7	11.1	28.6 IE	7.9	2.7	34.1 IE	46.6	13.8	29.5 IE
SLH-317	38.9	9.3	23.9 IE	8.1	2.2	26.9 IE	47.0	11.5	24.5 IE
N-444	42.4	22.1	52.0 E	8.5	3.1	36.5 E	50.9	25.2	49.4 E
MNH-1016	36.0	8.7	24.2 IE	7.9	2.5	31.6 IE	43.9	11.2	25.5 IE
N-1048	40.3	11.4	28.3 IE	8.8	2.6	29.4 IE	49.1	14.0	28.5 IE
SLH-33	37.4	9.8	26.3 IE	7.6	2.7	35.9 IE	45.1	12.6	27.9 IE
MNH-886	58.5	29.6	50.6 E	12.1	5.3	43.6 E	70.7	34.9	49.4 E
CYTO-515	44.0	23.8	54.1 E	9.8	3.8	38.7 E	53.9	27.6	51.3 E
CIM-707	58.9	28.5	48.4 E	14.0	5.9	42.2 E	72.9	34.4	47.2 E
IUB-2013	63.9	29.5	46.1 E	14.2	5.8	40.6 E	78.1	35.3	45.1 E
MNH-988	42.3	11.8	27.9 IE	7.8	2.8	35.6 IE	50.2	14.6	29.1 IE
VH-363	40.3	10.0	24.7 IE	8.3	3.0	35.7 IE	48.6	12.9	26.6 IE
FH-Lalahazar	45.3	21.3	47.1 E	8.1	3.1	38.9 E	53.3	24.5	45.9 E
BH-184	46.5	24.5	52.6 E	8.9	3.3	37.5 E	55.3	27.8	50.2 E
CIM-599	45.6	22.1	48.5 E	8.6	3.1	36.6 E	54.2	25.3	46.6 E
NIAB-78	37.7	10.5	27.7 IE	7.0	2.2	31.9 IE	44.7	12.7	28.4 IE
CIM-663	43.2	24.8	57.5 E	8.9	3.7	41.1 E	52.1	28.5	54.7 E
CIM-534	46.1	21.2	46.0 E	8.8	3.2	35.8 IE	54.9	24.3	44.3 E
CIM-443	43.4	22.4	51.6 E	9.5	3.3	35.1 IE	52.9	25.7	48.7 E
SLH-19	44.0	9.3	19.2 IE	7.8	2.7	34.9 IE	51.8	12.0	21.4 IE
SLH-381	44.3	9.9	20.7 IE	7.4	2.7	36.9 E	51.7	12.6	22.9 IE
BH-160	37.4	10.6	28.4 IE	7.0	2.3	33.6 IE	44.3	13.0	29.2 IE
VH-189	39.3	10.9	27.7 IE	7.2	2.4	33.6 IE	46.5	13.3	28.6 IE
VH-305	34.5	9.7	28.2 IE	8.2	3.3	40.4 E	42.6	13.0	30.5 IE
MNH-93	38.2	9.2	24.2 IE	7.7	2.4	31.0 IE	45.9	11.6	25.4 IE
CIM-496	36.0	11.3	31.4 IE	6.8	2.6	38.9 E	42.8	13.9	32.6IE
CYTO-124	63.7	37.4	58.6 E	15.6	7.6	48.3 E	79.4	44.9	56.6 E
VH-327	42.0	11.2	25.2 IE	7.6	2.9	38.3 E	49.6	14.1	27.1 IE
VH-369	45.7	19.4	42.4 E	8.7	3.0	34.8 IE	54.4	22.4	41.2 E
CIM-446	38.6	11.9	30.9 IE	7.6	2.6	34.1 IE	46.2	14.5	31.4 IE
CIM-544	67.5	32.3	47.8 E	15.8	7.2	45.3 E	83.3	39.4	47.3 E
BH-212	30.3	6.9	22.6 IE	6.5	2.0	30.0 IE	36.8	8.8	23.9 IE
CRS-M-38	39.7	9.8	24.8 IE	6.9	2.2	31.6 IE	46.6	12.0	25.8 IE
CYTO-313	34.3	10.2	29.7 IE	7.4	2.7	37.3 E	41.7	12.9	31.0 IE
FH-142	61.5	31.8	51.7 E	13.2	5.9	44.5 E	74.8	37.7	50.4 E
BZU-5	39.7	10.3	25.9 IE	7.9	2.5	31.3 IE	47.6	12.8	26.8 IE
CIM-573	37.1	8.5	22.8 IE	8.3	2.3	27.8 IE	45.4	10.8	23.7 IE
CIM-506	36.8	9.1	24.8 IE	8.8	2.5	28.8 IE	45.6	11.6	25.5 IE
CIM-473	41.3	11.7	28.4 IE	8.7	2.6	30.0 IE	49.9	14.3	28.6 IE
Mean	**42.7**	**15.3**	**34.3**	**8.7**	**3.2**	**35.6**	**51.6**	**18.5**	**34.7**

F-ratio for analysis of variance:						
K-level (K)	815.06**		746.63**		800.56**	
Cultivars (C)	125.80**		86.26**		121.32**	
K x C	5.86**		4.63**		5.77**	
LSD- Value	0.05 = *	0.01 = **	0.05 = *	0.01 = **	0.05 = *	0.01 = **
K-level (K)	1.3838	3.192	0.4354	1.0043	1.7901	4.1293
Cultivars (C)	2.989	3.9436	0.3809	0.5026	3.073	4.0544
(K x C)	4.2271	5.5771	0.5387	0.7108	4.3459	5.7338

KER = potassium efficiency ratio for each trait.

Mean values of KER followed by similar letter are statistically alike in performance.

Means of cultivars, K levels and their interaction were compared by F-Ratio analysis coupled with LSD.

*, ** Significant at p<0.05 and <0.01, respectively.

Table 4. Potassium use efficiency, dry matter index, potassium efficiency ratio and potassium stress factor of 46 cotton cultivars at early growth stage.

Cotton cultivars	K use efficiency		Dry matter yield index		Potassium use index		Potassium stress factor	
	KUE (g dry weight mg^{-1} K)		DMYI		KUI (%)		KSF (%)	
NIAB-777	70.1		0.79		1.13		57.6	
NIAB-111	72.5		0.75		1.03		60.0	
VH-289	75.8		0.84		1.10		50.4	
FH-901	84.0		0.62		0.74		62.7	
CIM-482	71.9		0.77		1.08		57.9	
SLH-377	72.7		0.69		0.95		60.4	
N-1042	72.6		0.80		1.10		58.5	
VH-383	72.4		0.78		1.08		57.7	
SLH-317	67.8		0.72		1.07		59.1	
N-444	47.6		1.15		2.42		27.1	
MNH-1016	74.2		0.65		0.87		62.5	
N-1048	69.2		0.86		1.24		56.1	
SLH-33	72.2		0.70		0.96		60.2	
MNH-886	43.0		1.67		3.88		29.7	
CYTO-515	47.1		1.44		3.05		25.2	
CIM-707	41.7		1.89		4.55		30.0	
IUB-2013	36.7		1.96		5.33		28.7	
MNH-988	71.8		0.84		1.17		58.6	
VH-363	70.0		0.83		1.19		57.8	
FH-Lalahazar	52.8		1.24		2.35		32.5	
BH-184	48.6		1.26		2.59		28.3	
CIM-599	55.2		1.27		2.30		32.2	
NIAB-78	75.9		0.71		0.94		58.5	
CIM-663	46.8		1.32		2.82		23.2	
CIM-534	52.5		1.35		2.58		32.5	
CIM-443	40.6		1.39		3.42		23.0	
SLH-19	78.9		0.77		0.98		68.8	
SLH-381	79.3		0.79		1.00		67.5	
BH-160	76.5		0.80		1.04		56.9	
VH-189	76.7		0.84		1.10		57.8	
VH-305	82.2		0.84		1.03		60.6	
MNH-93	71.7		0.73		1.01		60.2	
CIM-496	84.2		0.80		0.95		57.5	
CYTO-124	42.7		2.06		4.81		26.5	
VH-327	79.7		0.89		1.12		61.4	
VH-369	52.5		1.30		2.47		36.0	
CIM-446	75.8		0.83		1.10		55.8	
CIM-544	45.7		2.03		4.45		35.5	
BH-212	81.5		0.66		0.81		60.5	
CRS-M-38	80.1		0.88		1.09		60.3	
CYTO-313	83.5		0.76		0.91		59.9	
FH-142	45.9		1.81		3.95		30.8	
BZU-5	70.9		0.79		1.11		58.9	
CIM-573	70.6		0.76		1.07		59.7	
CIM-506	72.6		0.72		0.99		61.3	
CIM-473	70.7		0.85		1.20		57.1	
Mean	**65.8**		**1.03**		**1.81**		**49.6**	
F-ratio for analysis of variance:								
Cultivars (C)	**17.91**		**48.99**		**24.91**		**24.74**	
LSD- Value	0.05 = *	0.01 = **	0.05 = *	0.01 = **	0.05 = *	0.01 = **	0.05 = *	0.01 = **
Cultivars (C)	**9.8523**	**13.050**	**0.1633**	**0.2163**	**0.7427**	**0.9837**	**8.5079**	**11.270**

Lowest mean values of KUE and KSF and highest values of DMYI and KUI indicate the high potassium use efficiency of cultivar.
KUI is calculated by dividing DMYI with KUE; Means of cultivars.
K levels and their interaction were compared by F ratio analysis coupled with LSD.
*, ** Significant at $p<0.05$ and <0.01, respectively.

Table 5. Correlation matrix (Pearson's two tailed) for various morpho-physiological traits at low K supply level.

Parameters	SDW	RDW	TDW	SKC	RKC	TKC	SKU	RKU	TKU	DMYI
Shoot dry weight (SDW)	1									
Root dry weight (RDW)	0.75**	1								
Total plant dry weight (TDW)	0.98**	0.86**	1							
Shoot K concentration (SKC)	0.82**	0.86**	0.88**	1						
Root K concentration (RKC)	0.77**	0.87**	0.84**	0.88**	1					
Total K concentration (TKC)	0.82**	0.86**	0.88**	0.99**	0.89**	1				
Shoot K uptake (SKU)	0.97**	0.85**	0.99**	0.93**	0.86**	0.93**	1			
Root K uptake (RKU)	0.78**	0.98**	0.87**	0.94**	0.91**	0.94**	0.89**	1		
Total K uptake (TKU)	0.95**	0.88**	0.98**	0.94**	0.88**	0.94**	0.99**	0.92**	1	
Dry matter yield index (DMYI)	0.94**	0.92**	0.99**	0.90**	0.88**	0.90**	0.98**	0.93**	0.98**	1
Potassium utilization index (KUI)	0.94**	0.91**	0.98**	0.88**	0.89**	0.88**	0.97**	0.91**	0.97**	0.99**

** = Highly significant at $p \leq 0.01$ level; * = Significant at $p \leq 0.05$ level; NS = Non-significant

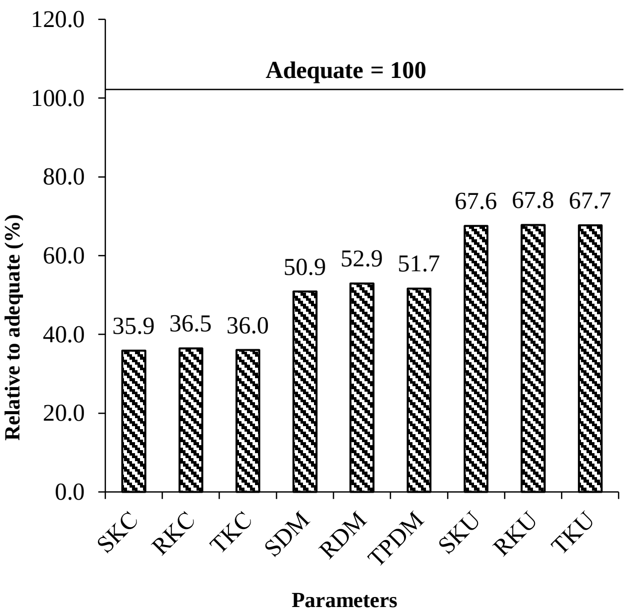

Fig. 1. Performance of cotton cultivars at deficient relative to adequate level of K in sand culture (SDW, RDW and TDW are shoot, root and total dry weight (g plant^{-1}), respectively). SKC, SKU, RKC, SKU and TKC, TKC are shoot, root and total K concentration and uptake (mg g^{-1} ; mg plant^{-1}), respectively.

Classification of cotton cultivars for potassium uptake and utilization: The classification of cotton cultivars was done by using different methods. The ranking of most cultivars remained unchanged at both K regimes. But it changed in some cultivars with method of classification. Remarkable was the point that the ranking of highly efficient or highly responsive cultivars, with high SDM production, remained unaffected due to classification method. In first method, each cultivar was ranked based on the potassium efficiency ratio (KER) against each trait. If the value of KER against each trait is less than the mean value it is declared as efficient (E) and if less than the mean it is declared as inefficient (IE).

In the 2nd method, cultivars were categorized into four groups based on averaged plant dry matter and KUE. According to this method cultivars CYTO-124, IUB-2013, MNH-886, CIM-554, FH-142 and CIM-707 were classed as efficient and responsive under both K supply levels (Table 6 & Fig. 2). While cultivars CIM-443, CYTO-515, CIM-534, CIM-599, VH-369, BH-184, FH-Lalazar and N-444 were fallen-in In-efficient and responsive but rest of the cultivars were a group as in-efficient and non-responsive at low K level. Four cotton cultivars BH-212, FH-901, SLH-33, and MNH-1016 were grouped as in-efficient and non-responsive at adequate K level.

In the third classification method cultivars were divided in to nine categories based on dry matter yield index and KUE. Out of 46 cotton cultivars, only six cultivars including CYTO-124, IUB-2013, MNH-886, CIM-554, FH-142 and CIM-707 fall under high potassium efficient and high dry matter yield index group while 28 cultivars like CIM-443, CYTO-515, CIM-534, CIM-599, VH-369, BH-184, FH-Lalazar and N-444 were moved to medium potassium efficient and medium dry matter yield index group (Table 6 and Fig. 3). Similarly, cultivars CYTO 313, CIM-496, CRS-M-38 were placed in low potassium efficiency and medium dry matter yield index class. Only one cultivar MNH-1016 was classed in medium potassium efficient and low dry matter yield index category. Two cultivars FH-901 and BH-212 were categorized as low potassium efficient with low dry matter yield index class.

In the fourth method, the cotton cultivars were classified into three groups by cluster analysis using complete and average linkage method to calculate the Euclidean squared distance metric (Table 6 and Fig. 4). A total of three clusters were developed in dendrogram across 46 cotton cultivars including high, medium and low K efficient groups (Fig. 4), respectively. The high K efficient group includes CIM-544, CYTO-124, IUB-2013, CIM-707, MNH-886 and FH-142. The cultivars CIM-599, N-444, CIM-534, FH-Lalazar, CIM-443, VH-369, CIM-663, CYTO-515, and BH-184, were included in moderately K efficient group, whereas, the rest of the 31 cultivars were placed in K in-efficient group. The cultivars viz CIM-544, CYTO-124, IUB-2013, CIM-707, MNH-886 and FH-142 were ranked as high potassium efficient – responsive with higher values of dry matter yield index. The cultivars FH-901 and BH-212 were categorized as low potassium efficient- nonresponsive with lower dry matter yield index.

Table 6. Comparative classification of 46 cotton cultivars at deficient and adequate K levels by using different methods at early growth stage.

Cotton cultivars	Method-II		Method-III		Method-IV	
	Adq. K	Low K	Adq. K	Low K	Adq. K	Low K
NIAB-777	INR	INR	MKE	LKE	LE	LE
NIAB-111	INR	INR	LKE	LKE	LE	LE
VH-289	ENR	INR	LKE	LKE	LE	LE
FH-901	INR	INR	LKE	LKE	LE	LE
CIM-482	INR	INR	MKE	LKE	LE	LE
SLH-377	INR	INR	LKE	LKE	LE	LE
N-1042	INR	INR	MKE	LKE	ME	ME
VH-383	INR	INR	MKE	LKE	ME	ME
SLH-317	INR	INR	LKE	LKE	LE	LE
N-444	INR	ER	MKE	MKE	ME	ME
MNH-1016	INR	INR	LKE	LKE	LE	LE
N-1048	INR	INR	MKE	LKE	LE	ME
SLH-33	INR	INR	LKE	LKE	LE	ME
MNH-886	IR	ER	HKE	HKE	HE	HE
CYTO-515	IR	ER	MKE	HKE	ME	ME
CIM-707	IR	ER	HKE	HKE	HE	HE
IUB-2013	IR	ER	HKE	HKE	HE	HE
MNH-988	ENR	INR	MKE	LKE	ME	ME
VH-363	ENR	INR	MKE	LKE	ME	ME
FH-Lalahazar	ENR	ER	MKE	MKE	ME	ME
BH-184	IR	ER	MKE	MKE	LE	ME
CIM-599	ER	ER	MKE	MKE	ME	ME
NIAB-78	ENR	INR	LKE	LKE	ME	ME
CIM-663	INR	ER	MKE	HKE	ME	ME
CIM-534	ER	ER	MKE	MKE	ME	ME
CIM-443	IR	ER	MKE	HKE	LE	ME
SLH-19	ER	INR	HKE	MKE	LE	ME
SLH-381	ER	INR	HKE	LKE	LE	LE
BH-160	ENR	INR	MKE	MKE	LE	LE
VH-189	ENR	INR	MKE	MKE	LE	LE
VH-305	ENR	INR	MKE	MKE	ME	ME
MNH-93	INR	INR	LKE	LKE	LE	LE
CIM-496	ENR	INR	MKE	MKE	ME	ME
CYTO-124	IR	ER	HKE	HKE	HE	HE
VH-327	ER	INR	MKE	MKE	ME	ME
VH-369	ER	ER	MKE	MKE	ME	ME
CIM-446	ENR	INR	MKE	MKE	ME	LE
CIM-544	IR	ER	HKE	HKE	HE	HE
BH-212	ENR	INR	LKE	LKE	LE	LE
CRS-M-38	ER	ENR	MKE	LKE	LE	LE
CYTO-313	ENR	INR	MKE	LKE	LE	LE
FH-142	IR	ER	HKE	HKE	HE	HE
BZU-5	INR	INR	MKE	LKE	LE	LE
CIM-573	INR	INR	MKE	LKE	LE	LE
CIM-506	INR	INR	MKE	LKE	ME	LE
CIM-473	INR	INR	MKE	LKE	LE	ME

The cultivar means were ranked into four groups, viz., ER: efficient responsive, ENR: efficient non-responsive, IR: inefficient responsive, and INR: inefficient non-responsive, by using PDW and KUE in method-II as described by Bilal *et al.*, 2018. The cultivar means were ranked into three groups, viz. LKE: low potassium efficient, MKE: medium potassium efficient, and HKE: high potassium efficient by using PDMYI and KUE in method-III as described by Hassan *et al.*, 2011; Fageria *et al.*, 2010. Similarly, LE: Low-efficient, ME: Medium-efficient, HE: Highly-efficient, respectively based on morpho- physiological traits at adequate K and low K supply level by using dendrogram as described by Haq *et al.*, 2014.

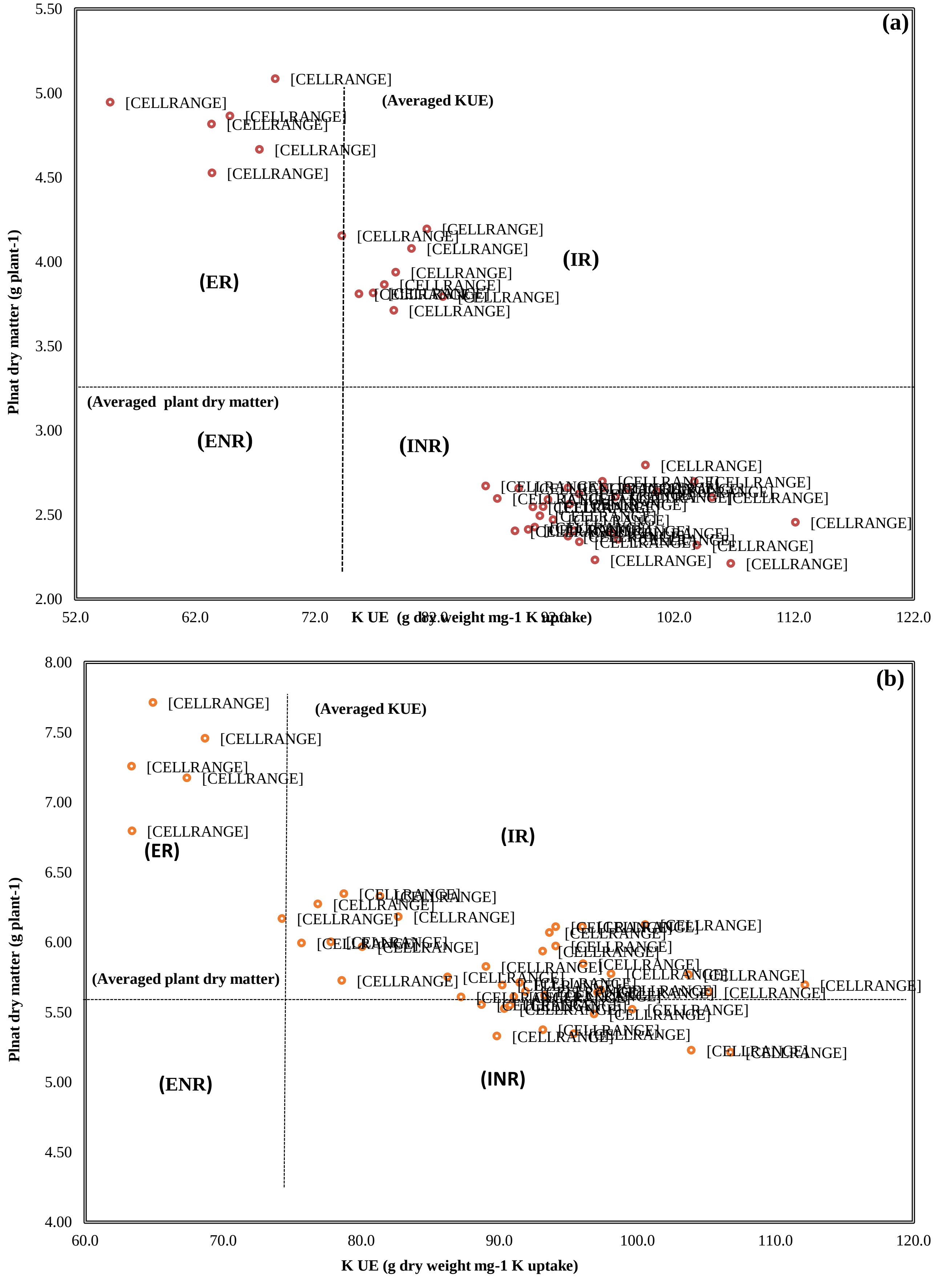

Fig. 2. Classification of cotton cultivars at vegetative growth stage for K use efficiency a) at low K and b) at adequate K supply. Data are the mean value of three replicates. This categorization divides cultivars into four categories i.e., efficient and responsive (ER), in-efficient and responsive (IR), efficient and non-responsive (ENR), and in-efficient and nonresponsive (INR). K use efficiency was calculated by the formula suggested by Fageria *et al.*, 2003. The classification of cultivars was done by using the method of Bilal *et al.*, 2018.

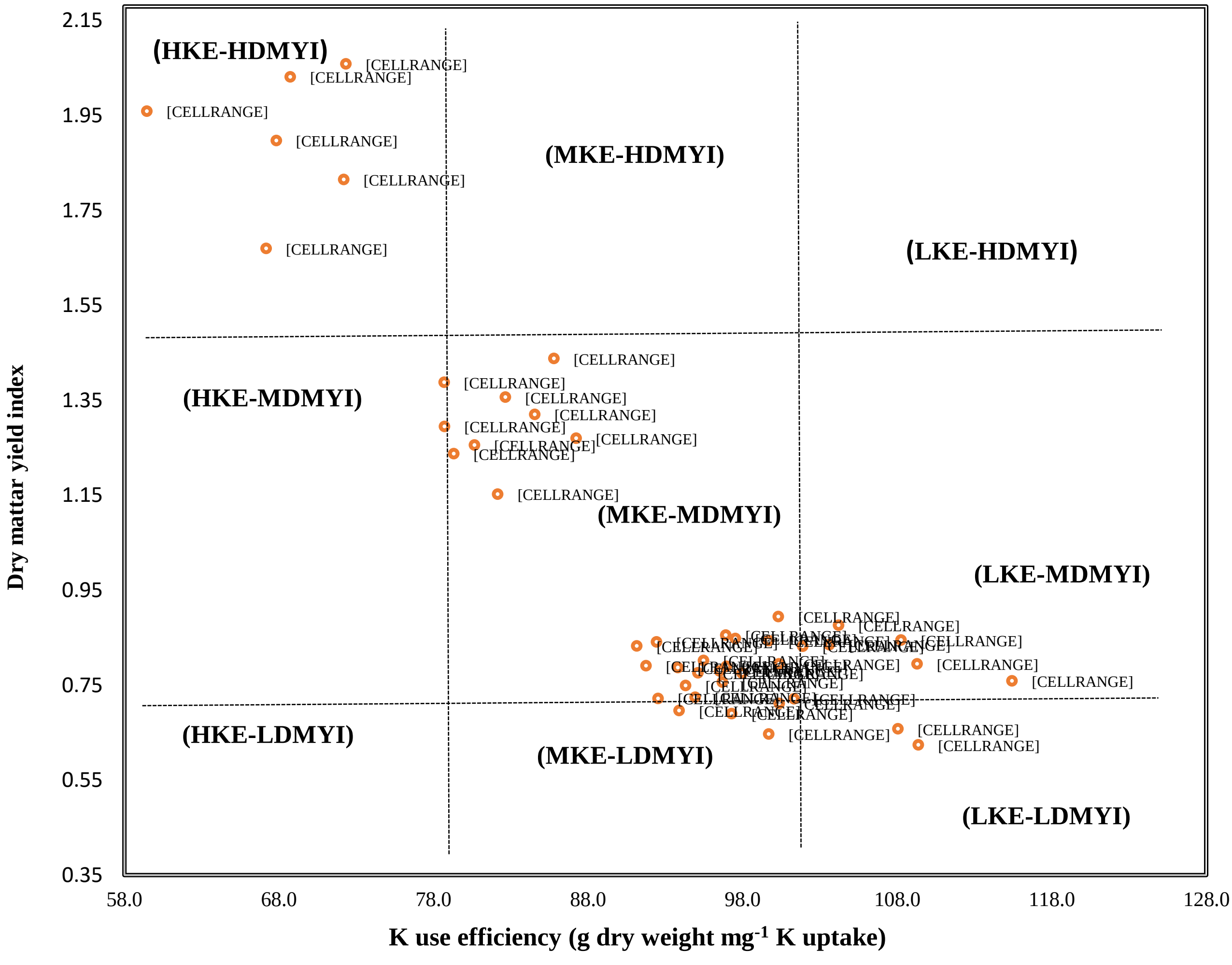

Fig. 3. Classification of cotton cultivar at vegetative growth stage (in sand culture) for K use efficiency at adequate and low K supply. Data are the mean value of three replicates. This categorization divides cultivars into nine categories i.e. (LKE: Low potassium efficient, MKE: Medium potassium efficient, HKE: High K efficient, LDMYI: Low dry matter yield index, MDMYI: Medium dry matter yield index, HDMYI: High dry matter yield index). K use efficiency and dry matter yield index was calculated by the formula suggested by Fageria *et al.*, 2010; 2001. The classification of cultivars was done by using the method of Hassan *et al.*, 2011.

Discussions

Plants take potassium (K) from soil through root epidermal and cortical cells, and then K is transported to shoot via xylem. Under deficiency, the uptake and distribution pattern of K in plant cells is mediated through different transport proteins and channels. The transport proteins can be classified into two main categories as high- affinity transporters that are active at low external K concentration, and low affinity channels that become active at a level of more than 0.3 mM external K (Wang *et al.*, 2013). The K concentrations that plant roots encounter in soil are relatively low, varying from only 0.1 to 5.0 mM K. Therefore, most plants are subjected to low K^+ stress (LK) during certain growth periods (Hirsch *et al.*, 1998; Dreyer & Uozumi, 2011; Jeanguenin *et al.*, 2011). The AtAKT1 and AtHAK5 are two major components that contribute to K^+ uptake by roots and its shift toward shoot.

The declining K content in soils of the world is affecting production and quality of cotton (Tan *et al.*, 2005). The genetic variation for K uptake in cotton germplasm is a key to develop superior cultivars with high KUE and once identified these traits can be used in future breeding programs as screening markers. We discovered genetic differences in cotton cultivars for biomass production, K uptake, and K utilization index at low K level (Tables 1, 3 and 4). The cotton cultivars MNH-886, FH-142, CIM-554, CYTO-142, CIM-707, and BS-13 produced greater biomass at low and adequate K levels indicating that these cultivars may be grown successfully in K deficient environments without compromising the yields. Our results of genetic variation for K acquisition in cotton cultivars are in agreement with previous findings which documented variable response for K uptake and biomass development in crop plants (Gill *et al.*, 1997; Zhang *et al.*, 2007; Hassan *et al.*, 2011 and Wang *et al.*, 2012; Aamer *et al.*, 2014).

Plant health is attributed to the production of dry matter and K uptake in nutrient limiting environments (Zhang *et al.*, 2007; Hassan *et al.*, 2011). The dry matter accumulation by the plant is directly associated with its ability to extract water and nutrients from the soil, which might be due to extended root surface area that stimulates active absorption of K from the rooting medium (Nawaz *et al.*, 2006); Zhang *et al.*, 2007; Hassan *et al.*, 2011).

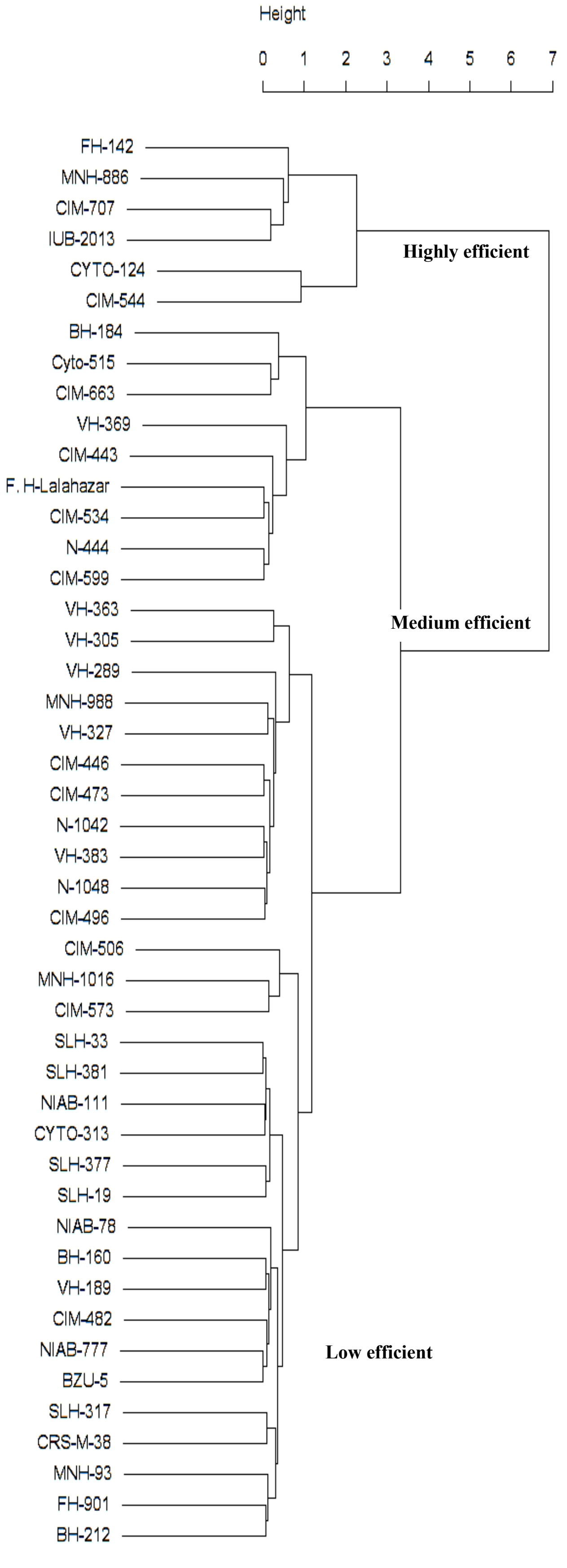

Fig. 4. Classification of cotton cultivar at vegetative growth stage (in sand culture) for K use efficiency at low K supply. Dendrogram showing the classification of 46 cotton cultivars into groups based on morpho-physiological traits by cluster analysis using Complete Linkage Method as described by Ul haq *et al.*, 2014.

The crop plants tend to increase root length and root hair density as an adaptive strategy for better K acquisition under low K environments. Dry matter yield index (DMYI) in crop plants is affected by genetic and environmental factors, and is a good indicator in discriminating cotton cultivars with better capacity to produce higher dry matter. It is well known that DMYI is an important marker to categorize promising genotypes for nutrient use efficiency (Fageria *et al.*, 2010). In our studies, the positive correlation (R^2 = 0.98**) between total plant dry matter produced and K accumulation in cotton cultivars at low K level confirms the previous findings (Table 5). The K efficient cultivars registered higher shoot dry weight (77%) and showed strong correlation (R^2 = 0.97**) with shoot K uptake and KUI (R^2 = 0.94**) at low K level. Our results are in agreement with other workers (Faeria *et al.*, 2001; Yang *et al.*, 2003; Tian *et al.*, 2008; Fageria *et al.*, 2010; Hassan *et al.*, 2011) who also documented that high yielding cultivars produced more plant dry matter. Therefore, promising cultivars have high K uptake efficiency with higher shoot and root dry weights, and dry matter yield index due to the existence of an efficient ion transport system. A weak association of K utilization efficiency with morphological traits suggests that this trait needs to be extensively studied and improved.

In soil, K moves to the root surface by diffusion and mass flow processes, and then taken up by root in the form of K ion. In cotton two-thirds of the required K is taken up by the plant during six weeks period at early bloom (Rosolem *et al.*, 2003; Dong *et al.*, 2004; Yang *et al.*, 2011; Oosterhuis *et al.*, 2013). In the current study, K uptake was very badly affected at low K supply level in general; however, K efficient cultivars exhibited 48% and 56% higher shoot and root K acquisition, respectively, compared with the K uptake at adequate K level (Table 2). This is explained by the higher root surface area of K uptake efficient cultivars; therefore, they have a greater capacity for K uptake at root surface and in maintaining diffusion flow between soil and surface of the roots (Rengel & Damon, 2008). The efficient cultivars probably used this as an adaptive strategy through continuous root growth, at the expense of shoot biomass, under low K stress, for improved extraction of water and nutrients in arid environments. Our results support this hypothesis as the highly efficient cotton cultivars (CYTO-124, IUB-2013, and CIM-554) recorded the highest root dry weight and K uptake at low K level (Tables 1 and 3).

The potassium use efficiency (KUE) is an increase in the yield of a crop per unit of K nutrient applied or yield per unit change in tissue concentration of K (Siddiqi & Glass, 1981). The cultivars with less reduction in biomass under induced low K stress are supposed to be more K-efficient. This is because, under low nutrient environment, plants either adapt to compatible nutrients or use efficient mechanisms to perform better, at functional sites, for that particular nutrient. There are a number of ways to express KUE like KUI, KSF and KER (Table 4) however, both acquisition and utilization are imperative. The trait of potassium utilization index (KUI) measures the plasticity of a cultivar to adjust to a low K environment (Aamir *et al.*, 2014) and it exhibits the relative decrease in the KUE in response to a decrease in K level, in the growth medium, from adequate to low K level. We have found significant variation among cotton cultivars for KUI under low and adequate K supply. The K efficient cotton cultivars, including MNH-886, CIM-554, CYTO-124, FH-142, CIM-707 and IUB-2013 performed better (102% higher) in KUI than poorly K efficient cultivars (Table 4). Therefore, these cultivars indicated their greater inherited plasticity in adjusting to low K stress environments (Hassan *et al*., 2011; Aamer *et al*., 2014). The traits of shoot dry weight and K utilization index of cultivars are associated with the dry matter yield index have strong positive relationship (Table 5) and thus can be used in selecting cultivars that suit K deficient conditions. A similar trend in KUE was also reported by Fageria *et al*., (2001; 2010) in upland rice genotypes. Similarly, a considerable variation for potassium efficiency ratio (KER) was also observed among the cultivars and it is another trait of interest that can be used in categorization of cultivars for nutrient use efficiency (Gunes *et al*., 2006; Hassan *et al*., 2011). Potassium stress factor (KSF) is also a useful trait in evaluating the relative tolerance of crop cultivars against low nutrient stress. Cultivars with higher KSF values have a low potential to grow under K limiting conditions while cultivars with low KSF values are regarded to be more suitable for low input sustainable agricultural systems. The K efficient cotton cultivars showed less KSF values (Table 5) owing to their genetic potential to survive under K deficient stress or greater ability to acquire more K from the growing medium (Irfan *et al.*, 2020; Gill *et al*., 2005).

The depleting levels of available K in agricultural soils demand that K efficient cultivars must be developed. Categorization and/or development for increased K efficiency is an approach that can help to sustain crop productivity in low input and environment friendly agriculture systems. Several procedures have been introduced for the selection and screening of cultivars against low K conditions (Fageria *et al*., 2001; 2010; Gill *et al.*, 2005; Gunes *et al.*, 2006; *Hassan et al*., 2011; Bilal *et al*., 2020). In this study, the cotton cultivars were classified, for K efficiency, by using more than one method. In the first method of classification, cultivars were categorized into two groups efficient and in-efficient considering each parameter based on KER (Gunes *et al.*, 2006; Hassan *et al*., 2011). According to the second method (Bilal *et al.*, 2020), the cultivars were categorized into four groups viz. i) efficient and responsive (ER), ii) efficient and non-responsive (ENR), iii) inefficient but responsive (IR), and (iv) inefficient and non-responsive (INR). The most ER cultivars were (*i.e*. MNH-886, IUB-2013, CYTO-124, FH-142, CIM-554 and CIM-707) because these cultivars produced more dry biomass under both K supply levels (Fig. 3a & b). The cultivars exhibited a narrow range between plant dry matter and KUE, and, therefore, this method may not distinguish the cultivars precisely.

The cultivars were categorized into further nine groups (Fageria *et al.*, 2003; Hassan *et al*., 2011; Bilal *et al*., 2020) *i.e*. low dry matter-low K efficient (LDMYI-LKE), low dry matter yield index-medium K efficient (LDMYI-MKE), low dry matter yield index-high K efficient (LDMYI-HKE), medium-dry matter yield index-low K efficient (MDMYI-LKE), medium-dry matter yield index-medium K efficient (MDMYI-MKE), medium-dry matter yield index-high K efficient (MDMYI-HKE), high dry matter yield index-low K efficient (HDMYI-LKE), high dry matter yield index-medium K efficient (HDMYI-MKE) and high dry matter yield index -high K efficient (HDMYI-HKE). Six cultivars out of 46 fall into HDMYI-HKE while one and two fall in LDMYI-LKE and LDMYI-MKE, respectively, (Fig. 3). By using this method, more groups are created to minimize the minor differences in the response of cultivars. In the last method, cultivar were categorized based on morpho-physiological traits. The 46 cotton cultivars were grouped into three classes viz. high, moderate, and low K efficient (Fig. 1) using the Dendrogram (Haq *et al.*, 2014) at low K supply level. The highly K efficient group of cultivars included MNH-886, CIM-554, CYTO-124, CIM-707, FH-142 and BS-13, whereas, the moderate K efficient group comprised of MNH-998, FH-Lalahzar, CIM-599, CIM-473 and CYTO-515. The cultivars BH-212, FH-901, MNH-93, SLH-393 and VH-189 were classed as low K efficient cultivars. Our results are in line with the previous findings (Fageria *et al*., 2003; Fageria *et al*., 2010; Hassan *et al.*, 2011) in which cultivars were grouped on the basis of K uptake and KUE. The cultivars with high KUE are desirable because of their flexibility under both low and adequate K input systems.

In conclusion, the ranking of cotton cultivars for K acquisition and utilization by using different classification methods have produced variable results. Therefore, screening of cotton cultivars by using more than one approaches is a good strategy for reliable selection of donors in breeding nutrient efficient cultivars or for recommending to farmers for general cultivation.

Conclusion

There exist genetic variation in cotton cultivars for K acquisition and utilization. The indicators such as DMYI and KUE, based on the mean and standard deviation, can be reliably used for classification of indigenous cotton germplasm. The cotton cultivars including MNH-886, CYTO-124, FH-142, CIM-554, CIM-707, and IUB-2013 were found to be highly K efficient and responsive. These cotton cultivars have a great potential for wider adaptation under both low and high K input agriculture systems and therefore, may be recommended for cultivation in soils with limited K supplies.

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