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RESEARCH ARTICLE

Potassium-solubilizing bacteria mediated soil potassium dynamics in sweet corn

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Abstract

Potassium (K) is an indispensable macronutrient for plant growth and development and is immensely important for agriculture. Potassium-solubilising bacteria (KSB) have gained importance due to their dual functionality as plant growth-promoting rhizobacteria (PGPR) and their ability to solubilise unavailable forms of soil potassium. This study assessed the potential of dual-mode application of KSB (seed treatment + soil drenching) on soil potassium fraction dynamics, nutrient uptake and yield of a heavy feeder crop (sweet corn). The experiment was conducted at the College Farm, Professor Jayashankar Telangana Agricultural University (PJTAU), Hyderabad, during the winter season (19 November 2022 to 23 February 2023). Results demonstrated that among different treatments, application of 100 % recommended dose of K (RDK; 50 kg ha^{-1}) ± KSB (*Bacillus amyloliquefaciens*) (Seed Treatment (ST) at 10 mL kg^{-1} seed + soil drenching (SD) at 2.5 mL L^{-1} water at 25 DAS) and 75 % RDK + KSB (ST + SD) resulted in significantly higher available soil K fractions and consequently, higher K uptake and sweet corn yield were observed with these treatments. Higher monetary returns per unit cost were recorded with recommended K fertiliser; however, they were statistically at par with 75 % RDK + KSB (ST + SD). There was a synergistic effect between N and K uptake. However, P uptake was not significantly affected by K management practices. Non-exchangeable K (Non-ExK) content remained unchanged due to treatment imposition. However, all soil K fractions viz., water-soluble K, exchangeable K (ExK) and Non-ExK, showed a numerically declining trend during the crop growth period.

Keywords: available K; *Bacillus amyloliquefaciens*; exchangeable K; MOP; non-exchangeable K; seed treatment; soil drenching; water-soluble K

Introduction

Potassium (K) is an essential macronutrient that ensures optimal plant growth and aids in sugar transport, nitrogen (N) and carbon metabolism as well as photosynthesis (1). It plays a significant role in the yield maximisation and quality improvement (2). Under climate change scenarios, K plays a crucial role in enhancing abiotic stress tolerance in plants (3). Scientific studies have shown that despite the application of chemical K fertilisers, soil K levels decline over time in different cropping systems over time due to higher nutrient mining by crops and leaching losses (4, 5). In contrast, the overuse or mismanagement of chemical fertilisers may lead to environmental pollution and degradation (6, 7). Corn varieties generally respond to high doses of chemical K fertilisers (8). Hence, sweet corn was selected for the experiment.

Potassium solubilising bacteria (KSB) are known for their ability to solubilise unavailable soil K (90–98 % of the total soil K) through acidolysis, chelation, complexolysis and ion-exchange reactions, enhancing nutrient recovery (9–11). Several studies have reported that KSB, functioning as plant growth-promoting rhizobacteria (PGPR), enhance crop yield and quality while increasing K availability to plants (12, 13). In light-textured soils, split application of K has been found to be more beneficial than basal application of the entire dose (14). As far as growth, yield and economics was concerned, K has also been reported as an indispensable element for corn (15). Moreover, the combined use of suboptimal chemical K fertilisers and KSB has been proven to be a sustainable approach (16). However, the effects of applying a KSB strain (*Bacillus amyloliquefaciens*) through seed treatment (ST) and soil drenching (SD) on soil K fraction dynamics, nutrient uptake and yield of sweet corn, in comparison to the sole and combined application of chemical K fertilisers, remain largely unexplored.

It was hypothesised that the crop K requirements could be met through the KSB-mediated solubilization in K-rich sandy loam soil and a constant level of available soil K pool would be maintained in soil, maintaining a stable available soil K pool and enhancing sweet corn yield through KSB-induced production of plant growth-promoting hormones. Based on this hypothesis, the objectives of this research were to evaluate the effect of dual-mode application of

KSB on soil K-fraction dynamics across different crop growth stages; to assess the effect of dual-mode application of KSB on primary macronutrient uptake and determine its impact on sweet corn yield and the benefit–cost ratio (B:C).

Materials and methods

Experimental site and design

An experiment was conducted with ten potassium management practices in sandy loam soil . The treatments included T_1: 0 % RDK, T_2: 100 % RDK (basal, 50 kg ha^{-1}), T_3: 50 % RDK (basal, 25 kg ha^{-1}), T_4: 75 % RDK (basal, 37.5 kg ha^{-1}), T_5: 50 % RDK (basal) + 50 % RDK (at 25 DAS), T_6: T_1 + KSB (ST – seed treatment at 10 mL kg^{-1} seed] + KSB [SD – soil drenching at 2.5 mL L^{-1} water at 25 DAS), T_7: T_2 + KSB (ST + SD), T_8: T_3 + KSB (ST + SD), T_9: T_4 + KSB (ST + SD) and T_{10}: T_5 + KSB (ST + SD). The recommended dose of K was adopted as per the guidelines of PJTAU (Professor Jayashankar Telangana Agricultural University). The experiment was laid out in a randomised block design with 3 replications. Before initiation of the experiment, the field had been under fallow for one year. Prior to land preparation, initial soil samples (0–15 cm) were collected from the experimental field.

Sweet corn variety "Madhuri" (seed rate: 10 kg ha^{-1}; spacing: 60 cm × 20 cm) was grown during the rabi season of 2022–23 at the College Farm of PJTAU (17°19' N, 78°24' E), Rajendranagar, Hyderabad, Telangana, India. The experimental site is located in a semi-arid tropics (SAT) region. During the crop growth period, the weekly average maximum and minimum temperature were 30.4 °C and 14.7 °C respectively and rainfall did not influence crop growth and development (Fig. 1). The full recommended dose of phosphorus (RDP: 60 kg ha^{-1}) was applied as basal and the recommended dose of nitrogen (RDN: 200 kg ha^{-1}) was applied in three equal splits at sowing, 25 DAS and at tasseling stage (60 DAS). Potassium was applied as per the aforementioned treatments. The sources of N, P and K fertilisers were urea, single super phosphate (SSP) and muriate of potash (MOP) respectively. The liquid biofertiliser KSB (*B. amyloliquefaciens*) was procured from the Biofertiliser Production Unit of PJTAU. Irrigation was provided as per crop requirement. Soil and plant samples were collected from each plot to decipher the temporal K dynamics.

Soil and plant sample analysis

Soil and plant samples were analysed based on standard scientific procedures (Table 1). Soil K fractions were analysed by stepwise extraction using chemical solutions of increasing strength. Available potassium (AvK) was extracted from each soil sample using ammonium acetate and measured by flame photometry. Water-soluble potassium (WsK) was determined by distilled water extraction at a standard soil-to-water ratio of 1:5 (w/v), while exchangeable potassium (ExK) was calculated by deducting the WsK value from the AvK. To assess non-exchangeable potassium (Non-ExK), each soil sample was boiled in nitric acid and the extract was measured by flame photometry; this value was corrected by subtracting AvK.

Plant samples were collected, dried (at 65 °C until constant weight) and finely ground. At harvest sweet corn cobs and green stover were dried and ground together for nutrient analysis. Nitrogen (N) analysis was carried out in Kjeldahl method, involving digestion with sulfuric acid followed by distillation and titration. For phosphorus (P) and K, ground plant samples were digested with a nitric acid:perchloric acid mixture (3:1). Phosphorus was measured colorimetrically using the yellow complex method at 430 nm spectrophotometer (Company: Systronics, model: 2206TS) and K quantified by flame photometry (Company: ELICO, model: CL378). Nutrient uptake was obtained by multiplying nutrient concentrations with dry matter yield (ha^{-1}) (17). Plant and soil

Table 1. Initial soil properties (0–15 cm depth) of the experimental site

Soil parameters	**Initial properties**	**Adopted method**
Soil pH	7.45	(18)
EC (dS m^{-1})	0.25	
Organic carbon (%)	0.41	(19)
Available N (kg ha^{-1})	177.2	(20)
Available P (kg ha^{-1})	26.2	(21)
AvK (mg kg^{-1})	188.3	(22)
WsK (mg kg^{-1})	25.5	(23)
ExK (mg kg^{-1}) = (AvK–WsK)	162.8	
Non-ExK (mg kg^{-1}) = (K extracted with hot 1N HNO_3 – AvK)	524.4	(24)

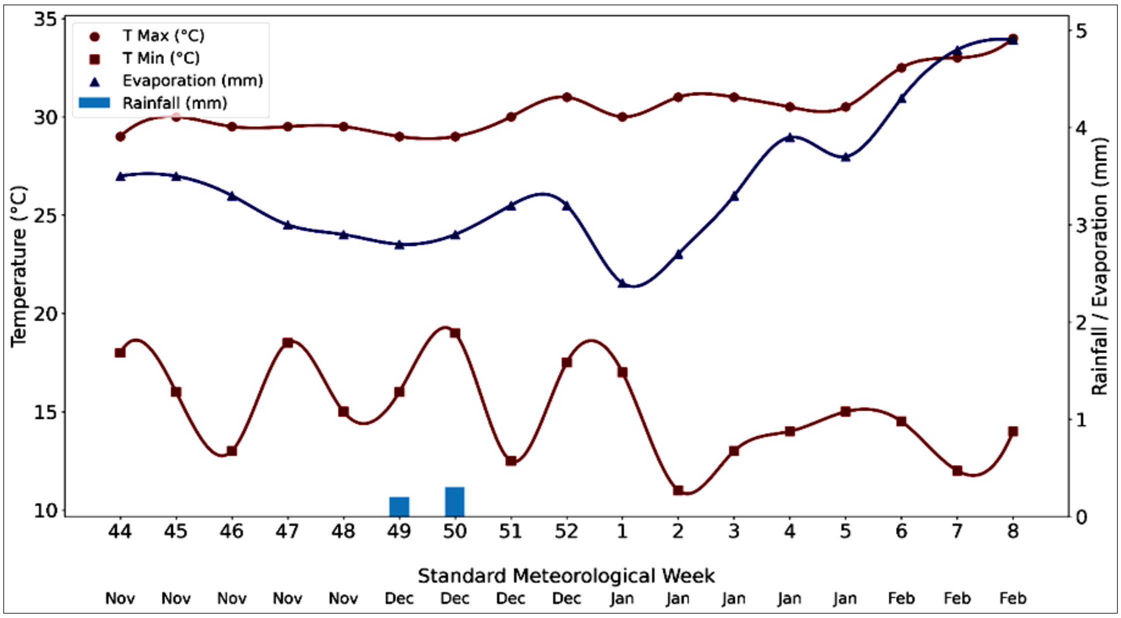

Fig. 1. Weekly maximum and minimum atmospheric temperatures, rainfall and evaporation during the crop growth period (19 November 2022 –23 February 2023).

samples were collected at 30 DAS (knee-height stage, KH), 60 DAS (tasseling) and at harvest. For plant sample analysis, destructive sampling was done from the penultimate two rows of the plots.

Yield, harvest index (HI) and benefit–cost ratio (B–C)

Green cobs were harvested from three random places (1 m^2 each) within the net plot area. The leftover plants from same area were cut at the base and the weight of green stover was recorded in kg m^{-2}. As destructive sampling for plant sample analysis was carried out from the penultimate two rows of the plots, plant competition within the net plot area was not compromised.

Harvest index represents the percentage of total biological yield obtained as economic yield. It was calculated using the formula given below (Eqn. 1). The benefit–cost ratio (B–C) was computed using Eqn. 2.

$$\text{Harvest Index (\%)} = \frac{\text{Economic yield (kg m}^{-2}\text{) x 100}}{\text{Biological yield (kg m}^{-2}\text{)}} \qquad \text{(Eqn. 1)}$$

$$\text{B:C ratio} = \frac{\text{Gross returns (Rs ha}^{-1}\text{)}}{\text{Cost of cultivation (Rs ha}^{-1}\text{)}} \qquad \text{(Eqn. 2)}$$

Statistical analysis

Analysis of variance (ANOVA) of the experimental data was carried out using the standard method (25). Treatment effects were evaluated statistically and treatment means were compared using the least significant difference (LSD) test. Differences were considered statistically significant at $p \leq 0.05$. This approach facilitated precise identification of treatment impacts and reliable interpretation of experimental outcomes. Moreover, the Pearson correlation coefficient and its significance level were analysed to determine the strength of the relationship between two parameters.

Results and Discussions

Soil K fractions and dynamics

Water-soluble potassium (WsK) is the smallest fraction of soil K and forms a part of available-K (AvK). When plant absorb WsK, it is replenished by exchangeable-K (ExK) and non-exchangeable-K (Non-ExK) pools (Non-ExK is unavailable for plant) (8). In the present experiment, with an increase in K application, WsK, ExK and AvK contents increased significantly irrespective of KSB treatments (Table 2). From the KH stage onward, a decreasing trend of AvK fractions (WsK + ExK) was observed irrespective of treatments. This decreasing trend resulted from crop uptake and leaching losses from the top soil (5). Some studies have reported that, irrespective of different levels of K fertilisation (without KSB), available soil K fractions decreased gradually with time (26, 27).

At the KH stage (30 DAS), highest WsK, ExK and AvK were recorded in T_7: 100 % RDK + KSB (ST + SD), which was statistically equivalent with 100 % RDK and 75 % RDK irrespective of KSB treatment. However, from the tasseling stage onward, significantly higher WsK, ExK and AvK were recorded in T_{10}: split application of 100 % RDK + KSB(ST+SD), which was statistically equivalent with T_2, T_5, T_7 and T_9. The same trend was observed until harvest. This indicated that the split application of RDK and higher doses of chemical K fertilisers, irrespective of KSB treatments, had a greater impact on WsK, ExK and AvK. However, all treatments receiving 100 % RDK with or without KSB and 75% RDK + KSB (ST + SD) showed statistically similar results. This may be attributed to the to the solubilisation process of KSB (9).

The Non-ExK fraction in soil did not vary significantly across treatments. However, numerically, a declining trend was observed from the KH stage to harvest. Non-ExK content was numerically higher in the sole application of different doses of chemical K fertilizer compared to the corresponding treatments combined with KSB (ST + SD). This may be due to the release of organic acids by the KSB strain (28). However, the solubilisation of the unavailable soil K pool was not sufficient to replenish the AvK lost due to crop uptake and leaching. This might be due to limited compatibility between the soil type and the KSB strain and short duration of experiment

Table 2. Soil K fractions at different crop growth stages as influenced by dual-mode application of KSB in conjunction with chemical fertilisers in Alfisols

Treatments	Water soluble K (mg kg^{-1})			Exchangeable K (mg kg^{-1})			Available K (mg kg^{-1})			Non-exchangeable K (mg kg^{-1})		
	30 DAS	60 DAS tasseling	At harvest	30 DAS	60 DAS tasseling	At harvest	30 DAS	60 DAS tasseling	At harvest	30 DAS	60 DAS tasseling	At harvest
T_1	20.1^{c}	16.5^{e}	13.7^{c}	152.5^{bc}	126.1^{c}	108.4^{c}	172.6^{c}	142.6^{b}	122.1^{c}	522.8^{a}	515.4^{a}	498.6^{a}
T_2	29.2^{ab}	23.8^{ab}	19.2^{a}	172.0^{ab}	145.7^{ab}	132.0^{a}	201.2^{a}	169.5^{a}	151.2^{a}	526.5^{a}	522.4^{a}	520.3^{a}
T_3	25.1^{b}	17.8^{de}	14.0^{c}	151.1^{c}	127.9^{c}	110.6^{bc}	176.2^{bc}	145.7^{b}	124.6^{c}	524.1^{a}	515.7^{a}	511.4^{a}
T_4	26.2^{a}	21.1^{bc}	16.6^{b}	163.4^{abc}	128.1^{bc}	114.6^{bc}	189.6^{abc}	149.2^{b}	131.2^{bc}	525.8^{a}	516.2^{a}	513.8^{a}
T_5	25.2^{b}	24.2^{a}	20.1^{a}	151.2^{c}	147.6^{a}	134.5^{a}	176.4^{bc}	171.8^{a}	154.6^{a}	524.2^{a}	523.8^{a}	521.6^{a}
T_6	20.5^{c}	17.4^{e}	13.8^{c}	153.3^{abc}	127.8^{c}	110.1^{bc}	173.8^{c}	145.2^{b}	123.9^{c}	522.1^{a}	504.6^{a}	494.6^{a}
T_7	29.6^{a}	24.0^{ab}	19.6^{a}	172.8^{a}	146.4^{a}	134.1^{a}	202.4^{a}	170.4^{a}	153.7^{a}	526.2^{a}	518.6^{a}	514.5^{a}
T_8	25.6^{b}	20.7^{cd}	16.5^{b}	156.8^{abc}	127.6^{c}	113.9^{bc}	182.4^{abc}	148.3^{b}	130.4^{bc}	523.2^{a}	506.2^{a}	499.6^{a}
T_9	28.5^{ab}	23.4^{abc}	18.7^{ab}	167.9^{abc}	137.8^{abc}	125.7^{ab}	196.4^{ab}	161.2^{ab}	144.4^{ab}	525.5^{a}	507.5^{a}	501.6^{a}
T_{10}	25.7^{b}	24.5^{a}	20.5^{a}	157.4^{abc}	151.0^{a}	138.0^{a}	183.1^{abc}	175.5^{a}	158.5^{a}	523.4^{a}	522.6^{a}	519.7^{a}
SEm ±	1.2	1.0	0.8	6.7	5.9	5.3	7.5	6.7	5.8	24.6	24.9	23.0

Values followed by the same lowercase letter are not significantly different.

might also be a constrain for K solubilization process. Therefore, the results suggest that, in short-term, the KSB strain (*B. amyloliquefaciens*) was partially capable in sandy loam soil to solubilise the stable soil K pool (i.e., Non-ExK) for replenishing the dearth of AvK pool.

Nutrient uptake

Among the treatments, the highest K uptake by sweet corn was recorded with T_{10}, which was comparable to T_2, T_5, T_7 and T_9 (Table 3). Application of KSB compensated for the 25 % reduction in RDK; as a result, the effect of T_9 was equivalent to 100 % RDK. However, some studies reported that 50 % RDK could be substituted by KSB as far as maize K uptake was concerned (29). In the present experiment, only 25 % substitution of K through KSB was observed, which may be attributed to the short-term exposure of sandy loam soil to KSB and the higher K requirement of sweet corn for its growth and development. Application of 100 % RDK (in split) + KSB (ST + SD) resulted in 34.6 % higher N uptake compared to the 0 % RDK treatment. However, all treatments with 100 % RDK, irrespective of KSB application, recorded statistically similar values along with 75 % RDK + KSB. In contrast, total P uptake by sweet corn was not significantly influenced by K management practices. The release of growth-promoting substances by KSB and their uptake by plants under recommended K supply contributed to higher biomass production and N assimilation in sweet corn (9). Similarly, in oil seeds, a synergistic interaction between K and N has been reported possibly due to the role of K in the nitrate reductase activity in plant leaves (30, 31).

Yield and economics

Higher green cob yield with 100 % RDK (irrespective of KSB treatment) resulted from the synergistic interaction between K and N (Table 3), proper partitioning of photosynthates from source to sink and efficient grain filling (32). Moreover, two equal split application of 100 % RDK resulted in numerically higher yield compared to basal application of 100 % RDK (Fig. 2). Minimal leaching loss in sandy loam soil and the constant availability of K may have resulted in better green cob yield with split application of K. Application of KSB as a seed treatment and soil drenching may have solubilised inherent unavailable soil K and stimulated the release of plant growth-promoting hormones (9), making 75 % RDK statistically equivalent to 100 % RDK in terms of yield.

It is noteworthy that, to achieve higher yield from a heavy feeder crop like sweet corn, the recommended dose of K (50 kg ha^{-1}) was imperative in K-rich light-textured soil due to its high demand and physiological benefits. Substitution of 25 % RDK without KSB or further reduction of RDK to 50 %, irrespective of KSB treatment, did not significantly impact green cob yield compared to 100 % RDK. This suggests that 25 % RDK could be substituted by KSB (ST + SD) treatment in K-rich Alfisols. However, HI was insignificantly varied across treatments. Response of maize to K supplementation in K-rich soil was also found due to its higher requirement for proper

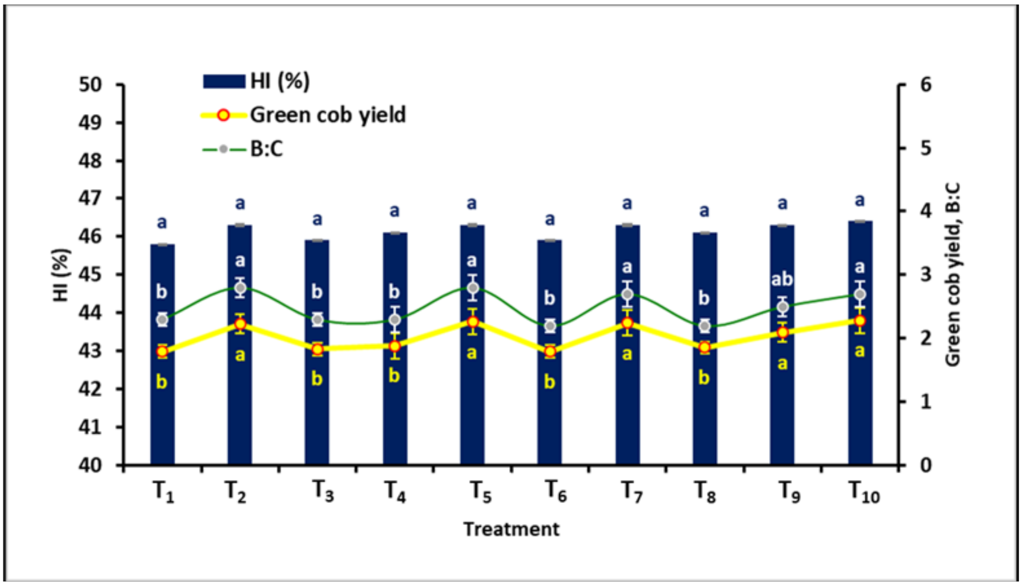

Fig. 2. Sweet corn green cob yield (kg m^{-2}), harvest index (HI) and benefit-cost (B-C)ratio as influenced by dual-mode application of KSB in conjunction with chemical fertilisers. Similar lowercase letters atop the bars are not significantly different.

Table 3. Primary macronutrient uptake by sweet corn as influenced by dual-mode application of KSB in conjunction with chemical fertilisers

Treatments	Nutrient uptake (kg ha^{-1}) by crop				
	Total K uptake			Total N uptake	Total P uptake
	30 DAS	Tasseling	At harvest	At harvest	At harvest
T_1	3.9^{b}	82.1^{b}	199.6^{b}	193.2^{e}	33.1^{a}
T_2	5.6^{a}	108.2^{a}	232.5^{a}	257.8^{a}	33.7^{a}
T_3	5.2^{a}	83.6^{b}	202.6^{b}	194.5^{de}	33.2^{a}
T_4	5.5^{a}	95.6^{c}	204.5^{b}	225.5^{bc}	33.5^{a}
T_5	5.3^{a}	109.7^{a}	238.2^{a}	258.6^{a}	33.8^{a}
T_6	4.1^{b}	82.7^{b}	201.8^{b}	193.8^{e}	35.2^{a}
T_7	5.8^{a}	109.4^{a}	235.6^{a}	258.1^{a}	36.2^{a}
T_8	5.4^{a}	93.8^{bc}	203.8^{b}	221.5^{cd}	35.7^{a}
T_9	5.6^{a}	104.6^{ac}	224.6^{ab}	252.2^{ab}	35.9^{a}
T_{10}	5.4^{a}	110.4^{a}	241.4^{a}	260.1^{a}	36.4^{a}
SEm ±	0.3	4.0	8.6	9.6	1.5

Values followed by the same lowercase letter are not significantly different.

growth and development (33, 34). Moreover, the use of KSB rendered additional benefit through the release of plant growth-promoting hormones in the rhizosphere (9).

In the present study, treatment involving two equal split applications of RDK resulted in highest B–C ratio, followed closely by the application of 100 % RDK as basal. However, these treatments were statistically equivalent to the split application of 100 % RDK in combination with KSB applied through seed treatment and soil drenching (T_{10}) and 75 % RDK with KSB (ST + SD) (T_9). A further reduction in RDK, irrespective of KSB inoculation, resulted in a significantly lower B–C ratio. The lowest B–C ratios were recorded with 0 % RDK and 50 % RDK coupled with KSB (ST + SD) treatments. These results indicate that the numerically higher B–C ratio in T_5 compared to T_{10}, was due to the additional cost associated with KSB application (through seed treatment and soil drenching) outweighing the corresponding increase in gross returns (Fig. 2).

Similarly, other studies have substantiated that, in order to maximise the productivity and profitability of maize varieties, application of K is imperative (15), as K plays an important role in photosynthesis, nitrate reductase activity, stomatal regulation and grain-filling process at the dough stage (31, 35). Additionally, recommended K can also be applied in two equal splits in sandy loam soil for more benefits, which is consistent with experiments conducted on wheat (14).

Correlation analysis

The correlation analysis indicated that green cob yield was strongly and positively influenced by plant N and K uptake ($p<0.01$), whereas P uptake did not show a significant association. This suggested that crop productivity under varying K doses was more dependent on N and K nutrition than on P. The positive relationship between N and K uptake further highlighted their synergistic role in supporting plant growth, as N is a key component of proteins and chlorophyll, while K regulates enzymatic activities (e.g., nitrate reductase), photosynthesis and assimilate translocation (1). Examination of soil K fractions revealed that WsK, ExK and AvK were not only highly intercorrelated but also strongly associated with both N and K uptake by the crop. This indicates that these readily available K pools directly contribute to nutrient acquisition and thereby enhance yield. In contrast, Non-ExK exhibited weak or negative correlations with nutrient uptake and yield, implying that this fraction remaines largely inaccessible to plants within the crop growth period and contributes little to immediate nutrient supply (Fig. 3).

Thus, KSB application positively influenced available K pools, which led to increased K and N uptake; as a result, optimum yield and economic returns were achieved with a 25 % reduction in K fertiliser when KSB was used as seed treatment and soil drenching.

Conclusion

Overall, in all fractions of soil K, a decreasing trend was observed from knee height stage (30 DAS) to harvest irrespective of treatments. At 30 DAS, the highest available soil K fractions were found with 100 % RDK (basal) + KSB (ST + SD); however, from the tasseling stage (60 DAS) onward, split application of 100 % RDK + KSB (ST + SD) was the best treatment with respect to soil K availability and it increased the K uptake by 20.9 % over control. A synergistic effect between K and N uptake was observed. However, P uptake did not vary significantly owing to K management practices. Hence, application of chemical K fertilisers is required to balance soil K levels and to maintain the higher productivity and profitability of sweet corn grown in sandy loam soils.

The present findings suggest that KSB alone was not sufficient to fulfil the K requirement of sweet corn in the short-term, but it could reduce chemical K fertilisers use by up to 25 % in K-rich Alfisols. Even after application of the recommended dose of K, a declining trend of soil K fractions across crop growth stages was noticed owing to higher uptake and other possible losses of K, such as leaching from topsoil layers. For sustaining soil K status, nutrient acquisition and sweet corn productivity, future long-term, soil-specific research should focus on optimising fertiliser K reduction by

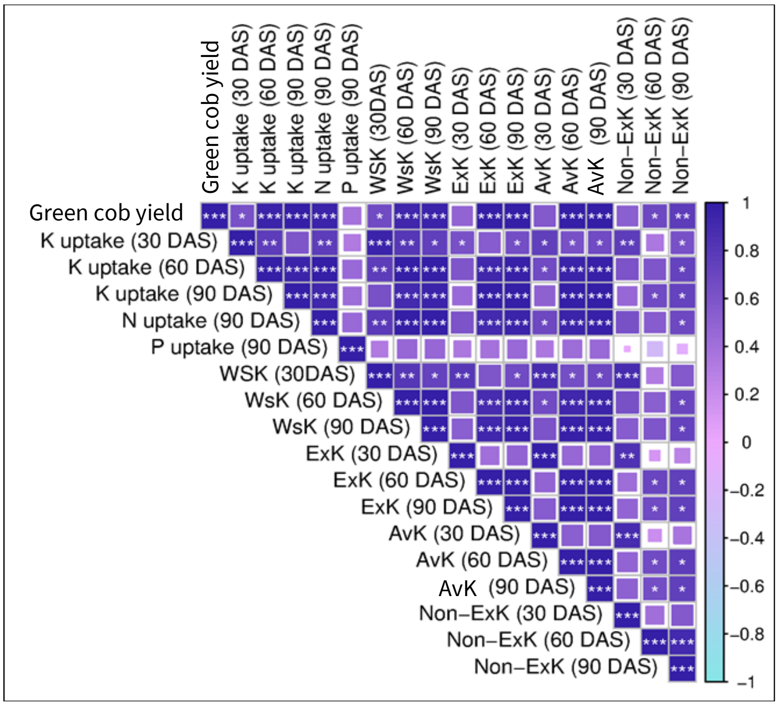

Fig. 3. Correlation matrix between soil K fractions, primary macronutrient uptake and green cob yield. *Significant at $p \leq 0.05$; ** Significant at $p \leq 0.01$; ***Significant at $p \leq 0.001$.

utilising KSB, while understanding soil K dynamics and minimising K losses under different cropping systems.

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Authors' contributions

SK conducted the original research, performed data analysis and wrote the manuscript. SKS, KRG and PL conceptualised the study, supervised the research and reviewed the work. SVK participated in the original research work. SKB, GMKG and PE contributed to laboratory work and assisted in writing and editing the draft. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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