Pak. J. Agri. Sci., Vol. 57(4),1045-1055;2020
ISSN (Print) 0552-9034, ISSN (Online) 2076-0906
DOI: 10.21162/PAKJAS/20.9788
http://www.pakjas.com.pk

INOCULATION OF POTASSIUM SOLUBILIZING BACTERIA WITH DIFFERENT POTASSIUM FERTILIZATION SOURCES MEDIATES MAIZE GROWTH AND PRODUCTIVITY

Muhammad Imran[1], Sher Muhammad Shahzad[1,*], Muhammad Saleem Arif[2], Tahira Yasmeen[2], Basharat Ali[3] and Asif Tanveer[3,*]

[1]Department of Soil and Environmental Sciences, College of Agriculture, University of Sargodha, Sargodha 10400, Pakistan; [2]Department of Environmental Sciences and Engineering, Government College University, Faisalabad 38000, Pakistan;[3]Department of Agronomy, University of Agriculture, Faisalabad 38040, Pakistan;
***Corresponding author's e-mail: smshahzad_uaf@yahoo.com**

Potassium (K) deficiency is becoming a major productivity constraint in semi-arid agriculture. It is an essential mineral nutrient that has key role in various plant physiological and biochemical functions. Balanced nutrient application always tends to ensure better plant growth and development. Therefore, in the present study, efficacy of different K fertilizers for mediating maize plant growth and productivity in the presence and absence of KSB inoculant was assessed. A potassium solubilizing rhizobacterial strain, *Klebsiella oxytoca* KSB-17, was used in a 5 × 2 factorial pot experiment involving maize plant. The treatments comprised of control, waste mica (WM), K chemical fertilizer (KCF), WM-enriched compost (WMEC) and KCF-enriched compost (KCFEC). Compared to control treatment, KCF fertilization increased all plant physiological parameters both in presence and absence of KSB inoculation. From the results obtained, KCFEC followed by CF alone with KSB, demonstrated the most pronounced effect with significant increase in plant height (50%), shoot biomass (59%), root biomass (73%), root length (92%), plant K uptake (154%), grain starch (16%), protein (31%), oil content (22%) as well as photosynthetic rate (104%), transpiration rate (30%) and water use efficiency (54%) compared to control. Potassium solubilizing bacteria (KSB) prompted down-regulation of plant antioxidant enzyme activities against all K fertilizer treatments. Compared to control treatment, catalase (CAT) activity decreased significantly on application of KCF as well as with KCFEC in the presence of KSB inoculation. Regardless of KSB inoculation, plant growth, physiological, antioxidant and K nutritional traits showed slight improvement with either of WM fertilizers compared to control. Our findings concluded that K enriched compost with efficient KSB inoculant can be used to enhance maize growth and productivity in semi-arid agroecosystems.
Keywords: Compost, bio-fertilizer; waste mica; plant nutrition, grain quality, maize.

INTRODUCTION

Maize (*Zea mays* L.) is third most widely cultivated crop, consumed not only for the fulfillment of energy and protein needs, but also for industrial and biofuel production (Cruz-Cárdenas *et al.,* 2019). Given the projected increase in world population by 2050, maize has been foreseen as an economically the most important crop to tackle future food security issue(Jones, 2009).Global dryland ecosystems, arid and semi-arid, cover ~42% of world terrestrial land surface (Bastin *et al.,*2017),and contribute largely to ensure both subsistence and livelihood benefits in these regions (Sujakhu *et al.*, 2018).Of various soil challenges, impoverished agricultural productivity is one of the major issues of dry land ecosystems, mainly due to historically low organic mattercontent, reduced soil fertility and exacerbated agriculture intensification (Shahzad *et al.,* 2017).

Being an important constituent of plant cell structure, K not only activates protein synthesis, carbohydrate metabolism and key enzyme reactions(Chérel, 2004), but also triggers variety of plant adaptive responses under stressful conditions (Anschütz *et al.,* 2014).Many soils of arid and semi-arid regions are increasingly being depleted in soil K fertility, primarily due to the coupled effect of intensive agriculture practices with little or no K application(Ameen *et al.*, 2018). The K availability fluctuates accordingly to the soil types and is mainly governed by nature of clay minerals and organic matter status (Yadav *et al.,*2016). Cereals are characteristically more efficient K absorber from soil compared to other crop plants, and resultantly cereal based agroecosystems are more likely to experience K deficiency because of negative K balance(Rao *et al.,* 2014).In semi-arid agroecosystem, farmers are paradoxically inclined to the application of N and P fertilizers in large quantities for higher productivity, and neglected altogether the use of K fertilizer in the past three decades(Samra *et al.,* 2008). Because of this incessant imbalanced fertilizer use in semi-arid ecosystem, K deficiency in crop plants has now become widespread and often inflicted crop productivity constraints in high K demanding crops i.e. maize, sugarcane, potato (Mian and

Ahmad, 2007).Moreover, the recent global estimate on potassium use efficiency of cereals crops reported a considerable decline in the last 50 years (Dhillon *et al.*, 2019). Therefore, a credible fertilization approach aiming to improve K utilization efficiency as well as farm productivity would be of great importance to conserve this non-renewable natural resource (Sui *et al.*, 2017).

Among various ecological approaches, use of compost amendments has frequently been advocated as a mean of promoting soil ecological functions for a resilient agroecosystems(Arif *et al.*, 2018).Often addition of compost can enhance agricultural productivity by its conditioning properties as well as recycling nutrients to the soil system (Conti *et al.*, 2014).The ancillary benefits of compost application may not be fully recognized with sole application largely because of insufficient nutrients supply that could reduce yield potential and farm productivity(Tian *et al.*, 2016). Integrating fertilizer nutrients such as K with organic materials could be a useful management option to counteract potassium deficiency in soils. It is well documented now that organic materials enriched fertilizer are environmentally safer and economically more feasible than chemical fertilizers alone(Zorb *et al.*, 2014). Numerous studies on the effects of nutrient enriched compost have highlighted the significance for being taken as an appealing soil management option in nutrient poor dryland ecosystems(Khalid *et al.*, 2014; Yadav *et al.*, 2017).

A hyphenating zone between plant roots and soil, known as rhizosphere, typically characterized for intense biochemical activities by releasing array of metabolites as well as recruiting variety of microbes (Hinsinger *et al.*, 2005).Potassium ions are usually taken up by the plants from root zone through facilitated process of diffusion and mass flow. In most soils, ~90% of potassium exist in unavailable mineral form i.e. feldspar, mica and orthoclase. Owing to their inherent resistivity against decomposition, only minor fraction of these mineral makes up into the pool of plant available K. Certain root associated bacteria called as potassium solubilizing bacteria (KSB) have shown exceptional affinity to solubilize the insoluble K minerals (Basak *et al.*, 2009; Meena *et al.*, 2018). The KSB can improve plant K acquisition while maintaining sufficient supply of K in soil solution via accelerated bacterial K solubilization and/or mobilization.The bacterial solubilization of insoluble K is usually driven by the secretions ofvarious polysaccharides and carboxylic acids(Meena *et al.*, 2014). Application of KSB to increase available K in soil has some substantial evidences for their practical application in crop plants. However, the nature and extent of K dissolution by KSB can vary ranging from different soils and plants.

Although rate of K fertilizer application in cereal crops has seen a worldwide increase in last few decades, utilization efficiency of the added K has decreased considerably, raising concerns of sustainable yield and farm profitability. Moreover, global K reserves are expected to last for next 100 years at current rate of consumption. The projected K fertilizer scenario establishes the needs to look for sustainable K fertilization approach in agroecosystems. The prospect of integrating K with organic materials such as compost in the presence of suitable KSB holds a great promise for semi-arid agriculture. Addition of compost not only could provide necessary substrate support to introduced KSB, but it could also safeguard K fertilizer from being fixed in these soils. The objectives of the present study were to evaluate the effect of two potassium fertilization material, WM and CF either alone or enriched compost on plant growth, physiological and biochemical attributes, plant K nutrition and grain quality of semi-arid grown maize. In addition, plant growth and productivity were also assessed, both in the presence and absence of KSB strain (*Klebsiella oxytoca*KSB-17).

MATERIALS AND METHODS

***Bacterial strain*:** The KSB strain, *Klebsiella oxytoca* KSB-17, chosen for this study was originally isolated from the root zone of maize. Pure culture of KSB-17 was maintained in tryptic soy broth (TBS) supplemented with 20% glycerol (w/v) at -40°C. The selected bacteria exhibited numerous plant growth promoting attributes (Table 1). 1-aminocyclopropane-1-carboxylate (ACC) deaminase, an ethylene regulating enzyme activity, wasq uantified by monitoring ACC cleavageinto α-ketobutyrate (Penrose *et al.*, 2003). Auxin biosynthesis byKSB-17was assayed according to Sarwar *et al.* (1992). Bacterial ability to produce siderophores was determined in Luria-Bertani (LB) using Chrome Azurol Sulphonate (CAS) according tothe modified method of Hu and Xu(2011).Briefly, 15 µL of freshly grown bacterial culture was inoculated into LB broth at28±1 °C. After 48 h, 0.5 mL of aliquot was mixed with an equal volume of CAS reagent followed by incubation for 3hr in dark.Bacterial siderophores was expressed in percent siderophores unit (PSU) by measuring absorbance at 630 nm. Chitinase activity of KSB-17 was executed following the method of Cattelan *et al.* (1999). Phosphate solubilization capacity of KSB-17 was quantified by using rock phosphate as sole P source of least solubility. Bacterial root colonization assay was performed as described by Simons *et al.* (1996).

Table 1. Characterization of K-solubilizing rhizobacterial strain used for inoculation of maize seeds.

Plant growth promoting (PGP) traits	Bacterial strain *Klebsiella oxytoca* - KSB17
ACC-deaminase	370.41±17.3

(α-KB µmol g^{-1} protein h^{-1})	
Indole-acetic acid production (mg L^{-1})	
-L-TRP	34.80±3.76
+L-TRP	64.43±5.23
Chitinase (µmol of Glc NAc min^{-1} mg^{-1} protein)	42.42±2.86
Exopolysaccharide production (µg mL^{-1})	84.64±4.65
K-solubilization [0.5% WMEM] (mg L^{-1})	116.83±5.62
P-solubilization [0.5% RPEM] (mg L^{-1})	47.31±1.92
Siderophores production (SU %)	54.32±3.84
Root colonization (CFU mL^{-1})	$6.58x10^7$±$2.31x10^6$

ACC: 1-aminocyclopropane-1-carboxylate,α-KB: α-ketobutyrate, L-TRP, L-tryptophan,GlcNAc: N-acetyl D-glucosamine,K-solubilization: Potassium solubilization, P-solubilization: Phosphate solubilization, WMEM: Waste mica enriched medium, RPEM: Rock phosphate enriched medium, CFU: Colony forming unit, FRB: Fresh root biomass

***Potassium (K) solubilization assay*:** Fresh bacterial culture of KSB-17 was grown in waste mica powder (K source) spiked Aleksandrov's medium broth. KSB culture was kept in shaking incubator at 28±2°C for 7 days and centrifuged (7,000×g) for 10 min at4°C.After cell harvesting, filtrate volume was extended up to 50 mL with distilled water in a volumetric flask. The solubilized K was quantified in the solution using Flame photometer (Sugumaran and Janarthanam,2007). The analysis was performed in triplicate using KCl standard.

***Compost materials*:** Potassium enriched composts i.e. potassium sulfate/chemical fertilizer enriched compost (CFEC) and waste mica enriched compost (WMEC) were prepared from fruit and vegetable wastes collected from main fruit and vegetable market of Faisalabad. The compost feedstock material was left under ambient temperature for 3-4 days and then exposed to oven drying for 24 hr at 65°C before fine crushing of ~2.0 mm. Whole, crushed material was shifted into a locally manufactured compost reactor. Moisture content was adjusted to40%, a pre-requisite for an efficient microbial activity, for an efficient compost process. A 9 weeks long composting process was carried out as described by Arif *et al.* (2018). The compost process was monitored as follow, a mesophilic phase at 30-40°C for 1 week; a thermophilic phase at 40-60°C for 5weeks; and concluded with 3 week's mesophilic phase at 28°C for a desired maturation. After this, compost was exposed to air drying and cut into a uniform size fraction by passing through 2 mm sieve. The CF and WM at 225 and 500 g kg^{-1} compost were used for enrichment as 100% recommended source of K, respectively. At the end of composting, sub-samples were taken out from the bulk compost for physio-chemical analysis of both compost products (Table 2).

Table 2. Physio-chemical and biochemical properties of different types of compost.

Compost properties	Types of compost	
	CF-EC	**WM-EC**
Physical properties		
Moisture (%)	46.00±3.11	45.63±2.13
Chemical properties		
pH	7.17±0.04	7.19±0.03
EC (µS cm^{-1})	3267.00±33.4	3156.00±27.2
Organic matter (g kg^{-1})	390.54±2.78	391.10±2.13
Total organic-C (g kg^{-1})	225.40±2.37	226.80±1.93
Total nitrogen (g kg^{-1})	19.53±1.23	19.56±1.29
Total phosphorus (g kg^{-1})	7.42±0.13	7.34±0.11
Total potassium (g kg^{-1})	63.17±2.47	62.48±2.29
C: N ratio	11.54±0.83	11.60±0.78
C: P ratio	30.37±1.06	30.89±1.13
C: K ratio	3.57±0.08	3.63±0.07
Biochemical properties		
Dehydrogenase activity (µg TPF g^{-1} EC h^{-1})	44.78±2.89	43.19±3.12
β-glucosidase activity (µg PNP g^{-1} EC h^{-1})	67.90±3.60	64.63±3.90
Microbial biomass-C (mg kg^{-1} EC)	192.56±8.12	184.41±7.34
Microbial biomass-N (mg kg^{-1} EC)	22.43±1.10	21.13±1.07

***Seed inoculation*:** Fresh seed inoculum was prepared by streaking previously isolated KSB onto tryptic soy agar (TSA) and incubated at 28±2°C for48 hr. A distinct colony of KSB-17 was further used to prepare bacterial culture by inoculating into the TSA brothat 28 ± 2°C under 120 rev min^{-1} shaking conditions. After 48 hr, KSB culture was centrifuged (6,000 rpm; 6 minutes) and the pellet was mixed in sterilized water. Bacterial cell suspension (10^8 -10^9 CFU mL^{-1}) of selected KSB-17 obtained at 600 nm was used as seed inoculum. Hybrid maize seeds [P7414] were used in this study. Surface sterilization of seeds was performed by soaking seeds into5 % NaClO solution for 3-5 min, three washing with 95% ethanol and final rinsing with sterilized water. For seed inoculation with KSB-17 inoculum mixture, 150 mL inoculant; 10% sucrose solution; 1, 4 peat to seed ratio w/w, was executed 24 hr before sowing. A homogenous mixture of sucrose and peat without KSB-17 inoculum was used as a control treatment.

***Experimental conditions*:** A sandy clay loam soil, classified as Haplic Yermosols, was collected from agricultural fields of the University of Agriculture Faisalabad. Soil samples were taken from 0-15 cm depth, hand sorted in the field, and uniformly mixed for a field representative sample. Sub-samples were separated to perform initial phyisco-chemical and biochemical analysis (Table 3). An earthen pot (15 kg soil pot^{-1}) experiment was set up at agricultural research farm, University of Agriculture Faisalabad. In this experiment, a 5×2 factorial treatment orientation was followed i.e. 5 level of K fertilizer (Control, WM, CF, CFEC and WMEC) and 2 inoculation level (Without KSB, With KSB). Nitrogen, phosphorus and potassium fertilizers were applied at a standard rate i.e. 296-167-125 kg ha^{-1}, as urea, diammonium phosphate (DAP) and K from two different sources (sulfate of potash and waste mica powder), respectively. Basal dose of phosphorus and potassium fertilizers were supplied at the time of sowing. In case of nitrogen, dose rate was splitted into three applications and applied at the time of sowing, knee height and flowering stage, respectively. Potassium fertilization, either WM or CF, was executed through compost application at 2000 kg ha^{-1}at the time of seed bed preparation. The pots were surface irrigated with canal water to maintain optimum moisture condition (~70% of WHC) for plant growth. Five maize seeds were sown and only one seedling per pot was retained. All pots were subjected to routine agronomic practices throughout the experiment.

Table 3. Physio-chemical and biochemical properties of the soil used for experiments.

Soil properties	Value
Physical properties	
Textural class	Sandy clay loam
Sand (g kg^{-1} of soil)	570.0
Silt (g kg^{-1} of soil)	200.0
Clay (g kg^{-1} of soil)	230.0
Chemical properties	
pH	7.93 ± 0.04
Electrical conductivity (µS cm^{-1})	1130.00 ± 12.6
Total organic-C (g kg^{-1})	5.82 ± 0.12
Dissolved organic C (mg kg^{-1})	45.54 ± 4.63
Total nitrogen (mg kg^{-1})	262.92 ± 9.23
Available P (mg kg^{-1})	6.93 ± 0.65
Available K (mg kg^{-1})	184.90 ± 9.23
Biochemical properties	
Microbial biomass C (mg kg^{-1})	286.43 ± 8.35
Microbial biomass N (mg kg^{-1})	12.48 ± 1.08
Dehydrogenase (µg TPF g^{-1} soil h^{-1})	15.13 ± 2.19
β-glucosidase (µg PNP g^{-1} soil h^{-1})	2.53 ± 0.83

***Plant sampling and analyses*:** At flowering stage, plant physiological attributes and antioxidant enzyme activities of maize were determined. Plant height was measured at physiological maturity. Both above and belowground biomass was determined at harvesting. After harvesting, grain and associated biomass were separated, dried and analyzed forprotein content, oil content, starch content and potassium concentration. Potassium (K) content in shoot, root and grain was determined by Flame Photometer (Perkin-Elmer 2340) using standard methods (Chapman and Pratt, 1961). For this, samples were washed twice with distilled water, air-dried at 70ºC for 48h and ground in a mill to pass through a thirty-mesh screen. Tissue extraction was made by dry ashing of a 0.5 g sample in a mufflefurnace at550ºCfor6hr. Subsequently, the ash was dissolved in 3 mL of 6 N HCl and the solution was diluted with deionized water to 50 mL final volume. Photosynthetic, transpiration rate and stomatal conductance (at flag leaf stage) were measured by Infrared Gas Analyzer (IRGA, LCA-4, ADC, Hoddesdon UK) as suggested by Long and Bernacchi (Long *et al.*, 2003). Water use efficiency (WUE) was calculated by dividing net photosynthetic rate by transpiration rate. The chlorophyll contents were measured by using chlorophyll meter.

Catalase (CAT) and peroxidase (POD) were measured by using the method of Chapman and Pratt (1961). Superoxide dismutase (SOD) was assayed using the procedure outlined by Gong *et al.* (2005). Shoot, root and grain K content were determined by using Flame Photometer (Perkin-Elmer 2340) according to the method of Chapman and Pratt (1961). Grain protein contents were quantified through Micro-Kjeldahl's procedure and starch contents were determined as described by McCleary *et al.* (1994). Oil contents were extracted and determined by Soxhlet system according to the American Oil Chemists' Society method (1993).

Statistical analysis: The whole data set was statistically analyzed by using SPSS, version 21. Two-way analysis of variance (ANOVA)was used to assess the effects of different K fertilization and KSB inoculation levels on selected physiological, biochemical, and qualitative variables of maize plant. Differences within K fertilizers and KSB inoculation were tested by using Tukey's post-hoc test. All figures and tables represent means of four replicates followed by standard error of means. All tests were reported as significant at a $p \leq 0.05$.

RESULTS

Shoot growth parameters: In the present study, data indicated that application of WM had non-significant effect on plant height, fresh and dry biomass of maize compared to both KSB inoculated and uninoculated control (Table 4). Without KSB inoculation, KCF application significantly ($p \leq 0.05$) increased plant height up to 48% compared to uninoculated control, while fresh and dry shoot biomass was increased up to 54% higher, respectively. Compared to both untreated and treated control, WMEC fertilization had significant effect on plant height, fresh and dry shoot biomass. Similarly, KCFEC application significantly improved plant height and shoot biomass compared to all fertilization treatments under non-KSB conditions. Whilst, the effect of KCFEC application was

Table 4. Effects of different K fertilizers on plant height, fresh and dry shoot biomass of pot grown maize under KSB inoculated and uninoculated conditions.

Treatments	Plant height (cm)		Fresh shoot biomass (g pot^{-1})		Dry shoot biomass (g pot^{-1})	
	-KSB	+KSB	- KSB	+ KSB	- KSB	+ KSB
Control	109.3±8.7g	120.5±9.4f	189.3±14.3g	213.3±15.3f	150.5±11.7h	167.2±13.9fg
WM	113.2±7.9fg	122.3±10.7f	195.8±15.2g	216.5±14.2f	156.7±12.3gh	172.4±14.1f
KCF	162.3±13.4c	170.7±12.7b	292.2±19.7c	313.4±21.5bc	232.5±17.6c	239.5±18.8bc
WMEC	133.3±10.4e	156.8±11.4cd	230.7±12.2e	261.6±15.3d	190.3±10.8de	212.7±11.9d
KCFEC	174.5±13.7ab	180.7±14.3a	323.2±22.6b	340.4±23.2a	246.9±16.5b	262.9±19.4a

KSB= Potassium solubilizing bacteria, WM = Waste mica, KCF = K chemical fertilizer, WMEC = WM-enriched compost, KCFEC = KCF-enriched compost. Values represent means ± standard error of four replicates (n=4), while values with different case letters, in each column, indicate level of significance at $p \leq 0.05$ among treatments

Table 5. Effects of different K fertilizers on root length, fresh -dry root biomass, rhizosphere KSB population of pot grown maize under KSB inoculated and uninoculated conditions.

Treatments	Root length (cm)		Fresh root biomass (g pot^{-1})		Dry root biomass (g pot^{-1})		KSB population (CFU g^{-1} dry soil)	
	- KSB	+ KSB	- KSB	+ KSB	- KSB	+ KSB	- KSB	+ KSB
Control	27.3±2.3e	30.3±2.8d	48.1±4.2f	54.5±5.2e	8.21±0.52f	9.12±0.81de	$4.23x10^4±2.69x10^3$e	$6.78x10^4±2.45x10^3$d
WM	28.5±2.4de	31.5±2.7d	49.3±4.1f	55.7±4.9e	8.74±0.48f	9.26±0.83de	$4.40x10^4±2.63x10^3$e	$7.23x10^4±2.57x10^3$d
KCF	39.1±2.6c	42.4±4.0b	70.4±5.4bc	74.4±6.4b	10.60±0.69d	12.46±1.21c	$4.30x10^5±3.31x10^4$c	$6.32x10^5±3.09x10^4$c
WMEC	32.9±2.2d	41.3±2.7b	61.2±4.4d	76.4±6.2b	11.7±0.72cd	14.30±1.13b	$3.29x10^6±3.89x10^5$b	$4.69x10^6±3.71x10^5$a
KCFEC	45.6±3.4b	52.5±4.1a	78.5±6.2ab	83.3±7.1a	14.67±1.24b	16.87±1.32a	$3.36x10^6±4.07x10^5$b	$4.72x10^6±4.26x10^5$a

KSB= Potassium solubilizing bacteria, WM = Waste mica, KCF = K chemical fertilizer, WMEC = WM-enriched compost, KCFEC = KCF-enriched compost. Values represent means ± standard error of four replicates (n=4), while values with different case letters, in each column, indicate level of significance at $p \leq 0.05$ among treatments

Table 6. Effects of different K fertilizers on net-photosynthesis, transpiration rate, water use efficiency, stomatal conductance and total chlorophyll contents of pot grown maize under KSB inoculated and uninoculated conditions.

Treatments	Net photosynthesis (μmol m^{-2} s^{-1})		Transpiration rate (mmol H_2O m^{-2} s^{-1})		Water use efficiency (μmol CO_2 $mmol^{-1}$ H_2O)		Stomatal conductance (mmol m^{-2} s^{-1})		Total chlorophyll content(mg g^{-1} FB)	
	-KSB	+ KSB	-KSB	+ KSB	-KSB	+ KSB	-KSB	+ KSB	-KSB	+ KSB
Control	9.74±0.91ef	10.82±0.88e	3.18±0.09d	3.36±0.11c	3.12±0.10d	3.22±0.08d	0.21±0.01d	0.23±0.02d	2.90±0.09d	3.07±0.10cd
WM	10.03±0.87e	10.88±0.93e	3.15±0.07d	3.38±0.13c	3.15±0.09d	3.24±0.09d	0.21±0.01d	0.23±0.02d	2.94±0.11d	3.12±0.10c
KCF	16.03±1.33b	18.82±1.47a	3.47±0.15c	3.96±0.21b	4.12±0.19b	4.75±0.13a	0.35±0.02ab	0.38±0.03a	3.80±0.15ab	3.89±0.15a
WMEC	12.52±1.13d	15.72±1.17b	3.27±0.19cd	3.85±0.12b	3.62±0.14c	4.08±0.11b	0.26±0.02cd	0.32±0.03b	3.19±0.13c	3.74±0.12b
KCFEC	15.48±1.32c	19.83±1.63a	3.76±0.22b	4.14±0.22a	4.61±0.18a	4.79±0.13a	0.38±0.03a	0.41±0.03a	3.86±0.14a	4.03±0.15a

KSB= Potassium solubilizing bacteria, WM = Waste mica, KCF = K chemical fertilizer, WMEC = WM-enriched compost, KCFEC = KCF-enriched compost. Values represent means ± standard error of four replicates (n=4), while values with different case letters, in each column, indicate level of significance at $p \leq 0.05$ among treatments

even more pronounced with KSB inoculation and increased plant height, fresh and dry shoot biomass up to 50, 59 and 57% respectively, than control treatment.

***Root growth parameters*:** Compared to control treatment, addition of WM had non-significant effect on root length, root biomass and root associated KSB population at both inoculation levels (Table 5). However, a marked increase in maize root traits and KSB population was recorded upon WMEC application. Similarly, KCF application significantly ($p \leq 0.05$) improved root traits and KSB population than control treatment at both inoculation levels. In the absence of KSB inoculation, compost enrichment of KCF significantly affected the root length, root biomass and KSB root population compared to control treatment. Addition of KCFEC with KSB inoculation always resulted in the highest root length (52.5 cm), fresh root biomass (83.3 g pot^{-1}), dry root biomass (16.87 g pot^{-1}) and root adhered KSB population (4.72×10^6 CFU g^{-1} dry soil), respectively, when compared to the rest of treatments.

***Physiological parameters*:** At both inoculation levels, WM addition did not influence the plant physiological parameters compared to both control treatments (Table 6). Whereas WMEC application significantly ($p \leq 0.05$) increased plant physiological parameters at both inoculation levels, except for transpiration rate and stomatal conductance, wherein no significant difference was recorded in the absence of KSB inoculation. Similarly, KCFEC application resulted in significantly higher net photosynthesis, transpiration rate, water use efficiency, stomatal conductance and total chlorophyll contents by 59, 18, 48, 81 and 33%, respectively, compared to control treatment under no KSB inoculation condition. The interactive effect of KCFEC with KSB inoculation was even stronger that led to the highest increase in all tested plant physiological parameters when compared to the rest of the treatments.

***Antioxidant enzymes activities*:** Results regarding the activities of antioxidant enzymes (CAT, POD, SOD) were examined in maize plant (Fig.1).

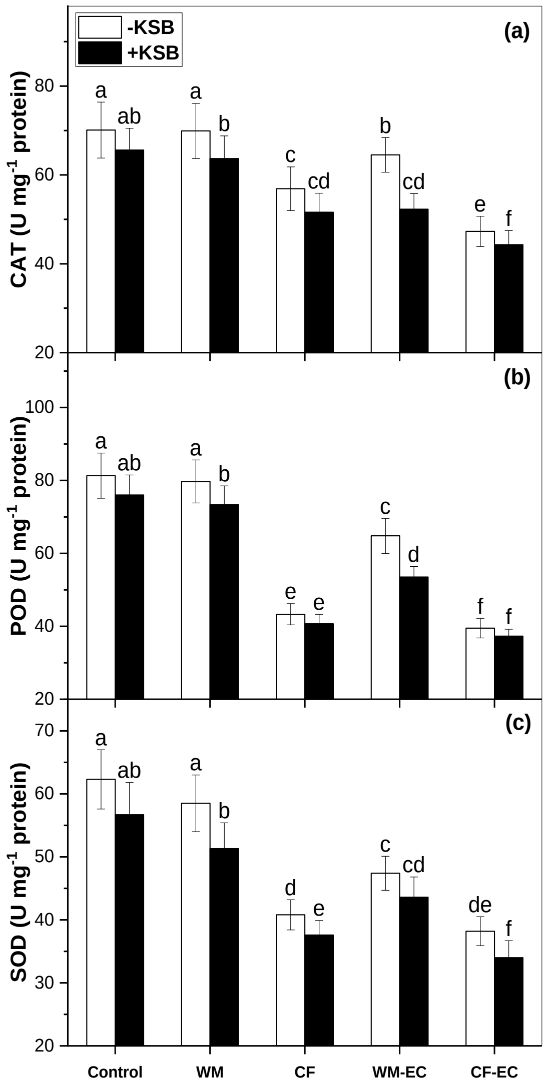

Figure 1. Efficacy of different K fertilizers on antioxidant enzymes activity of (a) CAT (b) POD, and (c) SOD in maize plant under KSB inoculated and uninoculated conditions. Values represent means ± standard error of four replicates (n=4), while values with different case letters indicate level of significance at $p \leq 0.05$ among treatments.

Under no KSB inoculation, all treatments, except for the WM decreased significantly the activity of CAT when compared with control treatment. With KSB inoculation, CAT activity of WM treated plants was comparable with that in control treatment (Fig.1a), and was significantly higher than rest of the treatments. Overall, KSB inoculation with KCFEC had the lowest CAT activity (44.30 U mg^{-1} protein) compared to the rest of treatments.

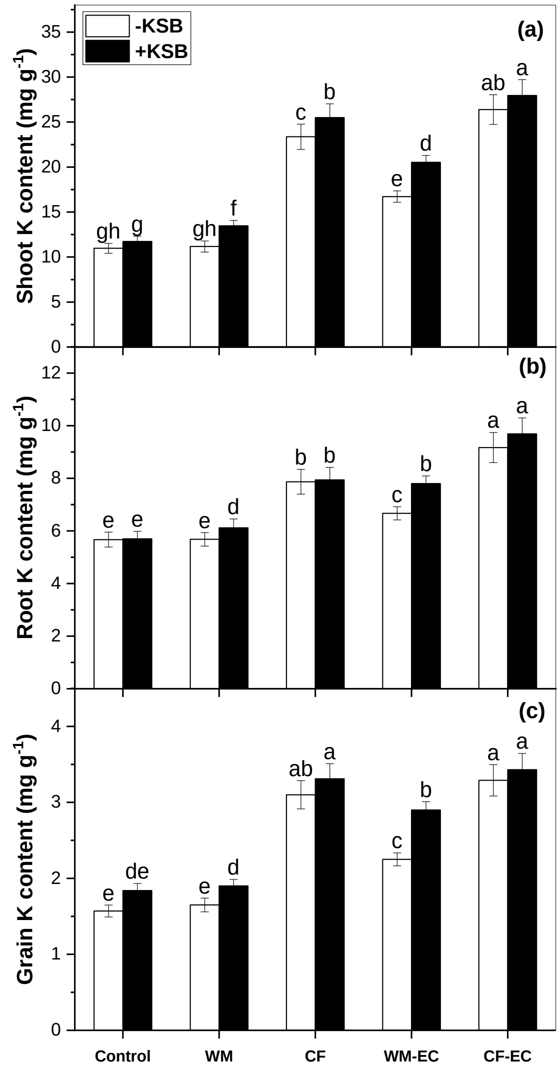

Figure 2. Efficacy of different K fertilizers on K contents of (a) shoot (b) root, and (c) grain in maize plant under KSB inoculated and uninoculated conditions. Values represent means ± standard error of four replicates (n=4), while values with different case letters indicate level of significance at $p \leq 0.05$ among treatments

POD activity was significantly reduced by the addition of WMEC compared to control treatment, but no effect was noted when WM was applied without compost at both inoculation levels (Fig.1b). Application of KCF and KCFEC had significant effect on POD activity at both inoculation levels. A significant decrease in POD activity by 47 and 51% than control was recorded with KCF and KCFEC, respectively, in the absence of KSB inoculation. However, reduction in POD activity was more pronounced with KCFEC followed by KCF under KSB inoculation.

Application of WM showed insignificant changes in SOD activity compared to control treatment at both inoculation levels (Fig.1c). However, WMEC addition led to significant decline in SOD activity compared to control under both inoculation conditions. Similarly, KCF also resulted in significant reduction of SOD activity, whilst KCFEC application along with KSB inoculation had the highest reduction of SOD activity by 40% in relation to control treatment.

***Plant potassium uptake*:** Without KSB inoculation, significant increase in shoot K contents was observed after KCF application, especially under compost fertilization, contributing the largest K contents of all treatments (Fig.2a). In the presence of KSB inoculation, application of KCF and KCFEC increased shoot K contents compared to control. Although to lesser extent, a similar trend was also observed for WM and WMEC treatment.

Without KSB inoculation, WM had non-significant effect on root K contents compared to control but showed significantly higher K content with WM under KSB inoculation (Fig.2b). At both inoculation level, root K content increased significantly compared to respective control treatments. In order of magnitude, the effects were highest for KCFEC followed by KCF and WMEC, respectively.

No significant difference in grain K uptake was detected when compared with control after WM application at both inoculation levels (Fig.2c). However, WMEC resulted in significantly higher grain K contents than control at both inoculation levels. Whilst statistically comparable but highest grain K contents were recorded in KCF and KCFEC fertilization when compared with the rests of treatments in KSB inoculated and uninoculated conditions.

***Grain quality*:** Without KSB inoculation, significant increase in grain protein content was recorded among treatments except for WM that revealed no significant difference when compared to control treatment (Fig.3a). The grain protein contents were highest in KCFEC treatment and lowest in control treatment under no KSB inoculation. Grain protein contents showed gradual but significant increase in response to all treatments under KSB inoculation.

WM addition had no significant effect on oil and starch contents compared to control treatments at both inoculation levels (Fig.3b,c). However, WMEC, KCF and KCFEC fertilization resulted in significantly higher oil and starch contents as compared to the respective control treatments under inoculated as well non-inoculated conditions.

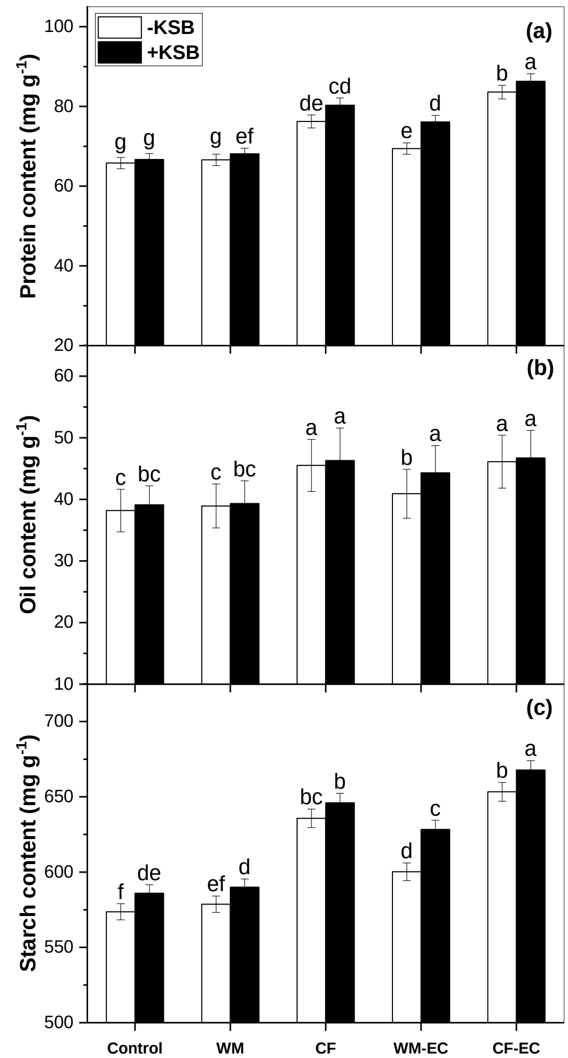

Figure 3. Efficacy of different K fertilizers on (a) protein (b) oil, and (c) starch contents of maize grain under KSB inoculated and uninoculated conditions. Values represent means ± standard error of four replicates (n=4), while values with different case letters indicate level of significance at $p \leq 0.05$ among treatments.

DISCUSSION

In the current study, selected potassium fertilizer sources exhibited varied effects on plant growth parameters of maize (Table 4). Application of KCFEC had a highly significant effect on plant height and biomass. Overwhelming evidence of nutrient enriched compost application and its positive impact on plant growth promotion can be found in literature (Iqbal *et al.,* 2012; Arif *et al.,* 2016). These positive effects were often attributed to the steady supply of plant nutrients and enhanced soil conditions following these amendments application (Agegnehu *et al.,* 2015). The effect on plant growth by compost enriched K sources was more pronounced with KSB inoculation than individual K fertilization sources; perhaps due to elevated functional response of inoculated KSB strain in the presence of compost, i.e. KSB can increase plant growth by a variety of direct and indirect plant growth promotion mechanisms (Table 1). Previous studies have also indicated a close linkage of balanced mineral nutrition and increased in plant growth inoculated with KSB in different crop plants (Zhang *et al.*, 2014). Our results also showed prolific effects of KCFEC application on root growth related parameters (Table 5). These results corroborate the findings of Postma *et al.* (2014), who demonstrated that root proliferation can be stimulated by the establishment of nutrient rich patches at root-soil interface. Application of suitable microbial inoculant can also improve plant root growth. Past reports showed that some species of root colonizing bacteria can promote maize root growth and modify root architecture by regulating ethylene concentration via the expression of ACC-deaminase activity(Arshad *et al.,* 2008).Overall, slower K releasing source i.e. waste mica enriched with compost, improved plant shoot and root growth, although to a lesser extent both in the presence and absence of KSB inoculant. This confirms that K dissolution potential of KSB can facilitate a slow release K pattern from compost. Higher population of root associated KSB also indicated the improvement in KSB rhizosphere competence. In some other studies, persistence and proliferation of introduced bacterial inoculum with various types of organic amendments has been reported (Fox *et al.,* 2014).

An improvement in plant photosynthetic rate, transpiration rate, water use efficiency, stomatal conductance and total chlorophyll content was recorded in KCFand KCFEC fertilization. Elevation in plant physiological responses and gaseous exchange has previously been noticed in soil treated with KSB (Supanjani *et al.,* 2006). Similarly, Han and Lee (2005)also observed increase in photosynthetic rate of eggplant up to 12% because of *B. mucilaginosus* inoculation, which led to higher K uptake from KSB solubilized minerals. A strong relationship between improved plant nutrition and resultantly higher chlorophyll contents, physiological and gaseous exchange parameters has been noticed in variety of crops viz. wheat (Sheng *et al.,* 2006), maize(Parmar *et al.,* 2013), sorghum (Basak *et al.,* 2009), and tomato(Lin *et al.,* 2001).Plants show antioxidant enzymes (CAT, SOD and POD) activity to combat the detrimental upshots of reactive oxygen species (ROS) produced because of K deficiency stress, like other biotic and abiotic stresses (Mittler, 2002). In this study, decrease in antioxidant enzyme activities following K fertilizer and compost application indicates a downregulation pattern of these stress indicators to counteract the harmful effects of K deficiency stress. Microbial inoculant led downregulation of antioxidants enzyme activities with higher plant growth as well as improved plant nutrition has recently been reported by Armada *et al.*(2015)and Fukami *et al.*(2018). Regulation of stomatal passage for gaseous exchange with adequate supply of K could avoid the deleterious effects of ROS by hindering their production under K deficiency(Kant *et al.,* 2002; Egilla *et al.,* 2005).Transport of K to the guard cells ensures gaseous regulation and normal photosynthetic activity which eventually attenuates the destructive effects of stress (Kant *et al.,* 2002).

In the present study, significantly higher uptake of K by shoot, root and grain in KCFEC treatment could highlight the shielding effect of additional compost substrate causing slower K release pattern of compost enriched K source compared its sole application (Fig.2). Slow release pattern of nutrient enriched organic amendments and their positive impacts on soil plant system are earlier reported by Ryals *et al.*(2016) and Gwenzi *et al.*(2018).The most significant finding from this study was that the KSB inoculation in combination with different K sources significantly improved plant K nutrition(Fig.2).In particular, combination of KSB and KCFEC that led to the highest accumulation of K in maize plant biomass. These results indicate that KSB inoculation was very efficient in exploiting compost enriched potassium by improving its solubility and/or mobility and thereby making it more available to crop plants.Compost, a rich carbon source, is known to induce positive effects on plant nutrition, and also stimulate microbial growth and activity (Arif *et al.*, 2016), such as to KSB that used in this study. Studies to date also suggest that nutrients solubilization activity of root associated microbes increase manifold when receiving suitable substrate material in the form of organic amendments (Shahzad *et al.,* 2017). Overall, KSB inoculation remained less effective in non-composted treatments, suggesting the functional loss of introduced KSB into the competitive root environment in the absence of suitable substrate material. In order to establish a successful plant-microbe interaction, sufficient supply of nutrients as well as access to compatible substrate medium is an essential component for an effective microbial inoculation conferring plant growth promotion(Song *et al.,* 2015).Differences in maize grain quality i.e. protein, starch and oil contents are generally attributed to the genetic potential of grown crop variety, rather than soil amendment or microbial inoculants. Our results demonstrate that addition of KCFEC with KSB was the most effective treatment combination and improved all the selected grain quality parameters. The extent of improvement in maize grain quality following these amendments may be explained by the improved plant K nutrition in this experiment. Similarly, Usherwood (1985) also reported higher carbohydrate, protein and oil contents of grain with increasing availability of K to maize. Moreover, Yang *et al.*(2004)also reported an increase of protein and amino acids in grain of well K fertilized plants as compared to control. Application of rock K supplemented with suitable microbial inoculant increased maize grain quality (Sheng *et al.*, 2006).

***Conclusions*:** Conclusively, it may be inferred that application of potassium fertilizer enriched compost with potassium solubilizing bacteria improved the plant shoot and root growth, also led to the enhancement of various physiological and biochemical traits. Noticeable improvement in plant potassium nutrition as well as grain quality were also found following the addition of these amendments. Integrated use of waste mica along with suitable potassium-solubilizing bacteria could offer some promise with regard to improving potassium-nutrition of maize, but it requires some extensive investigation across varied crop plants and soil conditions. Overall, use of potassium-solubilizing bacteria with different sources of potassium fertilizer could offer an environment friendly and economical option, which not only can counteract potassium deficiency in crop plants but also overall improvement in their growth and development.

REFERENCES

Agegnehu, G., M. Bird, P. Nelson and A. Bass. 2015. The ameliorating effects of biochar and compost on soil quality and plant growth on a Ferralsol. Soil Res.53:1-12.

Ameen, A., C. Tang, L. Han and G.H. Xie. 2018. Short-term response of switch-grass to nitrogen, phosphorus, and potassium on semiarid sandy wasteland managed for biofuel feedstock. Bioenergy Res. 11:228-238.

Anschütz, U., D. Becker and S. Shabala. 2014. Going beyond nutrition: regulation of potassium homoeostasis as a common denominator of plant adaptive responses to environment. J Plant Physiol. 171:670-687.

AOCS. 1993. Official methods and recommended practices of the American Oil Chemists' Society. AOCS press, USA. pp. 110-115.

Arif, M.S., M. Riaz, S.M. Shahzad, T. Yasmeen, M. Ashraf, M. Siddique, M.S. Mubarik, L. Bragazza and A. Buttler. 2018. Fresh and composted industrial sludge restore soil functions in surface soil of degraded agricultural land. Sci. Total Environ. 619-620:517-527.

Arif, M.S., M. Riaz. S.M. Shahzad, T. Yasmeen, M.J. Akhtar, M.A. Riaz, V.E.L. Jassey, L. Bragazza and A. Buttler. 2016. Associative interplay of plant growth promoting rhizobacteria (*Pseudomonas aeruginosa* QS40) with nitrogen fertilizers improves sunflower (*Helianthus annuus* L.) productivity and fertility of Aridisol. Appl. Soil Ecol. 108:238-247.

Armada, E., R. Azcón, O.M. López-Castillo, M. Calvo-Polanco andJ.M. Ruiz-Lozano. 2015. Autochthonous arbuscular mycorrhizal fungi and *Bacillus thuringiensis* from a degraded Mediterranean area can be used to improve physiological traits and performance of a plant of agronomic interest under drought conditions. Plant Physiol. Biochem. 90:64-74.

Arshad, M., B. Shaharoona and T. Mahmood. 2008. Inoculation with plant growth promoting rhizobacteria containing ACC-deaminase partially eliminates the effects of water stress on growth, yield and ripening of *Pisum sativum* L. Pedosphere, 18:611-620.

Basak, B.B. and D.R. Biswas. 2009. Influence of potassium solubilizing microorganism (*Bacillus mucilaginosus*) and waste mica on potassium uptake dynamics by Sudangrass (*Sorghum vulgare* Pers.) grown under two Alfisols. Plant Soil, 317:235-255.

Bastin, J.F., N. Berrahmouni, A. Grainger, D. Maniatis, D. Mollicone, R. Moore, C. Patriarca, N. Picard, B. Sparrow, E.M. Abraham, K. Aloui, A. Atesoglu, F. Attore, Ç. Bassüllü, A. Bey, M. Garzuglia, L.G. García-Montero, N. Groot, N.G. Guerin, L. Laestadius, A.J. Lowe, B. Mamane, G. Marchi, P. Patterson, M. Rezende, S. Ricci, SalcedoI, P. Diaz, F. Stolle, V. Surappaeva and R. Castro. 2017. The extent of forest in dryland biomes. Sci. 356:635-638.

Cattelan, A.J., P.G. Hartel and J.J. Fuhrmann. 1999. Screening for plant growth-promoting rhizobacteria to promote early soybean growth. Soil Sci. Soc. Am. J. 63:1670-1680.

Chapman, H.D. and F.P. Pratt. 1961. Ammonium vandate-molybdate method for determination of phosphorus. Methods Anal. Soils Plants Water 1:184-203.

Chérel, I. 2004. Regulation of K^+ channel activities in plants: from physiological to molecular aspects. J. Exp. Bot. 55:337-351.

Conti, S., G. Villari, S. Faugno, G. Melchionna, S. Somma and G. Caruso. 2014. Effects of organic vs. conventional farming system on yield and quality of strawberry grown as an annual or biennial crop in southern Italy. Sci. Hort. 180:63-71.

Cruz-Cárdenas, C.I., M. Cortés-Cruz, C.A. Gardner and D.E. Costich. 2019. Wild Relatives of Maize. In *North American Crop Wild Relatives*, Volume 2, Important Species. Springer: USA. pp. 3-39.

Dhillon, J.S., E.M. Eickhoff, R.W. Mullen and W.R. Raun. 2019. World potassium use efficiency in cereal crops. Agron. J. 111:1-8.

Egilla, J.N., F.T. Davies and T.W. Boutton. 2005. Drought stress influences leaf water content, photosynthesis, and water use efficiency of *Hibiscus rosasinensis* at three potassium concentrations. Photosynthetica 43:135-140.

Fox, A., W. Kwapinski, B.S. Griffiths andA. Schmalenberger. 2014. The role of sulfur and phosphorus mobilizing bacteria in biochar induced growth promotion of *Lolium perenne*. FEMS Microbiol. Ecol. 90:78-91.

Fukami, J., C. de la Osa, F.J. Ollero, M. Megías and M. Hungria. 2018. Co-inoculation of maize with *Azospirillum brasilense* and *Rhizobium tropici* as a strategy to mitigate salinity stress. Funct. Plant Biol. 45:328-339.

Gong, L., S. Kyriakides and N. Triantafyllidis. 2005. On the stability of Kelvin cell foams under compressive loads. J. Mech. Phys. Solids 53:771-794.

Gwenzi, W., T.J. Nyambishi, N. Chaukura and N. Mapope. 2018. Synthesis and nutrient release patterns of a biochar-based N-P-K slow-release fertilizer. Int. J. Environ. Sci. Technol. 15:405-414.

Han, H.S. and K.D. Lee. 2005. Phosphate and potassium solubilizing bacteria effect on mineral uptake, soil availability and growth of eggplant. Res. J. Agric. Biol. Sci. 1:176-80.

Hinsinger, P., G.R. Gobran, P.J. Gregory and W.W. Wenzel. 2005. Rhizosphere geometry and heterogeneity arising from root-mediated physical and chemical process, research view. New Phytol. 168:293-303.

Hu, Q.P. and J.G. Xu. 2011. A simple double-layered chrome azurol S agar (SD-CASA) plate assay to optimize the production of siderophores by a potential biocontrol agent *Bacillus*. Afr. J. Microbiol. Res. 5:4321-4327.

Iqbal, M.A., M. Khalid, S.M. Shahzad, M. Ahmad, N. Soleman and N. Akhtar. 2012. Integrated use of *Rhizobium leguminosarum*, plant growth promoting rhizobacteria and enriched compost for improving growth, nodulation and yield of lentil (*Lens culinaris* Medik.). Chil. J. Agric. Res. 72:104-110.

Jones, T.J. 2009. Maize Tissue Culture and Transformation: the first 20 years. In Molecular Genetic Approaches to Maize Improvement Biotechnology in Agriculture and Forestry, Springer, USA.Pp. 369.

Kant, S. and U. Kafkafi. 2002. Potassium and Abiotic Stresses in Plants. In : *Potassium for Sustainable Crop Production*. Potash Institute of India Publications. India.Pp. 233-251.

Khalid, I., A. Nadeem, A. Ahmedand A. Husnain. 2014. Conjunctive and mineralization impact of municipal solid waste compost and inorganic fertilizer on lysimeter and pot studies. Environ. Technol. 35:487-498.

Lin, Q.M., Z.A. Rao,Y.X. Sun, J. Yao and L.J. Xing. 2001. Identification and practical application of silicate-dissolving bacteria. Agric. Sci. China. 1:81-85.

Long, S.P. and C.J. Bernacchi. 2003. Gas exchange measurements, what can they tell us about the underlying limitations to photosynthesis? Procedures and sources of error. J. Exp. Bot. 392:2393-2401.

McCleary, B.V., T.S. Gibson,V.Solah and D.C. Mugford. 1994. Total starch measurement in cereal products, interlaboratory evaluation of a rapid enzymic test procedure. Cereal Chem. 71:501-504.

Meena, V.S., A. Zaid, B.H. Maurya, S.K. Meena, I. Bahadur, M. Saha, A. Kumar, R. Verma and S.H. Wani. 2018. Evaluation of potassium solubilizing rhizobacteria (KSR) enhancing K-bioavailability and optimizing K-fertilization of maize plants under Indo-Gangetic Plains of India. Environ. Sci. Poll. Res. 25:36412-36424.

Meena,V.S., B.R. Maurya and J.P. Verma. 2014. Does a rhizospheric microorganism enhance K^+ availability in agricultural soils. Microbiol. Res. 169:337-347.

Mian, S.M. and Z. Ahmad. 2007. Potassium scenario in Pakistani Punjab. In : Proceeding of international symposium on balanced fertilization for sustainable crop productivity, Punjab Agriculture University: Ludhiana.Pp. 428-429.

Mittler, R. 2002. Oxidative stress, antioxidants and stress tolerance. Trends Plant Sci. 7:405-410.

Parmar, P. and S.S. Sindhu. 2013. Potassium solubilization by rhizosphere bacteria, Influence of nutritional and environmental conditions. J. Microbiol. Res. 3:25-31.

Penrose,D.M. and B.R. Glick. 2003. Methods for isolating and characterizing ACC deaminase containing plant growth-promoting rhizobacteria. Physiol. Plant. 118:10-15.

Postma,J.A., A. Dathe and J.P. Lynch. 2014. The optimal lateral root branching density for maize depends on nitrogen and phosphorus availability. Plant Physiol. 166:590-602.

Rao, C.H., S. Kundu, B.K. Ramachandrappa, S. Reddy, R. Lal, B. Venkateswarlu, K.L. Sahrawat and R.P. Naik. 2014. Potassium release characteristics: potassium balance, and finger millet (*Eleusine coracana* G.) yield sustainability in a 27- year long experiment on an Alfisol in the semi-arid tropical India. Plant Soil 374:315-330.

Ryals, R., V.T. Eviner, C. Stein, K.N. Suding and W.L. Silver. 2016. Grassland compost amendments increase plant production without changing plant communities. Ecosphere. 7:e01270. 10.1002/ecs2.1270

Samra, J.S. and S. Anand. 2008. Impact of long-term intensive cropping on soil potassium and sustainability of crop production. Geoderma.148:173-179.

Sarwar, M., M. Arshad, D.A. Martens, and W.T. Frankenberger. 1992. Tryptophan-dependent biosynthesis of auxins in soil. Plant Soil 147:207-215.

Shahzad, S.M., M.S. Arif, M. Ashraf, T. Yasmeen, A. Zaheer, L. Bragazza, A. Buttler and B.J.M. Robroek. 2017. Interaction of compost additives with phosphate solubilizing rhizobacteria improved maize production and soil biochemical properties under dryland agriculture. Soil Till. Res. 174:70-80.

Shahzad, S.M., A. Khalid, M. Arshad, J. Tahir and T. Mahmood. 2010. Improving nodulation, growth and yield of (*Cicer arietinum* L.) through bacterial ACC-deaminase induced changes in root architecture. Eur. J. Soil Biol. 46:342-347.

Sheng, X.F. and L.Y. He. 2006. Solubilization of potassium bearing minerals by a wild-type strain of *Bacillus edaphicus* and its mutants and increased potassium uptake by wheat. Can. J. Microbiol. 52:66-72.

Simons, M., A.J. van der Bij, I. Brand, L.A. deWeger, C.A. Wijffelman and B.J.J. Lugtenberg. 1996. Gnotobiotic system for studying rhizosphere colonization by plant growth promoting *Pseudomonas* bacteria. Mol. Plant Microbe Inter. 9:600-607.

Song, X., M. Liu, D. Wu, B.S. Griffiths, Jiao, H. Li and F. Hu. 2015. Interaction matters, Synergy between vermicompost and PGPR agents improves soil quality, crop quality and crop yield in the field. Appl. Soil Ecol. 89:25-34.

Sugumaran, P. and B. Janarthanam. 2007. Solubilization of potassium containing minerals by bacteria and their effect on plant growth. World J. Agric. Sci. 3:350-355.

Sui, N., C. Yu, G. Song, F. Zhang, R. Liu, C. Yang, Y. Meng and Z. Zhou. 2017. Comparative effects of crop residue incorporation and inorganic potassium fertilization on apparent potassium balance and soil potassium pools under a wheat-cotton system. Soil Res. 55:723-734.

Sujakhu, N.M., S. Ranjitkar, R.R. Niraula, M.A. Salim, A. Nizami, D.Schmidt-Vogt and J. Xu. 2018. Determinants of livelihood vulnerability in farming communities in two sites in the Asian Highlands. Water Int. 43:165-182.

Supanjani, H.H., J.S. Jung and K.D. Lee. 2006. Rock phosphate potassium and rock solubilizing bacteria as alternative sustainable fertilizers. Agron. Sustain. Dev. 26:233-240.

Tian, Y.,Q. Wang, W. Zhang and L. Gao. 2016. Reducing environmental risk of excessively fertilized soils and improving cucumber growth by *Caragana microphylla*-straw compost application in long-term continuous cropping systems. Sci. Total Environ. 544:251-261.

Usherwood, N.R. 1985. The Role of Potassium in Crop Quality. In: Potassium in Agriculture. American Society of Agronomy, Madison, USA.Pp. 489-513.

Yadav, B.K. and A.S. Sidhu. 2016. Dynamics of potassium and their bioavailability for plant nutrition. In : Potassium solubilizing microorganisms for sustainable agriculture, Springer.Pp. 187-201.

Yadav, H., R. Fatima, A. Sharma and S. Mathur. 2017. Enhancement of applicability of rock phosphate in alkaline soils by organic compost. Appl. Soil Ecol. 113:80-85.

Yang, S., F. Li,S.S. Malhi, P. Wang, D. Suo and J. Wang. 2004. Long term fertilization effects on crop yield and nitrate nitrogen accumulation in soil in northwestern. China Agron. J. 96:1039-1049.

Zhang, C. and F. Kong. 2014. Isolation and identification of potassium solubilizing bacteria from tobacco rhizospheric soil and their effect on tobacco plants. Appl. Soil Ecol. 82:18-25.

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