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Optimizing potassium fertilization rates for enhancing salt tolerance in maize and gram crops in rainfed, semi-arid region of India

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Abstract

Salt accumulation in the rhizosphere from ions like sulfate, chloride, and sodium hampers nutrient uptake, particularly in saline-alkali soils, limiting crop growth. Potassium (K) acts as an osmoprotectant, enhancing plant tolerance to these stresses. This study evaluated the effect of soil test-based potassium (ST-K) fertilization at varying rates (0%, 75%, 100%, 125%, and 150% ST-K) on the K/Na ratio in saline and alkali soils. Lab results showed that saline soils responded quickly to K fertilization, displacing Na, while alkali soils needed more time due to Na retention. Incubation study reveals that saline soils exhibited swift reaction to K fertilization, with K availability increasing immediately and Na being displaced. In contrast, alkali soils required longer periods to attain optimal potassium levels due to their higher tendency to retain sodium. Based on these findings, pot experiments were conducted with maize and green gram and results confirmed that 150% ST-K improved maize growth, including germination, height, yield, and nutrient uptake (N, P, Ca, Mg), while reducing Na and enhancing the K/Na ratio. Green gram showed a moderate response but still benefited from higher K levels. Field validation study highlights the importance of K fertilization in improving crop resilience and productivity in saline-alkali soils of arid region.

Keywords: Na/K ratio, Maize, Green gram, Potassium nutrition, abiotic stress

Introduction

Salinity and alkalinity in soils pose significant challenges to agricultural productivity, particularly in semi-arid regions where limited rainfall exacerbates soil degradation and nutrient imbalances. In India, approximately 6.73 million hectares of land are affected by saline and alkali soils, with many farmers relying on rainfed systems for crop production (Shrivastava and Kumar, 2015). Alkalinity stress, marked by high pH and carbonate and or bicarbonate levels, reduces crop quality by inducing osmotic imbalance and reactive oxygen species (ROS) accumulation. Plants counter this through osmotic regulation, ionic homeostasis, antioxidant gene expression, and secondary metabolite production, supporting photosynthesis and stress tolerance. Responses depend on plant type, growth stage, and stress duration. The accumulation of salt in these soils disrupts plant water uptake, nutrient availability, and cellular metabolism, resulting in reduced growth and yield (Munns and Tester, 2008). The cultivation of salt-sensitive crops like maize *(Zea mays* L.) and green gram (*Vigna radiata* L.) is especially vulnerable under these conditions, and strategies to mitigate saline-alkali stress are urgently needed for sustaining agricultural productivity.

One promising solution for managing saline-alkali stress is potassium (K) fertilization. Potassium is a critical macronutrient that regulates several physiological and biochemical processes in plants, including water uptake, enzyme activation, and nutrient translocation. More importantly, K plays a pivotal role in mitigating the toxic effects of sodium (Na) in saline-alkali soils by enhancing the K:Na ratio within plant tissues, thus reducing sodium-induced ion imbalances (Wang *et al.*, 2013). Several studies have demonstrated that higher K availability improves plant tolerance to salinity, leading to better growth, nutrient uptake, and yield in crops like maize and green gram (Hussain *et al.*, 2013; Iqbal *et al.*, 2021; Islam *et al.*, 2024). The ability of potassium to enhance osmotic regulation and stomatal conductance also contributes to its effectiveness in semi-arid environments where water stress and soil salinity often coincide (Pettigrew, 2008; Johnson *et al.*, 2022).

The effectiveness of potassium fertilization can vary based on soil salinity, crop type, and environmental

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conditions. Under saline conditions, elevated sodium disrupts the sodium-to-potassium ratio. Potassium application restores this balance, mitigating sodium's harmful effects. The enhancement of tolerance to Na+ ions through potassium application, achieved by increasing the K+/Na+ ratio and enabling selective Na+ transport via K+ transporters, was reported by Su *et al.* (2015). Additionally, potassium fertilization has been linked to increased drought tolerance, which is beneficial for crops in saline-alkali soils under rainfed conditions. Recent studies highlight the importance of adequate potassium levels in mitigating salt-induced oxidative stress and improving water-use efficiency, ultimately sustaining higher yields (Patwa *et al.*, 2024).

Optimum soil potassium level limits Na uptake and promotes a higher K/Na ratio in maize plant tissues, which is crucial for maintaining normal physiological processes like photosynthesis and nutrient transport (Iqbal *et al.*, 2020; Kumari *et al.*, 2021). Significant enhancement of salt tolerance of maize in saline soils due to the higher rates of potassium fertilization and increased potassium content in maize grains and stalks was reported by El-Dissoky *et al.* (2013).

However, the effectiveness of K fertilization in alleviating saline-alkali stress under rainfed conditions, particularly in semi-arid regions of India, has not been extensively studied. Rainfed agriculture, which accounts for nearly 60% of India's cropped area, is characterized by erratic rainfall and minimal irrigation infrastructure, making crops even more susceptible to stress (Manikandan *et al.*, 2025). Given the importance of potassium in stress mitigation, optimizing K fertilization could prove vital for improving crop resilience and yield under these challenging conditions. This study aims to evaluate the impact of different levels of potassium fertilization on K and Na dynamics in soil over time and on maize and green gram growth and yield under saline-alkali soils in semi-arid, rainfed environments.

Materials and Methods

Soil type

A laboratory incubation and pot experiments were organized using processed, 2 mm sieved saline and alkali soils collected from the semi-arid region of India. A sub-sample of the processed soil was analyzed for physico-chemical characteristics. The properties of the soils are shown in Table 1. The soils were classified as loamy sand (saline soil from Ramnad district, coastal Tamil Nadu) and sandy clay loam (alkali soil from Salem dt, Tamil Nadu). The saline soil had a very high EC (9.96 dS m^{-1}) and ESP (27.10%), while the alkali soil had a pH of 9.06 and a medium ESP (14.00%). Both soils were low in available N, medium in available P, and high in available K. The saline soil was classified as coarse loamy, *Fluventic Hapulstalf,* and the alkali soil as fine loamy, mixed, calcareous, *Typic Haplustalfs*.

Treatment detail

The experiment was set up in a Factorial Randomized Block Design (FCRD) with two soils (saline and alkali) as factor 1, and four potassium (K) fertilizer levels (0, 75, 100, 125, and 150% of the recommended K dose) as factor 2. Based on the incubation study results, except 75%K level, all other levels were adopted as treatments in pot and field experiments. Treatments were replicated four times. A fertilizer dose of 313, 75, and 56 kg NPK ha^{-1} (100% ST dose) was applied based on soil test (ST) nutrient levels. While N and P doses were constant, 56 kg K was used as the 100% soil test K. Fertilizers applied were urea, superphosphate, and potassium chloride, and 5 t ha^{-1} of farmyard manure (FYM) was common to all pots.

Laboratory incubation experiment

The incubation experiment was conducted using the saline and alkali soils filled in 500 g containers. The processed soils were filled in the container with the average bulk density of 1.35 Mg m^{-3} by manual compaction and then irrigated to field capacity moisture. Then the treatments were imposed to investigate the changes in the status of exchangeable K dynamics for three months. Soils of all treatment were subjected to alternate wetting and drying cycles (water added whenever the soil moisture reaches 10% which was 13 and 21 days, respectively for saline and alkali soils). Soil samples were collected from each container after thorough mixing at weekly interval, air dried and then subjected to exchangeable K and Na analysis.

Pot experiment

Maize hybrid CO-8 was used for both pot and field trials. The pot experiment was conducted during the Kharif season (July-August, 2022) in a controlled glasshouse at the Radio Isotope Lab, Department of Soil Science and Agricultural Chemistry, TNAU, Coimbatore. Pots (7 kg) were filled with homogenized soil at an optimum bulk density (1.33 to 1.37 Mg m^{-3}) and moistened to field capacity. Three maize seeds were sown per pot, and life irrigation was given 5 days after sowing, followed by irrigation at critical growth stages (30, 55, 75, and 90 Days After Sowing, DAS). After the maize harvest, green gram (VBN 5) was sown with a fertilizer dose of 31, 25, and 18 kg NPK/ha (100% ST dose), and K fertilizer was varied as per the treatments.

Table 1: Physico-chemical properties of the soils employed for conducting pot and field experiments

S. No	Soil characteristic	Saline Soil	Alkali soil
1.	Texture	Loamy sand	Sandy Clay
2.	pH (1:2.5)	7.98	9.06
3.	EC (dS m^{-1}) (1:2.5)	9.96	0.51
4.	Organic carbon (%)	0.12	0.49
5.	Alkaline $KMnO_4$ - N (kg ha^{-1})	55.0	196
6.	Olsen – P (kg ha^{-1})	17.0	25.0
7.	Neutral N NH_4OAc – K (kg ha^{-1})	305	383
8.	Exchangeable Na^+ (meq 100 g^{-1})	5.39	4.19
9.	Cation Exchange Capacity (cmol (p^+)kg^{-1})	14.5	29.40
10.	Exchangeable Sodium Percentage (ESP)	27.1	14.00

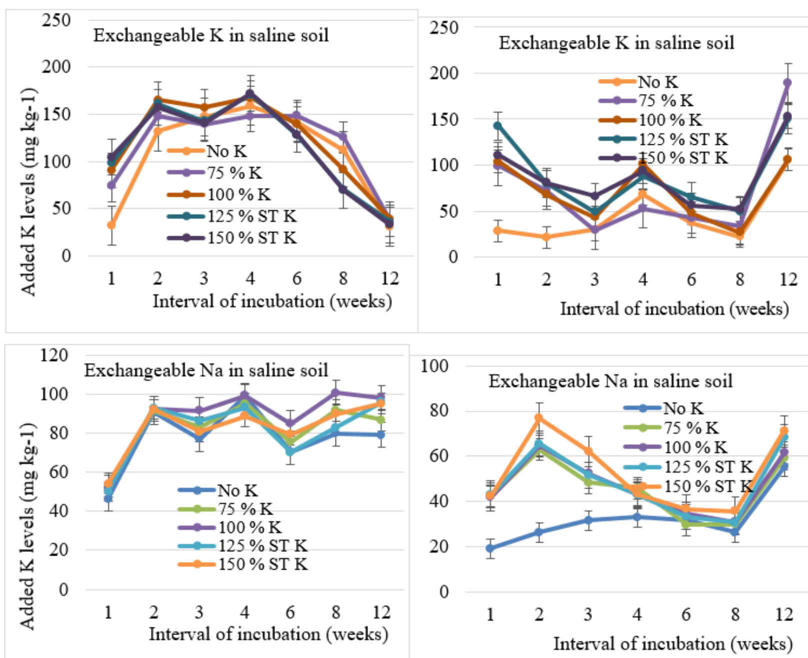

Figure 1: Influence of K fertilization levels on exchangeable K and Na (mg kg^{-1}) in different soils during various time intervals of incubation

Field experiment

The field experiment was conducted during Kharif 2023 on the same farm where soils were collected for the pot experiment. Maize was sown at a spacing of 60 x 25 cm with a population of 66,666 plants ha^{-1}. Life irrigation was provided 5 days after sowing and again during the tasseling stage (60 DAS). Pest and disease management followed the recommendations from the Crop Production Guide (CPG, 2020) for maize cultivation in Tamil Nadu, India.

Sampling, observations and analysis

Soil samples were collected at harvest (120 days) from five random points in each replicated plot for the field experiment, and from the entire soil of the pots. Approximately 500 g of soil was collected from each treatment at a depth of 0-15 cm using a spade, after giving a 'V' shaped cut. Pebbles and plant debris were removed manually. Samples from each pot $plot^{-1}$ were pooled, mixed, air-dried, powdered with a wooden mallet, and passed through a 2 mm sieve and stored at room temperature until analysis.

On the 5th day after sowing, germination percentage was recorded by counting the germinated seeds in each pot. Growth parameters such as plant height and number of leaves were recorded at the tasseling stage, while yield parameters were measured at physiological maturity (110 and 75 DAS for maize and green gram, respectively). At harvest, maize cobs and green gram pods were collected randomly, sun-dried for 3 days to reach less than 12% moisture and weighed. Grains were threshed to measure 100-grain weight and processed for nutrient analysis. Dried grains from each treatment were mixed, sub-sampled to 100 g, and powdered using a Willey mill after oven drying at 108°C for 10 hours. Powdered samples were stored at 25^{0}C until analysis.

Soil mineral nutrients were estimated following Jackson (1973) methods, while plant nutrient elements were analyzed using protocols outlined by the Association of Official Analytical Chemists (AOAC, 1990). Nitrogen concentration was determined via the micro-Kjeldahl method using a Kelplus Classic-DX VA instrument. Total phosphorus concentration was measured with a Shimadzu UV-VIS Double Beam Spectrophotometer (Model 1800). Potassium and sodium concentrations were analyzed using an Elico flame photometer. Calcium and magnesium content was analysed adopting versenate titration method.

Statistical analysis

Data were statistically analyzed using Microsoft Excel (Windows 2007) with the XLSTAT. Significant differences between treatments were determined using one-way ANOVA at a 5% significance level. Correlations between variables were assessed using Pearson correlation coefficients, with significance accepted at 5% level (p= 0.05).

Results

Effect of K level on exchangeable K and Na in different soils

The influence of potassium (K) fertilization on exchangeable potassium (K) and sodium (Na) showed distinct patterns between saline and alkali soils across various incubation periods (Figure 1). The interaction between soil type and K fertilization levels (S × K) was significant (p = 0.05), indicating differential responses based on soil conditions.

In saline soil, K fertilization led to an immediate rise in exchangeable K levels across all treatments, with peak levels typically observed by week 4. The control (0 mg kg^{-1} K) started at 46.53 mg kg^{-1} and peaked at 98.80 mg kg^{-1} in week 4, stabilizing around 79.00 mg kg^{-1} by week 12. For treatments with added K, the 100% K level achieved the highest exchangeable K at 99.23 mg kg^{-1} in week 4 and maintained a high level (98.00 mg kg^{-1}) by week 12. Higher K rates (125% and 150%) exhibited a similar pattern, with early peaks (93.11 and 88.57 mg kg^{-1} in week 4, respectively) and slight declines, thereafter. In alkali soil, exchangeable K levels rose more gradually across all treatments, with lower peaks compared to saline soil. The control started at 19.20 mg kg^{-1}, reaching 55.40 mg/kg by week 12. The 75% and 100% K treatments showed a slow increase in K availability, peaking around 46.00–52.50 mg/kg in the initial weeks and ending at 59.00–61.60 mg kg^{-1} by week 12. The 150% K level achieved the highest exchangeable K at 71.20 mg kg^{-1} by week 12, indicating a slower but more sustained release pattern of K in alkali soil. Exchangeable Na levels in alkali soil followed a different trend

Exchangeable Na showed contrasting patterns between saline and alkali soils in response to K fertilization. In saline soil, Na concentrations increased rapidly and peaked around the 3rd–4th week across all treatments (ranging 140.56–172.02 mg kg^{-1}), followed by a steady decline toward week 12. By the end of incubation, Na levels dropped sharply in all treatments, with values ranging from 30.69 to 39.00 mg kg^{-1}, indicating effective Na displacement with time. Mean Na levels were similar across K treatments, with slightly higher values under 100% ST-K. In alkali soil, Na levels fluctuated during the early weeks but increased sharply by week 12, especially under 75% and 150% K (reaching 188.62 and 153.35 mg kg^{-1}, respectively). Mean Na values gradually increased with higher K application but remained lower than the peak values observed at week 12, reflecting the stronger Na retention capacity of alkali soils.

Effect of K level on Na/K balance in different soils

Potassium (K) fertilization affected the Na/K ratio differently in saline and alkali soils throughout the incubation period (Figure 2). In saline soil, the Na/K ratio generally increased from week 1, peaking between weeks 4 and 6 before declining by week 12. The control (0 mg kg^{-1} K) began at 0.69, reached a peak of 2.22 in week 6, and then fell to 0.39 by week 12, with an overall mean of 1.46. All the K rates of 75%, 100%, 125%, and 150% showed similar trends, with peak Na/K ratios occurring around weeks 4 to 6, followed by decreases toward the end of the period. The mean Na/K ratios across treatments in saline soil remained relatively stable, ranging from 1.44 to 1.48. In alkali soil, Na/K ratios were more variable, especially at higher K application rates. The control (0 mg kg^{-1} K) exhibited a peak Na/K ratio of 2.06 in week 4, which then decreased slightly, ending at 1.90 by week 12 with an average of 1.32. Higher K levels had peaks between weeks 1 and 4, followed by declines, but retained higher values by week 12. Mean Na/K ratios across K treatments in alkali soil ranged from 1.52 to 1.90. Overall, the K fertilization consistently lowered Na/K ratios in saline soil, while in alkali soil, ratios remained comparatively higher over time, particularly under increased K levels.

Effect of potassium levels on growth, nutrient uptake, and yield of maize

Various maize growth parameters, including germination percentage, plant height, number of leaves, and yield components such as cob weight, 100-grain weight, and grain and straw yields, were recorded at harvest (Figure 3). Germination percentage and plant height were significantly influenced by potassium levels and varied depending on soil type. However, the number of leaves per plant showed no significant variation. In the control treatment on saline soil, germination was notably low but increased with higher potassium levels in both saline and alkali soils. Similarly, plant height followed the same trend. Among the yield parameters, potassium levels significantly affected 100-grain weight, grain yield, and straw yield, but cob weight remained unaffected regardless of soil type. The 150% ST-K treatment resulted in the highest grain and straw yields and the most substantial 100-grain weight, closely followed by the 125% ST-K treatment.

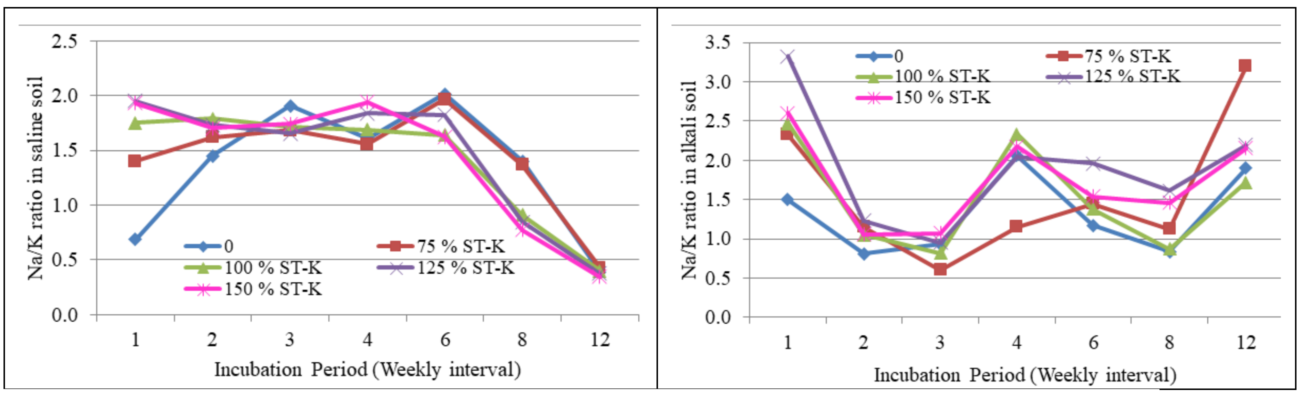

Figure 2: Influence of K levels on the ratio of Na/K in saline and alkali soils over period of incubation.

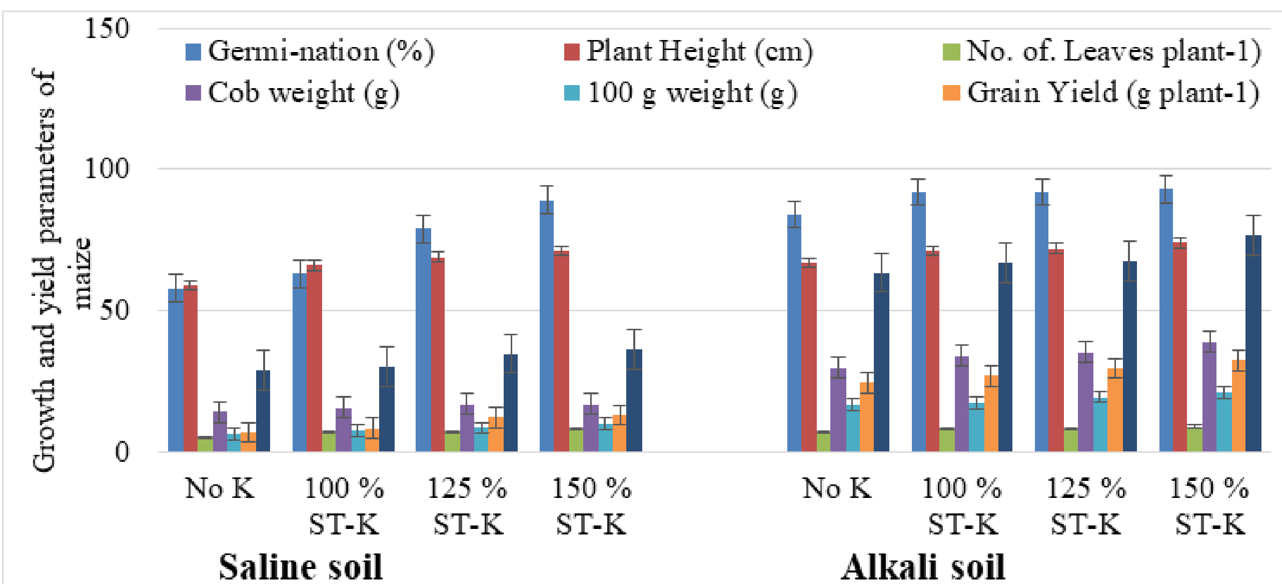

Figure 3: Growth and yield parameters of maize as influenced by the K levels in saline and alkali soil

The uptake of major and secondary nutrients (N, P, K, Ca, Mg, and Na) in maize grain and straw was analyzed to evaluate the effect of different potassium levels in saline and alkali soils (Table 2 and Figure 4). Maize nutrient uptake in both grain and straw was significantly influenced by potassium levels, with the 150% ST-K treatment showing the highest nutrient uptake, comparable to the 125% ST-K treatment for all nutrients except potassium uptake. This highlights maize's strong response to potassium under saline and alkali conditions.

Table 2: Nutrients uptake (mg plant-1) in maize grain as influenced by the K levels in saline and alkali soils

K level added	N	P	K	Na	Ca	Mg
Saline soil						
No K	80	13	38	6	14	20
100 % of ST-K	86	14	47	5	16	21
125 % of ST-K	107	19	70	5	21	30
150 % of ST-K	116	20	78	5	23	33
Alkali soil						
No K	314	42	138	21	57	71
100 % of ST-K	354	49	184	18	62	81
125 % of ST-K	390	53	221	18	71	95
150 % of ST-K	429	62	268	18	84	107
CD(P=0.05)						
S	2.7	2.1	2.3	NS	1.5	3.3
K	5.6	4.4	4.9	NS	3.1	6.9
S x K	7.9	6.1	6.9	NS	4.4	9.6

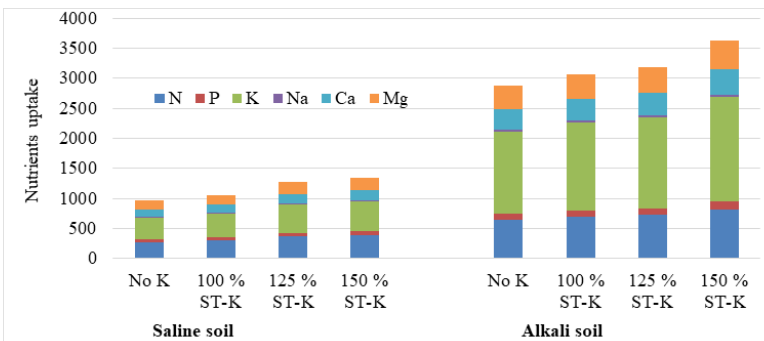

Figure 4: Nutrients uptake (mg plant^{-1}) in maize straw as influenced by the K levels in saline and alkali soils

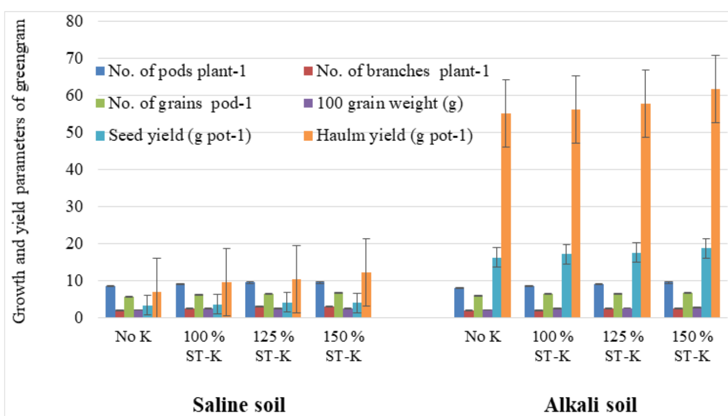

Figure 5: Influence of K levels on the yield parameters and yield of green gram

Effect of potassium levels on growth, nutrient uptake, and yield of green gram

Growth parameters of green gram, including germination percentage, plant height, and number of leaves, were recorded at 60 DAS and are presented in Figure 5. Germination rates for green gram were affected by both saline (22%) and alkali (52%) soils, with no significant influence from potassium levels. Plant height and the number of leaves at 60 DAS did not show significant differences across potassium treatments, although higher potassium levels numerically improved growth. Yield parameters, such as the number of pods per plant, number of branches per plant, number of seeds per pod, and 1000-grain weight, were recorded at harvest (Figure 5). All yield components were significantly higher in the 150% ST-K treatment. This treatment also produced the highest grain and haulm yield, with the 125% ST-K treatment closely following. The control plot (without K) recorded the lowest seed yield of 944 kg ha^{-1}.

Analysis of nutrient uptake in green gram grain revealed an increase in all major and secondary nutrients (N, P, K, Ca, Mg), except Na, with higher potassium addition. Among the soils, uptake of all nutrients was significantly higher in alkali soil than saline soil. However, these results were statistically non-significant (Figure 6 and Table 3) with potassium fertilization.

Effect of K levels and Na/K ratio on crop performance

To assess the effect of Na on crop growth and yield, the potassium-to-sodium (K/Na) ratio in grain of maize and green gram, straw of maize and haulm of green gram was

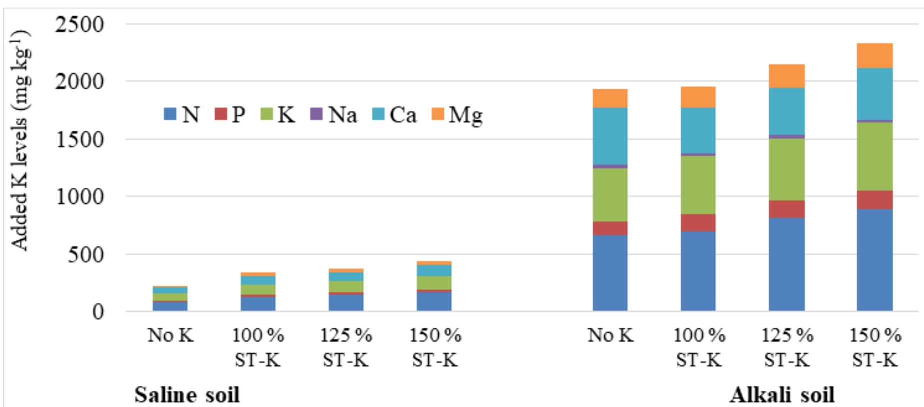

Figure 6: Nutrients uptake (mg $plant^{-1}$) in green gram haulm as influenced by the K levels in saline and alkali soils

Table 3: Nutrients uptake (mg $plant^{-1}$) in green gram grain as influenced by the K levels in saline and alkali soils

K levels added	N	P	K	Na	Ca	Mg
Saline soil						
No K	95.90	9.66	26.31	1.30	1.60	4.60
100 % of ST-K	104.24	10.71	29.99	1.25	1.86	5.03
125 % of ST-K	128.03	13.63	35.93	1.49	2.64	5.82
150 % of ST-K	126.40	14.00	36.00	1.36	2.64	5.68
Alkali soil						
No K	470.67	48.69	120.10	6.49	6.33	22.56
100 % of ST-K	504.45	53.01	131.67	6.67	7.01	24.11
125 % of ST-K	527.10	56.22	137.05	6.50	9.49	24.95
150 % of ST-K	584.38	63.68	147.97	6.56	10.49	26.97
CD(P=0.05)						
S	3.0	1.8	3.4	1.2	1.3	3.6
K	NS	NS	NS	NS	NS	NS
S x K	8.9	6.2	10.1	3.7	3.1	11.1

*S- soil type (Saline and alkali); K – Potassium applied level calculated. A higher K/Na ratio indicated reduced Na uptake from the soil and/or increased K uptake. The relationship between K/Na ratios and various crop parameters was evaluated using Pearson's correlation and regression analysis (Table 4; Figure 7). In maize, the K/Na ratio in grain and straw ranged from 5.7–18.0 and 18.0–34.4 in saline soil and from 5.8–16.6 and 30.4–57.5 in alkali soil, indicating higher Na uptake in alkali soils. For green gram, the K/Na ratio in grain and haulm ranged from 20.3–36.0 and 19.5–24.5 in saline soil and from 17.9–29.5 and 20.1–24.5 in alkali soil, demonstrating that salinity had a greater influence on K uptake than alkalinity. A significant positive correlation was observed between plant height, grain, and straw/haulm biomass with the corresponding K content and K/Na ratio, while a negative correlation was observed with Na content.

Effect of potassium levels on soil nutrient status at harvest

In maize, the availability of nitrogen (N) and phosphorus (P) was not significantly affected by the potassium treatments in both soil types, except for N availability at 70 DAS (Table 5). However, soil potassium availability was significantly influenced by the applied potassium levels. The 150% ST-K treatment recorded the highest available K, followed by the 125% ST-K treatment. Potassium availability in the soil decreased from 60 DAS to

Table 4: Correlation of plant height and plant biomass with K, Na and K/Na ratio in maize grain and straw

Parameters	Maize			Green gram		
	Plant height	Grain biomass	Straw biomass	Plant height	Grain biomass	Straw biomass
Saline soil						
Grain K	0.982**	0.983**	-	0.990**	0.939**	-
Grain Na	-0.970**	-0.877*	-	-0.837*	-0.980**	-
Grain K/Na ratio	0.948**	0.938**	-	0.891*	0.824*	-
Straw K	0.968**	-	0.879*	0.975**	-	0.873*
Straw Na	-0.900*	-	-0.882*	-0.985*	-	-0.985**
Straw K/Na ratio	0.873*	-	0.898*	0.977*	-	0.978**
Alkali soil						
Grain K	0.983**	0.983**	-	0.990**	0.830*	-
Grain Na	-0.998**	-0.915**	-	-0.995**	-0.755	-
Grain K/Na ratio	0.984**	0.982**	-	0.984**	0.809	-
Straw K	0.933**	-	0.916**	0.975**	-	0.857*
Straw Na	-0.997**	-	-0.946**	-0.985**	-	-0.789
Straw K/Na ratio	0.994**	-	0.962**	0.977**	-	0.838*

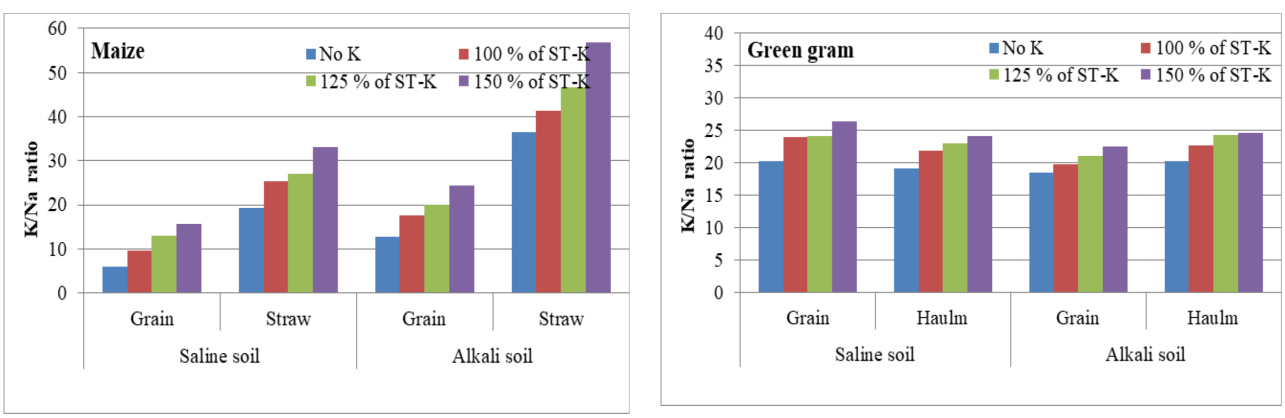

Figure 7: Effect of K levels on K/Na ratio of maize and green gram biomass yields under saline and alkali soils

95 DAS but remained higher than the control throughout. The percentage increase in available potassium over the control ranged from 5–35% in saline soils and 5–74% in alkali soils (Table 6). In green gram (VBN 5) soils, nitrogen and phosphorus availability was not significantly affected by potassium treatments, but soil potassium availability followed a similar trend as in maize.

Field validation

The results of the pot culture experiment were validated under rainfed field conditions using maize as the test crop, as green gram results were not promising. Potassium levels did not significantly influence 100-grain weight in maize. However, both 125% and 150% ST-K treatments resulted in

Table 5: Influence of K fertilization levels on available NPK (kg ha^{-1}) grown with maize at different interval in saline and alkali soils

K levels added (kg ha^{-1})	Available N			Available P			Available K		
	30 DAS	60 DAS	95 DAS	30 DAS	60 DAS	95 DAS	30 DAS	60 DAS	95 DAS
Saline soil									
No K	125	111	82	13.7	13.0	11.1	307	284	269
100 % ST-K	127	115	103	17.6	13.1	12.4	322	309	279
125 % ST-K	140	122	106	19.3	17.5	15.1	354	320	296
150 % ST-K	141	126	104	20.2	18.0	16.6	415	348	301
Alkali soil									
No K	196	202	181	19.2	16.1	12.9	432	454	405
100 % ST-K	206	206	192	20.6	17.7	14.1	456	509	425
125 % ST-K	215	218	201	22.2	18.9	17.1	595	663	608
150 % ST-K	219	222	202	24.4	20.5	18.6	631	770	704
CD(P=0.05)									
S	3.8	4.8	3.6	1.8	2.1	NS	6.3	5.3	6.5
K	NS	NS	NS	NS	NS	NS	13.0	11.1	13.4
S x K	13.1	14.1	11.7	NS	NS	NS	18.2	15.5	18.7

*S- soil type (Saline and alkali); K – Potassium applied level

Table 6: Influence of K fertilization levels on available NPK (kg ha-1) in saline and alkali soils grown with green gram

K levels added (kg ha^{-1})	Available N			Available P			Available K		
	Flowe-ring	Pod filling	Har-vest	Flowe-ring	Pod filling	Har-vest	Flowe-ring	Pod filling	Har-vest
Saline soil									
No K	161	145	139	10.7	9.7	8.0	390	348	310
100 % ST-K	163	148	139	11.9	11.0	8.3	404	428	365
125 % ST-K	166	149	138	14.6	11.0	8.1	429	447	352
150 % ST-K	165	150	141	15.6	11.4	8.1	437	454	358
Alkali soil									
No K	185	177	168	15.5	13.6	11.6	353	361	343
100 % ST-K	204	187	183	17.8	16.1	12.3	450	434	426
125 % ST-K	205	190	189	21.6	18.0	12.9	573	555	535
150 % ST-K	207	191	189	23.4	19.1	13.3	591	562	546
CD(P=0.05)									
S	3.1	3.6	4.1	1.9	1.6	1.3	6.3	4.9	7.8
K	NS	NS	NS	NS	NS	NS	13.1	10.2	16.1
S x K	9.3	11.1	12.6	6.7	5.6	4.1	18.3	14.3	22.6

*S- soil type (Saline and alkali); K – Potassium applied level significantly higher grain and straw yields (Figure 8). The increase in potassium levels improved maize grain yield by 13–37% and straw yield by 7–10%, with 125% and 150% ST-K treatments showing comparable results for both grain and straw yield (Figure 9).

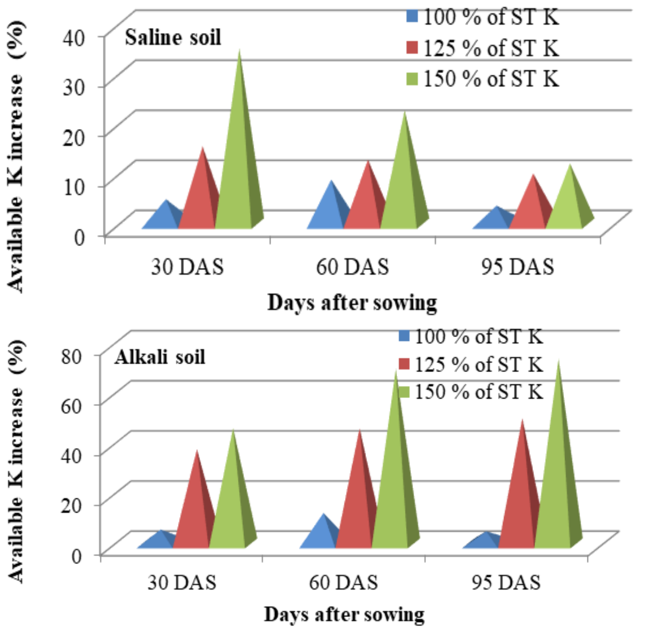

Figure 8: Influence of K levels on increase in K availability over control at different intervals of maize in saline and alkali soils

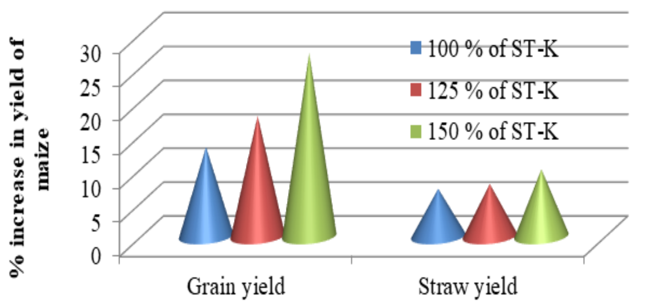

Figure 9: Effect of K levels on increase in grain and straw yield of maize over control under field validation

Discussion

This study examined how potassium (K) fertilization improves soil K availability and reduces saline–alkali stress in maize and green gram under rain-fed, semi-arid conditions. The findings confirm that K is crucial for crop growth and stress tolerance, especially in saline–alkali soils (Wang *et al.*, 2013).

K Fertilization and Exchangeable Na/K dynamics in saline and alkali soils

In saline soils, K fertilization rapidly increased exchangeable K levels, peaking around week 4 for all application rates. This quick response is due to the high ionic strength of saline soils, which enhances the solubility and availability of added K (Balasubramaniam *et al.*, 2023). Elevated Na in saline soils may also promote K desorption from exchange sites, increasing K availability during early incubation (El-Ramady *et al.*, 2024). However, after this initial increase, both K and Na levels declined, likely due to leaching associated with irrigation, a common practice for managing saline soils (Hussain *et al.*, 2016). Saline soils require lower K doses because they release potassium quickly. However, without periodic or split applications matched to crop water demand, long-term K availability may decline. The decline in exchangeable Na, at higher K rates emphasizes K's potential to improve the K/Na ratio and reduce sodicity, though the effect is temporary (Stavi *et al.*, 2021).

Conversely, alkali soils showed a delayed increase in exchangeable K, with peak levels observed by week 12. This slower response is due to the high CEC and elevated carbonate–bicarbonate levels in alkali soils, which restrict K desorption and promote its precipitation into less exchangeable forms (Zewd and Siban., 2021; Xu *et al.*, 2023). The high CEC of alkali soils allows better retention of K, but this also restricts its immediate availability for plant uptake without careful management (Yang *et al.*, 2024). To ensure sustained K availability throughout the growing season, higher or more frequent K applications may be necessary. Na dynamics also varied and its Na levels remained stable or increased over time, particularly at higher K rates. This could be attributed to the CEC and carbonate content of alkali soils, which limit Na desorption and promote the formation of non-exchangeable Na complexes. Consequently, K fertilization alone may not be sufficient to manage Na effectively in alkali soils, and additional strategies like pH-lowering amendments to enhance Na leaching may be necessary (Wang *et al.*, 2023).

Na/K ratios in saline and alkali soils

The influence of K fertilization on Na/K ratios reveals distinct patterns in cation exchange and nutrient dynamics. In saline soil, the Na/K ratio initially increased, peaking around weeks 4 to 6 before declining towards week 12. This suggests that K application initially displaces Na^{+} from exchange sites, lowering the Na/K ratio. This effect is consistent with the properties of saline soils, where high soluble salt concentrations facilitate competitive cation exchange, enabling K to replace Na^+ (Wakeel *et al.*, 2023). After the peak, the decline in Na/K ratios may be due to K^+ leaching, which is common in saline soils under irrigation (Xu *et al.*, 2023). The stable Na/K ratios (1.44 to 1.48) indicate that while K fertilization can temporarily alter the Na/K balance, these effects are short-lived. Therefore, moderate K applications may suffice to optimize nutrient balance in saline soils, reducing the risk of excessive K loss and supporting more efficient nutrient use Cao *et al.*, 2022).

In alkali soil, Na/K ratios fluctuated more, especially at higher K levels, with early peaks that remained high even after 12 weeks. The consistently high ratios show that K is less effective at displacing Na due to high CEC and carbonate–bicarbonate effects that immobilize K (Stavi *et al.*, 2021). As a result, alkali soils may need repeated or higher K doses, along with amendments or acidifying agents, to improve K availability and reduce Na buildup (Bello *et al.*, 2021). In saline soils, K fertilization temporarily but significantly lowers the Na/K ratio, helping reduce salinity stress. Alkali soils respond weakly to K, indicating the need for additional management to improve K availability and reduce Na/K ratios. This highlights the importance of soil-specific K management.

In saline soils, lower K doses applied in splits with crop water demand can improve K availability and reduce leaching. In alkali soils, higher or more frequent K applications, along with pH-modifying amendments, may be needed to maintain nutrient levels and soil health. Under arid conditions, careful moisture management and timely K application are essential for efficient nutrient use and improved crop resilience.

Effect of potassium fertilization on growth and yield of crops

Potassium fertilization significantly enhances maize growth, germination rate, plant height, and grain yield, particularly under saline-alkali conditions. These benefits are attributed to potassium's role in improving root development, water-use efficiency, and osmotic adjustment. Higher K applications improved germination and plant height, especially in saline soil, while leaf number remained unchanged. Low germination in the control confirms maize's sensitivity to salinity, which was reduced by increased K, consistent with Abdel-Farid *et al.* (2020) and Khalid *et al.* (2023).

Maize recorded its highest yields under the 150% ST-K treatment, which improved cob weight, grain weight, and biomass. This aligns with Zhang *et al.* (2023), who reported K-mediated improvements in physiological and biochemical processes under salinity stress. Although overall yield increased, the non-significant response in cob weight suggests that K plays a greater role in grain filling than cob development. Green gram, however, showed reduced germination in saline-alkali soils, indicating that soil type had a stronger effect than K level. Yields were similar under 125% and 150% ST-K, with potassium enhancing photosynthesis and nutrient movement under moisture stress (Pettigrew, 2008). Potassium's role in enhancing water-use efficiency and reducing oxidative damage under salinity aligns with findings of Praveen and Singh (2024). However, green gram's poor response compared to maize may be due to its higher sensitivity to salinity, consistent with Ashraf and Harris (2013), who noted legumes' lower salinity tolerance than cereals.

Effect of K rates on nutrient acquisition and Na/K ratio

Nutrient analysis of maize showed increased uptake of N, P, K, Na, Ca and Mg with higher K levels, with 150% ST-K treatment yielding the highest nutrient accumulation. A higher K/Na ratio in maize indicated potassium's efficacy in mitigating sodium toxicity by enhancing K uptake and limiting Na accumulation. These findings are supported by Ahanger and Agarwal (2017) and Xu *et al.* (2021), who reported that potassium supplementation improves nitrogen assimilation, osmotic balance, and ion homeostasis under salinity stress. In green gram, K fertilization had a minimal impact on nutrient uptake, likely due to the stronger influence of salinity and moisture stress. Despite this, potassium's ability to enhance nutrient-use efficiency and water relations remains critical in stress management, as highlighted by Hasanuzzaman *et al.* (2018). The differences in nutrient dynamics between maize and green gram highlight the importance of crop-specific K management strategies in saline-alkali soils.

Effect of K rates on soil nutrient availability

Potassium fertilization significantly improved soil K availability, particularly with 150% ST-K treatment. This aligns with findings by Ul-Allah *et al.* (2020), who emphasized potassium's role in maintaining soil fertility under rainfed conditions. The N and P availability showed minor changes, while K availability peaked during critical growth phases, enhanced nutrient uptake and biomass in maize. In green gram, K fertilization increased soil K levels but had no significant effect on N and P availability. This suggests that K management alone cannot overcome the constraints posed by salinity and alkalinity, particularly under rainfed conditions where nutrient cycling depends on moisture availability (Marschner, 2012).

Practical implications

Field validation showed that K fertilization improves maize yield under saline–alkali and rainfed conditions. The strong performance of 150% and 125% ST-K treatments underscores the value of optimized K management for enhancing crop resilience. The study recommends integrating K into nutrient management to reduce salinity stress and boost productivity, while long-term studies are needed to assess sustainability and refine strategies for saline soils

Conclusion

The incubation study showed that saline soils responded more quickly to K fertilization, with higher exchangeable K and greater Na displacement, while alkali soils reacted more slowly due to stronger Na retention. The 125% ST-K dose provided the best balance of K buildup and Na reduction in both soil types. Pot and field experiments further demonstrated that higher K levels, especially 150% ST-K, significantly improved maize growth, yield, nutrient uptake, and soil K availability. These results highlight the value of maintaining higher K/Na ratios to reduce salinity effects and enhance crop performance. Targeted K strategies—such as 125% and 150% ST-K—are effective in improving nutrient use and soil fertility in rainfed systems with limited water and nutrients. The study also shows that maize benefits strongly from K under stress, while green gram is more sensitive to salinity but adapts better to alkalinity. Overall, potassium plays a crucial role in improving crop resilience and productivity in saline and alkali soils under rainfed conditions

Conflicts of interest

The authors declare no conflicts of interest

References

Abdel-Farid, I. B., M. R. Marghany, M.M. Rowezek, and M.G. Sheded. 2020. Effect of salinity stress on growth and metabolomic profiling of *Cucumis sativus* and *Solanum lycopersicum*. *Plants* 9(11):1626. .

Ahanger, M.A. and R.M. Agarwal. 2017. Salinity stress induced alterations in antioxidant metabolism and nitrogen assimilation in wheat (*Triticum aestivum* L) as influenced by potassium supplementation. *Plant Physiology and Biochemistry* 115: 449–460.

Ashraf, M. and P. J. C. Harris. 2013. Photosynthesis under stressful environments: An overview. *Photosynthetica* 51(1): 163-190.

Association of Official Analytical Chemists (AOAC). 1990. *Official Methods of Analysis* (15th Ed.). Washington, DC: AOAC.

Balasubramaniam, T., G. Shen, N. Esmaeili and H. Zhang. 2023. Plants' response mechanisms to salinity stress. *Plants* 12 ((12): 2253.

Bello, S. K., A. H. Alayafi, S. G. Al-Solaimani, and K. A. M. Abo-Elyousr. 2021. Mitigating soil salinity stress with gypsum and bio-organic amendments: A review. *Agronomy* 11(9): 1735

Cao, Y., H. Song and L. Zhang. 2022. New insight into plant saline-alkali tolerance mechanisms and application to breeding. *International Journal of Molecular Sciences* 23(24): 16048.

El-Dissoky, R.A., M. Ebtsam, M. Morsy and M. A. El-Shazly. 2013. Beneficial effect of potassium fertilization and yeast strains on maize plants grown on salt-affected soil. *Journal of Soil Science and Agricultural Engineering* 4(9): 827–842.

El-Ramady, H., J. Prokisch, H. Mansour, Y.A. Bayoumi, T. A. Shalaby, S. Veres and E.C. Brevik. 2024. Review of crop response to soil salinity stress: Possible approaches from leaching to nano-management. *Soil Systems* 8(1): 11.

Hasanuzzaman, M., M. A. Hossain and M. Fujita. 2018. Potassium: A vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy for Sustainable Development* 38(5): 31.

Hussain, Z., R.A. Khattak, M. Irshad and A. E. Eneji. 2013. Ameliorative effect of potassium sulfate on the growth and chemical composition of wheat (*Triticum aestivum* L.) in salt-affected soils. *Journal of Soil Science and Plant Nutrition* 13*(*2): 401–415.

Hussain, Z., R.A. Khattak, M. Irshad, Q. Mahmood and P. An. 2016. Effect of saline irrigation water on the leachability of salts, growth, and chemical composition of wheat (*Triticum aestivum* L.) in saline-sodic soil supplemented with phosphorus and potassium. *Journal of Soil Science and Plant Nutrition* 16(3): 689–699.

Iqbal, S., S. Hussain, M. Abdul Qayyaum, M. Ashraf and Saifullah. 2021. The response of maize physiology under salinity stress and its coping strategies. IntechOpen. https://doi.org/10.5772/intechopen.92213.

Islam, M. R., U. Sarker, M. G. Azam, J. Hossain, M.A. Alam, R. Ullah, A. Bari, N. Hossain, A. El. Sabagh and M.S. Islam. 2024. Potassium augments growth, yield, nutrient content, and drought tolerance in mung bean (*Vigna radiata* L. Wilczek). *Scientific Reports 14*: 9378.

Jackson, M. L. 1973. *Soil Chemical Analysis*. Prentice Hall of India Pvt. Ltd.

Johnson, R., K. Vishwakarma, M. S. Hossen, V. Kumar, A.M. Shackira, J.T. Puthur, G. Abdi, M. Sarraf and M. Hasanuzzaman.2022. Potassium in plants: Growth regulation, signaling, and environmental stress tolerance. *Plant Physiology and Biochemistry* 172: 56–69.

Khalid, N., Á. Tarnawa, I. Balla, S. Omar, R. Abd Ghani, M. Jolánkai and Z. Kende. 2023. Combination effect of temperature and salinity stress on germination of different maize (*Zea mays* L.) varieties. *Agriculture* 13(10): 1932.

Kumari, S., H. Chhillar, P. Chopra, R. R. Khanna and M. I. R. Khan. 2021. Potassium: A track to develop salinity-tolerant plants. *Plant Physiology and Biochemistry* 167: 1011–1023.

Manikandan, M., B.B. Saliha, B. Narsimlu, J.V.N.S. Prasad, K. Baskar, V. Sanjiv kumar, M. Solaisamy, G. Guru, G.R. Chary, K.V. Rao, R. Rejani and V.K. Singh. 2025. Design of rainwater harvesting pond for runoff storage and utilization in smi-arid Vertisols. Water 17. 3034.

Marschner, P. 2012. Marschner's Mineral Nutrition of Higher Plants (3rd Ed.). Academic Press.

Munns, R. and M. Tester. 2008. Mechanisms of salinity tolerance. *Annual Review of Plant Biology* 59(1): 651–681.

Patwa, N., V. Pandey, O.P. Gupta, A. Yadav, M.R. Meena, S. Ram and G. Singh. 2024. Unraveling wheat genotypic responses: Insights into salinity stress tolerance in relation to oxidative stress, antioxidant mechanisms, osmolyte accumulation, and grain quality parameters. *BMC Plant Biology* 24*:* 875.

Pettigrew, W.T. 2008. Potassium influences on yield and quality production for maize, wheat, soybean, and cotton. *Physiologia Plantarum* 133(4): 670–681.

Praveen, A. and S. Singh. 2024. The role of potassium under salinity stress in crop plants. *Cereal Research Communications* 52*:* 315–322.

Shrivastava, P. and R. Kumar. 2015. Soil salinity: A serious environmental issue and plant growth-promoting bacteria as one of the tools for its alleviation. *Saudi Journal of Biological Sciences* 22(2): 123–131.

Stavi, I., N. Thevs and S. Priori. 2021. Soil salinity and sodicity in drylands: A review of causes, effects, monitoring, and restoration measures. *Frontiers in Environmental Science* 9*:* 712831.

Su, Y., W. Luo, W. Lin, L. Ma and M. H. Kabir. 2015. Model of cation transportation mediated by high-affinity potassium transporters (HKTs) in higher plants. *Biological Procedures Online* 17: 1–13.

Sun, Y., C. Mu, H. Zheng, S. Lu, H. Zhang, X. Zhang and X. Liu. 2018. Exogenous Pi supplementation improved the salt tolerance of maize (*Zea mays* L.) by promoting Na^+ exclusion. *Scientific Reports* 8(16203):1-13.

Ul-Allah, S., M. Ijaz, A. Nawaz, A. Sattar, A. Sher, M. Naeem, U. Shahzad, U. Farooq, F. Nawaz and K. Mahmood. 2020. Potassium application improves grain yield and alleviates drought susceptibility in diverse maize hybrids. *Plants* 9(75):1-11.

Wakeel, A. 2013. Potassium–sodium interactions in soil and plant under saline-sodic conditions. *Journal of Plant Nutrition and Soil Science* 176(3): 344–354.

Wang, M., Q. Zheng, Q. Shen and S. Guo. 2013. The critical role of potassium in plant stress response. *International Journal of Molecular Sciences* 14(4): 7370–7390.

Wang, Y., M. Gao, H. Chen, Y. Chen, L. Wang and R. Wang. 2023. Organic amendments promote saline-alkali soil desalinization and enhance maize growth. *Frontiers in Plant Science 14:* 1177209.

Xu, Q., H. Fu, B. Zhu, H.A. Hussain, K. Zhang, X. Tian, M. Duan, X. Xie and L. Wang. 2021. Potassium improves drought stress tolerance in plants by affecting root morphology, root exudates, and microbial diversity. *Metabolites* 11(3): 131.

Xu, X., L. Guo, S. Wang, X. Wang, M. Ren, P. Zhao, Z. Huang, H. Jia, J. Wang and A. Lin. 2023. Effective strategies for reclamation of saline-alkali soil and response mechanisms of the soil-plant system. *Science of the Total Environment* 905*:* 167179.

Yang, M., D. Zhou, H. Hang, S. Chen, H. Liu, J. Su, H. Lv, H. Jia and G. Zhao. 2024. Effects of balancing exchangeable cations Ca, Mg, and K on the growth of tomato seedlings (*Solanum lycopersicum* L.) based on increased soil cation exchange capacity. *Agronomy* 14(3): 629.

Zewd, I. and M. Siban. 2021. The effects of alkalinity on physical and chemical properties of soil. *Journal of Plant Biology and Agriculture Science* 3(2): 1–5.

Zhang, Y., J. Fang, X. Wu and L. Dong. 2018. Na^+/K^+ balance and transport regulatory mechanisms in weedy and cultivated rice (*Oryza sativa* L.) under salt stress. *BMC Plant Biology* 18*:* 375.

Zhang, M., Y. Hu, W. Han, J. Chen, J. Lai and Y. Wang. 2023. Potassium nutrition of maize: Uptake, transport, utilization, and role in stress tolerance. *The Crop Journal* 11(4): 1048-1058.