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Enhanced Potassium Fertilization Improved Rice (*Oryza sativa*) Yield and Nutrient Uptake in Coastal Saline Soil of Bangladesh

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Abstract

Despite the saline soils of Bangladesh having high potassium (K) availability, the acquisition of K by rice (*Oryza sativa* L.) is unsatisfactory. The study was designed to quantify the performance of rice yield components, macro-nutrient uptake, K^+/Na^+ ratio, and nutrient use efficiency under the influence of improved K fertilization in a salt-affected soil. The salt-tolerant Boro rice cultivar (BRRI-47) was tested with seven different K treatments (0, 20, 40, 60, 80, 100, and 120 kg K ha^{-1}) with three replications followed by a complete randomized design (CRD). The results indicated that increasing K levels had a positive influence on most of the growth and yield parameters of rice except plant height, unfilled grain number, and 1000 grain weight. Application of 100 kg K ha^{-1} raised the grain yield by 49% over control and 19.13% over the present national recommended dose (40 kg K ha^{-1}). Straw yield increased by 42% in treatment K_{120} and 36% in treatment K_{100} over control, respectively. The K^+/Na^+ ratio in plants was observed to be higher when K was applied at higher rates. Additionally, the different K doses improved the nutrient (N, P, K, S) uptake and decreased the internal N and K use efficiencies of rice. It can be summarized that 100 kg ha^{-1} K fertilization could be effective to improve rice production and nutrient uptake in coastal saline soil of Bangladesh while maintaining a high K^+/Na^+ ratio.

Keywords Soil salinity · Rice yield · K^+/Na^+ ratio · Nutrient uptake · Internal nutrient use efficiency

1 Introduction

Coastal salinity, a limiting factor for crop cultivation in Bangladesh, becomes more apparent with serious concern for food security. At present, 53% of coastal area that constitutes around 1.06 million hectares of the country's arable lands is affected by different levels of salinity (SRDI 2010). Regions under salinity are expanding over time as a result of rising sea level that increases with the global temperature. In Bangladesh, only over the past 40 years that a total of 0.223 million ha of new land is damaged by salinity (Hasan et al. 2019). Salinity problem adversely affects the plants growth and soil productivity. There are three types of direct effects of salinity on plants: osmotic stress, nutritional imbalances, and element ion toxicity (Isayenkov and Maathuis 2019; Zörb et al. 2019; Billah et al. 2021). Na^+, Cl^-, SO_4^{2-}, and HCO_3^- are some common ions that are found in saline soil in a wide range of concentrations and proportions. The increasing influx of these ions into plant root cells with high osmotic stress prevents the uptake of other essential nutrients especially potassium, K^+ (Arif et al. 2020; Makhlouf et al. 2022). Osmotic pressure and ionic toxicity from salinity can also disrupt a variety of physiological processes, including carbohydrate metabolism, respiration, and photosynthesis (Abbasi et al. 2016). Apart from that, in saline soil, the effectiveness of applied fertilizers is decreased by high salt concentration that results in poor plant development (Mohiti et al. 2011).

A number of chemical, biological, and genetic approaches have developed to counteract the harmful effects of salt stress. In the chain of stress-reduction mechanisms, mineral nutrients play a critical role to resist environmental stresses, including salinity problem (Mekdad et al. 2021b). Among the nutrients, potassium (K) is a macro-element with phyto-beneficial properties that organizes physio-biochemical

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processes to help plants to tolerate abiotic stresses like salinity (Mekdad et al. 2021a; El-Mageed et al. 2022). Selective K+ uptake to maintain a high K+/Na+ ratio in plant throughout the growing season is an effective method for enhancing plants capacity to withstand salt stress (Pi et al. 2016; Tittal et al. 2021). In plant tissue, mainly the highly appealed K transporters (*HAKTs*) and a channel arbitrated low affinity transporter (*LAT*) are accounted for K+ uptake (Van Zelm et al. 2020). Nonselective cation channels (*NCCs*), on the other hand, are most likely the primary transporter responsible for Na+ uptake at root-soil interface (Assaha et al. 2017). Due to similar physicochemical characteristics, excessive Na+ in saline soil inhibits K+ uptake by plants through *HAKTs* and *NCCs*, even though there is an adequate amount of K+ present in the soil (Wu et al. 2018; Raddatz et al. 2020). Thus, by disturbing the cytoplasmic K+/Na+ homeostasis, salt stress leads to the increasing Na+ to K+ ratio in the plant cytosol (Javed et al. 2020). Therefore, reducing plant salt stress includes more than just adapting to Na+ toxicity; it also demands consuming enough K+ (Zhang et al. 2010; Pi et al. 2016).

Rice (*Oryza sativa* L.) is the most extensively consumed starchy cereal grain in Bangladesh, with 144.5 kg of consumption per person annually (Yunus et al. 2019), and rice security is considered the ultimate food security in this country as well as in South Asia. However, because of salinity stress, rice production usually declines by 30 to 50% of total production (Eynard et al. 2005). The increasing saline water intrusion as a consequence of global climate change is thus frustrating the food security in Bangladesh. Available K+ in soil is considered a crucial factor for rice production (Yang et al. 2003). The modern high yielding varieties (HYVs) are reported to remove significant amount of K from soil, sometimes, even more than N to ensure the yield at optimum level (Sharma et al. 2013; Wakeel 2013). Based on a report of Bangladesh Rice Research Institute (BRRI), rice crops remove 19.13 to 22.31 kg K for every ton of rice production (Choudhury et al. 2013). Unexpectedly, like several other Asian nations, Bangladeshi farmers typically overlook K fertilization and focus on N and P application for improving crop production (Islam and Muttaleb 2016). Potassium acts as a counter cation for anion accumulation and helps to mitigate salt stress by decreasing the Na+/K+ ratio in a wide range of crops (Ali et al. 2019; Jan et al. 2020). According to Banerjee et al. (2018), an increase in K+ uptake in the initial developmental stage of rice alleviates the negative impact of Na+ uptake. Further, K plays a significant role in plant physiology, viz., osmoregulation, photosynthesis, enzyme activation, starch, and protein synthesis (Ahanger and Agarwal 2017; Mardanluo et al. 2018). In addition, K application can increase nutrients solubility in saline soil (Niu et al. 2020).

However, in Bangladesh, the research knowledge regarding the rice response under K fertilization in saline soil is still limited and diverse to recommend K for lessening the detrimental impact of salinity. Therefore, we hypothesized that the K application could be an effective method to reduce salinity effect while improving nutrients availability and rice yield. The current research work was thus undertaken (i) to investigate the effect of different K levels on the yield attributes and production of rice, (ii) to study the macro-nutrients uptake trends as well as use efficiencies, and (iii) to find out the K+/Na+ ratio of rice in a salt-affected soil.

2 Material and Methods

2.1 Experiment Site and Soil Description

A pot study was conducted from January to May 2020 at the net house of Soil, Water and Environment Discipline, Khulna University, Bangladesh, where all the prevailing biotic and abiotic environmental factors were present like a real field experiment. Throughout the study, recorded temperature and humidity data for the study site were 15.4–34.3 °C and 74–79%, respectively.

Soil sample was collected from a salinity-affected agriculture field of Batiaghata Upazila, Khulna, before the plowing of the field for the next crop. The soil developed from Gangetic Alluvium parent material and belongs to the Inceptisol order. The associated agro-ecological zone (AEZ) of the experimental soil was the Ganges tidal river floodplain. After collection, the soil was air dried, grinded, and passed through 2-mm sieve. Preliminary soil properties were determined by the standard methods prior to the experiment (see Table 1). Analyses showed that the soil was saline in nature and had a high K content (Table 1).

2.2 Experimental Setup and Cultural Operations

A salinity-tolerant rice variety, BRRI-47 (148–152-day duration) was selected for the experiment. This variety can withstand salinity level up to 12–14 dSm^{-1} at seedling stage and 8–10 dSm^{-1} during the vegetative growth stages. The study comprised of complete randomized design (CRD) with seven K treatments (0, 20, 40, 60, 80, 100, and 120 kg ha^{-1}) and three replications. Muriate of potash (KCl) was used as the source of K (60% K$_2$O). Apart from the K treatments, recommended doses of N, P, S, and Zn were also applied into each of the experimental pots at a rate of 125, 24, 6, and 1.5 kg ha^{-1}, respectively, as suggested by Bangladesh Agricultural Research Council (BARC 2018). Fertilizers were applied on a g pot^{-1} basis from kg ha^{-1} after calculation by using Eq. 1. The sources of N, P, S, and Zn were urea, triple super phosphate (TSP), gypsum, and zinc sulfate (ZnS),

Table 1 Initial characteristics of the experimental soil sample

Soil characteristics	Values	Methodology	Reference
Textural class	Silty clay loam	Hydrometer method	Dewis and Freitas (1970)
pH	7.4	Soil–water ratio of 1:2.5	Jackson (1973)
Electrical conductivity/EC (dSm^{-1})	9.78	Soil–water ratio of 1: 5	Allison and Richards (1954)
Organic matter (%)	1.73	Wet oxidation method	Walkley and Black (1934)
Total nitrogen (%)	0.126	Micro-Kjeldahl method	Jackson (1973)
Available sulfur (µg g^{-1})	7.1	Turbidimetric method	Hunt (1980)
Available phosphorus (µg g^{-1})	14.8	Olsen extraction	Olsen (1954)
Exch+WS K$^+$ (Cmol(+) kg^{-1})	0.57	Flame photometric method	Kundsen et al. (1982)
Exch+WS Na$^+$ (Cmol(+) kg^{-1})	1.68	Flame photometric method	Kundsen et al. (1982)
Cation exchange capacity (Cmol(+) kg^{-1})	20.11	Distillation	Chapman (1965)

Note: Exch exchangeable, *WS* water soluble

respectively. Muriate of potash (treatment) was applied into 2 splits: 50% before transplantation, during the final soil preparation, and 50% at 25 days after transplantation. The others recommended fertilizers (TSP, gypsum, and ZnS) were applied as basal dose in all the pots at the time of soil preparation. Urea was applied into three splits: 7, 30, and 50 days after transplantation, respectively. Following that, each pot was filled with 5 kg of soil, and three 23-day-old seedlings were transplanted into each pot after puddling under irrigated condition. For cultural operations, proper crop management measures including irrigation and weeding were followed throughout the growing period and kept uniform across all experimental pots. Harvesting was done when the grain reached at 80% of its maturity stage, and afterwards, the cut crops were threshed, winnowed, cleaned, and packed separately for laboratory analyses.

$$\text{Per pot fertilizer (gm)} = \frac{\text{TD or RD dose}(\text{kg ha}^{-1}) \times \text{Pot area }(\text{m}^2)}{10000} \times 1000 \quad (1)$$

Here, TD or RD represents treatment dose or recommended dose.

2.3 Growth Parameters and Yield Measurement

The plant height (PH), number of tillers hill^{-1} (TN), and the number of panicle hill^{-1} (PN) of rice was measured in this experiment. The PH was measured from the base of the plant to the tip of the tallest panicle, and the TN and PN were enumerated manually. After threshing, filled grains panicle^{-1} (FG) and unfilled grains panicle^{-1} (UFG) were differentiated by dipping the seeds into water. The FG was settled down, and the light floating UFG was removed from the water. Fresh grain yield (GY) and straw yield (SY) were recorded in g pot^{-1} basis, and the yield was then converted into t ha^{-1} unit (Eq. 3). Dry matter yield (DMY) was estimated after the green biomass was oven-dried at 65 °C temperature.

Agronomic efficiency of K (AE$_K$) is the grain yield response of rice due to per unit of applied K, and partial factor productivity (PFP$_K$) is the estimation of K fertilizer productivity. Following that, grain harvest index (GHI), agronomic K use efficiency (AE$_K$), and partial factor productivity (PFP$_K$) were calculated as Eq. 4, Eq. 5, and Eq. 6, respectively.

$$\text{GY, SY or DMY (kg ha}^{-1}) = \frac{\text{GY, SY or DMY (g pot}^{-1}) \times 10^4}{\text{Area of the pot }(\text{m}^2) \times 10^3} \quad (2)$$

$$\text{GY, SY or DMY (t ha}^{-1}) = \frac{\text{GY, SY or DMY (g pot}^{-1}) \times 10^4}{\text{Area of the pot }(\text{m}^2) \times 10^6} \quad (3)$$

$$\text{Grain harvest index (GHI)\%} = \frac{\text{GY}}{\text{GY + SY}} \times 100 \quad (4)$$

$$\text{AE}_K = \frac{\text{GY in K treated pot (kg ha}^{-1}) - \text{GY in control pot (kg ha}^{-1})}{\text{Amount of applied K (kg ha}^{-1})} \quad (5)$$

$$\text{PFP}_K = \frac{\text{GY (kg ha}^{-1})}{\text{Amount of applied K (kg ha}^{-1})} \quad (6)$$

2.4 Internal Nutrient Use Efficiency

Internal nutrient use efficiency (INUE) is a concept of taking up and utilizing nutrients for maximum grain yield. The nutrient uptake and internal nutrient use efficiencies (INUE) were calculated followed by Eq. 7 and Eq. 8 (Yang et al. 2004).

$$\text{Nutrient uptake (kg ha}^{-1}) = \frac{\text{Nutrient content (\%)} \times \text{DMY (kg ha}^{-1})}{100} \quad (7)$$

Here, DMY represents Dry Matter Yield in kg ha^{-1}, which was estimated from *Eq. 2*

$$\text{Internal nutrient use efficiency} = \frac{\text{GY (kg ha}^{-1})}{\text{Nutrient uptake (kg ha}^{-1})} \quad (8)$$

2.5 Statistical Analysis

One-way analysis of variance (ANOVA) was performed by using Minitab (version 19.0, Minitab LCC, Triola Statistics Company, 1972) at 95% significant level. The linear regression graph was illustrated for demonstrating the correlations between nutrient uptake parameters and treatments by using Origin 2021 (Origin Lab, Northampton, MA, USA). Besides, principal component analysis (PCA) was done to depict the correlations of a group of agronomic attributes and nutrient uptake parameters using R 3.6.1 (R Core Team 2013).

3 Results

3.1 Growth Parameters of BRRI-47

In this experiment, different K levels did not show any significant influence ($p \leq 0.05$) on the plant height (PH). However, the result revealed a significant effect on tiller number (TN) and panicle number (PN) under the application of K (Table 2). Observation showed that treatment K_{100} had the maximum TN (16), whereas the minimum TN (9) was recorded from treatment K_0. Treatment K_{100} resulted in maximum PN (16) and was statistically identical to treatment K_{40}, K_{60}, K_{80}, and K_{120}, while the minimum PN (7) was attained from treatment K_0. A significant correlation was observed for TN ($r = 0.87$, $p \leq 0.001$) and PN ($r = 0.81$, $p \leq 0.001$) with different K rates (Fig. 1).

The filled grain panicle^{-1} (FG) of BRRI-47 was positively ($p \leq 0.05$) affected by different K treatments (Table 2). The FG was maximum at treatment K_{100}, accounting for 29% more FG than control. The

magnitude of different treatments for FG was recorded as $K_{100} > K_{120} > K_{80} > K_{40} > K_{60} > K_{20} > K_0$. A significant correlation ($r = 0.84$, $p \leq 0.001$) was obtained between the FG and increasing K doses (Fig. 1). However, no significant effect of K was obtained on unfilled grain panicle^{-1} (UFG) and 1000-grain weight (100-G.wt) production of rice (Table 2).

3.2 Yield Parameter of BRRI-47

The grain yield (GY) and straw yield (SY) were significantly influenced by different K levels ($p \leq 0.05$) (Table 3). Statistically no significant variation was found in GY and the SY from treatment K_{80} to K_{120}. Treatment K_0 accounted for lower GY (3.51 t ha^{-1}) compared to treatments getting higher K dose. GY in K_{100} was increased by 49% over K_0 (control) and 19.13% over treatment K_{40} (current recommended rate). Under different K doses, K_{120} produced the maximum SY (8.08 t ha^{-1}) followed by K_{100}. On the contrary, minimum SY (5.67 t ha^{-1}) was obtained from control treatment. Increasing K application had a significant correlation ($r = 0.89$, $p \leq 0.001$) with the GY (Fig. 1). Variable K treatments appeared to have a significant influence on dry matter yield (DMY) production (Table 3). Treatment K_{100} and K_{120} showed the highest DMY response, and the lowest response was obtained from treatment K_0. Treatment K_{120} produced 46% more DMY than K_0. Statistically, an identical DMY was obtained from treatment K_{60}, K_{80}, K_{100}, and K_{120}. However, application of K did not show a significance effect on the grain harvest index (GHI %) of rice (Table 3).

3.3 Potassium Use Efficiency

In saline soil, added K found to have a significant influence on the agronomic efficiency of K (AE_K) and partial factor productivity of K (PFP_K). Data perusal showed a declining

Table 2 Response of K fertilizer on the growth parameters of BRRI-47

Treatment	PH (cm)	TN	PN	FG	UFG	1000-G.wt (g)
K_0	93.83 ± 1.76^a	9.0 ± 1.00^c	7.0 ± 1.52^c	89.33 ± 6.81^b	24.00 ± 5.29^a	20.45 ± 0.91^a
K_{20}	94.16 ± 0.56^a	12 ± 1.52^{bc}	8.0 ± 2.52^{bc}	92.00 ± 3.00^b	23.67 ± 6.03^a	22.25 ± 1.20^a
K_{40}	95.40 ± 1.56^a	14 ± 0.70^{ab}	12 ± 1.52^{abc}	104.50 ± 4.95^{ab}	19.50 ± 10.61^a	21.88 ± 1.01^a
K_{60}	95.57 ± 2.57^a	13 ± 0.57^{ab}	11 ± 1.00^{abc}	102.0 ± 3.00^{ab}	16.00 ± 2.65^a	23.45 ± 1.39^a
K_{80}	94.37 ± 1.21^a	15 ± 1.00^{ab}	13 ± 1.52^{ab}	111.67 ± 6.51^a	18.67 ± 4.51^a	23.51 ± 2.41^a
K_{100}	94.53 ± 2.60^a	16 ± 1.00^a	13 ± 1.41^{ab}	115.33 ± 8.08^a	13.00 ± 1.73^a	23.78 ± 0.89^a
K_{120}	96.30 ± 1.93^a	14 ± 2.08^{ab}	14 ± 0.57^a	114.33 ± 11.37^a	14.67 ± 5.13^a	24.17 ± 2.15^a
LSD ($p=0.05$)	ns	*	*	*	ns	ns

Note: In each column, mean ± standard deviation value denoted by common letters indicates no significant variation at LSD 5% significant level

*Significant difference at $p = 0.05$; *ns*, non-significant difference

Abbreviations: Treatment K_0 = control, K_{20} = 20 kg K ha^{-1}, K_{40} = 40 kg K ha^{-1}, K_{60} = 60 kg K ha^{-1}, K_{80} = 80 kg K ha^{-1}, K_{100} = 100 kg K ha^{-1}, K_{120} = 120 kg K ha^{-1}; *PH* plant height, *TN* number of tillers hill^{-1}, *PN* number of panicle hill^{-1}, *FG* filled grain panicle^{-1}, *UFG* unfilled grain panicle^{-1}, *1000-G.wt* 1000-grain weight
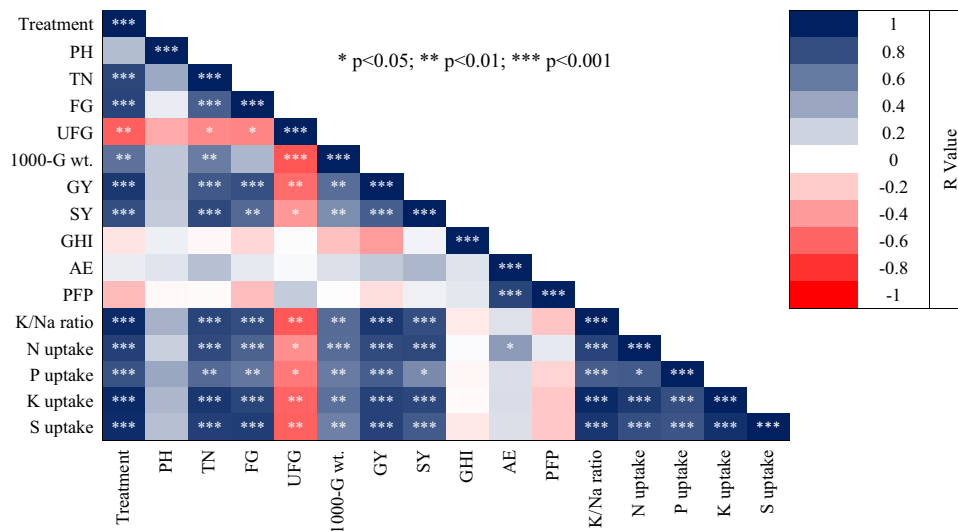
Fig. 1 Pearson correlation matrix among rice growth and yield parameter and nutrient uptake parameters. The blue, red, and white color correspond positive, negative, and neutral correlation, respectively. *, **, and *** represent significance levels at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively. Here: Treatment = 0, 20, 40, 60, 80, 100, and 120 kg K ha^{-1}; PH, plant height; TN, number of tillers hill^{-1}; PN, number of panicle hill^{-1}; FG, filled grain panicle^{-1}; UFG, unfilled grain panicle^{-1}; 1000-G.wt, 1000-grain weight; GY, grain yield; SY, straw yield; DMY, dry matter yield; GHI, grain harvest index; AE, agronomic use efficiency of K; PFP, partial factor productivity of K

Table 3 Influence of added K on the yields and agronomic K use efficiencies of BBRI-47 in a saline soil

Treatment	Yield (t ha^{-1})			GHI %	AE$_K$ (kg grain increased with kg^{-1} K)	PFP$_K$ (kg grain with kg^{-1} K)
	GY	**SY**	**DMY**			
K$_0$	3.51 ± 0.19^e	5.67 ± 0.33^b	7.31 ± 0.14^d	38.23 ± 0.26^a	0^c	0^f
K$_{20}$	4.09 ± 0.24^d	6.83 ± 0.51^{ab}	8.79 ± 0.28^c	37.52 ± 2.56^a	29.21 ± 12.39^a	204 ± 12.69^a
K$_{40}$	4.39 ± 0.05^{cd}	7.44 ± 0.07^a	9.50 ± 0.71^{bc}	37.11 ± 0.53^a	22.09 ± 1.44^{ab}	109.84 ± 1.44^b
K$_{60}$	4.66 ± 0.13^{bc}	7.06 ± 0.61^a	9.98 ± 0.18^{abc}	39.86 ± 2.74^a	19.28 ± 2.23^{ab}	77.78 ± 2.23^c
K$_{80}$	4.95 ± 0.09^{ab}	7.68 ± 0.67^a	10.57 ± 0.58^{ab}	38.00 ± 1.32^a	18.02 ± 1.12^{ab}	62.51 ± 0.61^d
K$_{100}$	5.23 ± 0.08^a	7.74 ± 0.44^a	11.16 ± 0.21^a	40.37 ± 1.67^a	17.28 ± 0.80^{ab}	54.93 ± 5.09^{de}
K$_{120}$	5.07 ± 0.07^{ab}	8.08 ± 0.31^a	11.21 ± 0.07^a	39.84 ± 2.24^a	12.01 ± 0.75^{bc}	41.26 ± 0.75^e
LSD (*p=0.05*)	*	*	*	ns	*	*

Note: In each column, mean ± standard deviation value denoted by common letters indicates no significant variation at LSD 5% significant level

*Significant difference at $p = 0.05$; *ns,* non-significant difference

Abbreviations: Treatment K$_0$ = control, K$_{20}$ = 20 kg K ha^{-1}, K$_{40}$ = 40 kg K ha^{-1}, K$_{60}$ = 60 kg K ha^{-1}, K$_{80}$ = 80 kg K ha^{-1}, K$_{100}$ = 100 kg K ha^{-1}, K$_{120}$ = 120 kg K ha^{-1}; *GY* grain yield, *SY* straw yield, *DMY* dry matter yield, *GHI* grain harvest index, *AE$_K$* agronomic use efficiency of K, *PFP$_K$* partial factor productivity of K

trend of AE$_K$ and PFP$_K$ indices with the increment of K doses (Table 3). Application of K$_{120}$ minimized the AE$_K$ (12.01) and PFP$_K$ (41.26). On the contrary, K$_{20}$ resulted in maximum AE$_K$ (29.21) and PFP$_K$ (204), respectively.

3.4 Macro-nutrients Uptake of Rice

The nitrogen (N), potassium (K), phosphorus (P), and sulfur (S) uptake of rice were significantly influenced by increasing

rates of K (Table 4). Nitrogen uptake did not show any significant difference ($p \leq 0.05$) from treatment K$_{40}$ to K$_{100}$. The study showed that in saline soil, K fertilization increased the N uptake by 164% in treatment K$_{100}$ and 188% in treatment K$_{120}$ over control treatment. Overall, the highest response in terms of N uptake (112.9 kg ha^{-1}) was obtained from treatment K$_{120}$, while the lowest response of K on N uptake (39.18 kg ha^{-1}) was recorded in treatment K$_0$. Lowest P uptake (12.16 kg ha^{-1}) by rice was noticed in treatment

K_0 which gradually increased the uptake to 27.75 kg ha^{-1} in treatment K_{100}. Effects of added K on N and P uptake can be expressed by Eq. 9 and Eq. 10, respectively. The N uptake and P uptake by rice with K treatments were linear and accounted for 74% (Fig. 2a) and 60% (Fig. 2b) of the variability in this experiment.

$$y = 0.5111x + 55.677, R^2 = 0.7411 *** \tag{9}$$

$$y = 0.1257x + 12.412, R^2 = 0.6009 *** \tag{10}$$

where y = quantity of nutrient uptake (kg ha^{-1}), x = amount of applied K (kg ha^{-1}), and *** = $p \leq 0.001$.

Result revealed that K uptake by rice was significantly ($p \leq 0.05$) affected by the application of different K doses in saline soil (Table 4). In this experiment, a progressive increment of K uptake was noticed with the increasing levels of K fertilization. The mean K uptake for all treatments ranged from 54.48 to 136.8 kg ha^{-1}. Treatment K_{80}, K_{100}, and K_{120} resulted in better performance in terms of K uptake compared to treatments receiving lower K dose. Treatment K_{120} resulted 150% more K uptake than K_0. Total S uptake by BRRI-47 registered a significant ($p \leq 0.05$) effect with the improved K doses. Minimum S uptake was obtained by treatment K_0 (6.54 kg ha^{-1}), whereas treatment K_{120} showed the maximum uptake (13.83 kg ha^{-1}) and was significantly higher than treatment K_{60}, K_{40}, K_{20}, and K_0. Influence of applied potassium on K and S uptake can be explained by Eq. 11 and Eq. 12, which accounted for 92% (Fig. 2c) and 89% (Fig. 2d) of the variability, respectively.

$$y = 0.668x + 59.33, R^2 = 0.9256 *** \tag{11}$$

$$y = 0.061x + 6.742, R^2 = 0.8964 *** \tag{12}$$

where y = quantity of nutrient uptake (kg ha^{-1}), x = amount of applied K (kg ha^{-1}), and *** = $p \leq 0.001$.

3.5 K^+/Na^+ Ratio of Plant

The K^+/Na^+ ratio of studied rice responded significantly ($p \leq 0.05$) with the application of higher K doses (Fig. 3). The K^+/Na^+ ratio progressively increased with the increasing K levels. Among the treatments, K_{120} demonstrated the highest ratio (0.95) followed by K_{100} (0.94) which were 206% and 203% more than the K control treatment, respectively. A strong significant correlation ($r = 0.95$, $p \leq 0.001$) was noticed between K^+/Na^+ ratio and the application of K (Fig. 1).

3.6 Internal Nutrient Use Efficiency (INUE)

In this study, different K doses implied a significant effect on the internal N use efficiency (IUEN) and internal K use efficiency (IUEK). The influence, on the other hand, was indifferent for internal P and S use efficiencies (Table 5). Highest IUEN (89.86) was obtained by 0 kg K ha^{-1} that significantly decreased to 44.65 with the application of 120 kg K ha^{-1}. Similarly, mean IUEK was at maximum (64.45) in treatment K_0 and decreased to 38.56 in treatment K_{120}.

3.7 Principal Component Analysis and Correlation

Principal component analysis (variables (Fig. 4a) and bi-plot PCA (Fig. 4b)) of growth, yield, and nutrient uptake were done as influenced by K. Based on the findings, first two principal components (PC) accounted for 74.77% of dataset variance, where PC1 accounted for 61.89% of the
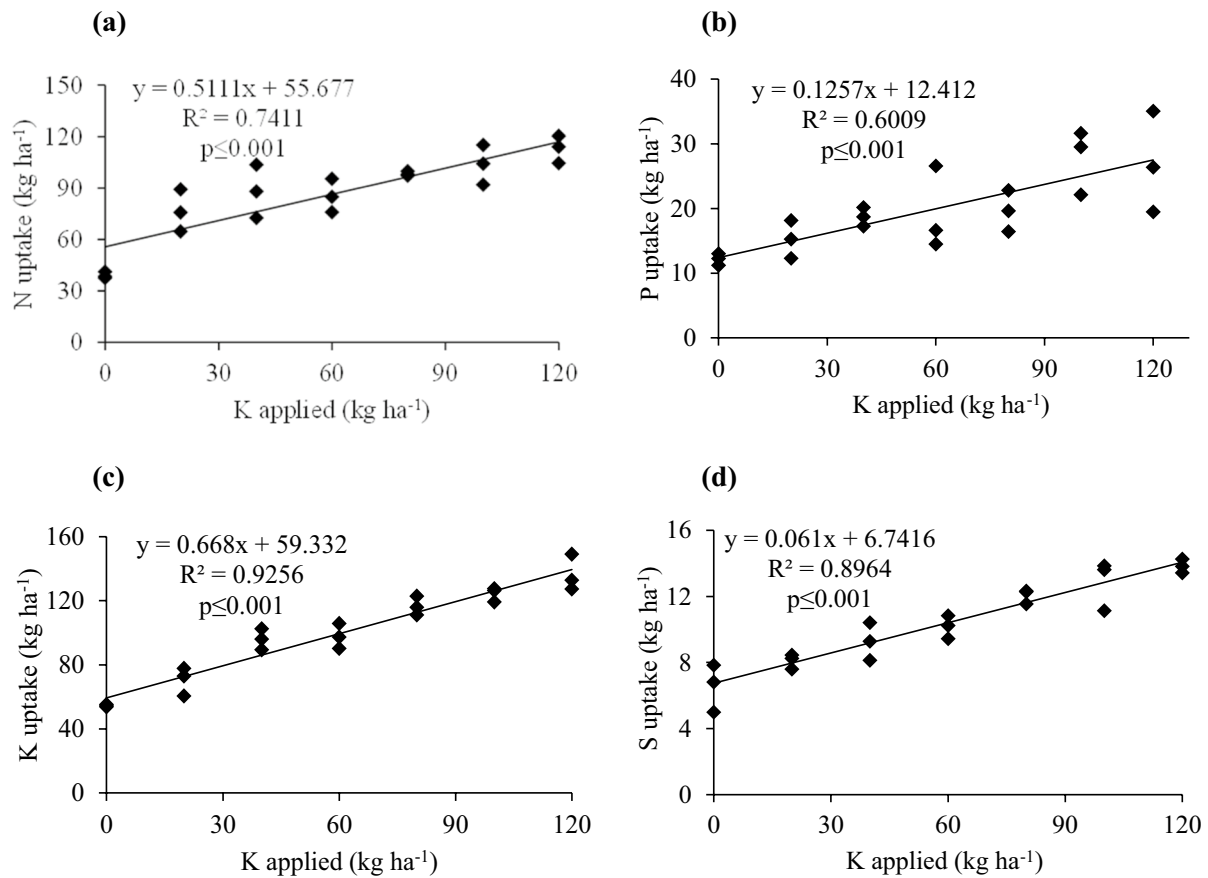
Table 4 Effect of K fertilizer on the macro-nutrient's uptake of BBRI-47 in a saline soil

Treatment	Uptake (kg ha^{-1})			
	N	**P**	**K**	**S**
K_0	39.14 ± 1.94[c]	12.16 ± 0.89[b]	54.48 ± 0.97[c]	6.54 ± 1.43[e]
K_{20}	76.56 ± 12.34[b]	15.22 ± 4.13[ab]	70.45 ± 8.91[c]	8.09 ± 0.44[de]
K_{40}	88.10 ± 22.1[ab]	18.70 ± 2.06[ab]	95.94 ± 9.27[b]	9.27 ± 1.62[cde]
K_{60}	85.38 ± 9.80[ab]	19.24 ± 6.45[ab]	97.73 ± 7.81[b]	10.16 ± 0.70[bcd]
K_{80}	98.37 ± 1.35[ab]	19.62 ± 4.50[ab]	116.60 ± 5.96[ab]	12.04 ± 0.44[abc]
K_{100}	103.80 ± 11.61[ab]	27.75 ± 4.99[a]	124.31 ± 4.45[ab]	12.86 ± 1.51[ab]
K_{120}	113 ± 7.97[a]	26.97 ± 7.79[ab]	136.38 ± 11.31[a]	13.83 ± 0.41[a]
LSD ($p = 0.05$)	*	*	*	*

Note: In each column, mean ± standard deviation value denoted by common letters indicates no significant variation at LSD 5% significant level

[*]Significant difference at $p = 0.05$; *ns,* non-significant difference

Abbreviation: Treatment K_0 = control, K_{20} = 20 kg K ha^{-1}, K_{40} = 40 kg K ha^{-1}, K_{60} = 60 kg K ha^{-1}, K_{80} = 80 kg K ha^{-1}, K_{100} = 100 kg K ha^{-1}, K_{120} = 120 kg K ha^{-1}

(a)

$y = 0.5111x + 55.677$
$R^2 = 0.7411$
$p \leq 0.001$

N uptake (kg ha^{-1})

K applied (kg ha^{-1})

(b)

$y = 0.1257x + 12.412$
$R^2 = 0.6009$
$p \leq 0.001$

P uptake (kg ha^{-1})

K applied (kg ha^{-1})

(c)

$y = 0.668x + 59.332$
$R^2 = 0.9256$
$p \leq 0.001$

K uptake (kg ha^{-1})

K applied (kg ha^{-1})

(d)

$y = 0.061x + 6.7416$
$R^2 = 0.8964$
$p \leq 0.001$

S uptake (kg ha^{-1})

K applied (kg ha^{-1})

Fig. 2 General linear regression between K application and nitrogen (a), phosphorus (b), potassium (c), and sulfur (d) uptake by BRRI -47

Fig. 3 K^+/Na^+ ratio of rice with K treatments. Data included as mean $\pm$ SE (standard error). Small common letters denote no significant difference in mean values at 0.05% level of significance. Here, Treatment K0 = control, K20 = 20 kg K ha^{-1}, K40 = 40 kg K ha^{-1}, K60 = 60 kg K ha^{-1}, K80 = 80 kg K ha^{-1}, K100 = 100 kg K ha^{-1}, K120 = 120 kg K ha.$^{-1}$

K$^+$/Na$^+$ ratio
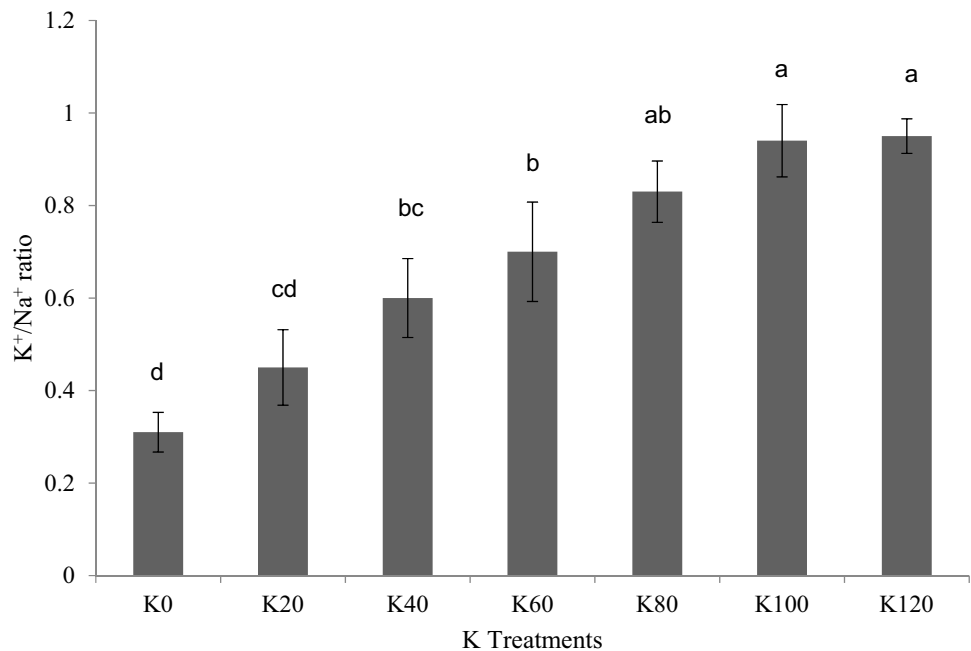
K Treatments

Table 5 Internal N, P, K, and S use efficiencies of BRRI-47 with varying K rates

Treatment	INUE (kg grain kg^{-1} nutrient uptake)			
	N	**P**	**K**	**S**
K$_0$	89.86 ± 8.96^a	289.2 ± 16.45^a	64.45 ± 4.24^a	560.3 ± 165^a
K$_{20}$	54.06 ± 5.47^b	273.5 ± 36.7^a	58.76 ± 8.57^{ab}	505 ± 16.07^a
K$_{40}$	47.20 ± 12.20^b	217.9 ± 35.6^a	42.43 ± 6.72^c	442 ± 46.4^a
K$_{60}$	55.20 ± 7.22^b	258.4 ± 72.3^a	48.03 ± 5.18^{bc}	459 ± 18.8^a
K$_{80}$	51.60 ± 1.33^b	263.2 ± 41.8^a	43.80 ± 2.21^c	421 ± 11.98^a
K$_{100}$	48.08 ± 5.15^b	182.8 ± 36.4^a	39.86 ± 1.66^c	389 ± 55.8^a
K$_{120}$	44.65 ± 0.73^b	205 ± 56.6^a	38.56 ± 2.80^c	378 ± 10.49^a
LSD ($p = 0.05$)	*	ns	*	ns

Note: In each column, mean $\pm$ standard deviation value denoted by common letters indicates no significant variation at LSD 5% significant level

*Significant difference at $p = 0.05$; *ns,* non-significant difference

Abbreviation: Treatment K$_0$ = control, K$_{20}$ = 20 kg K ha^{-1}, K$_{40}$ = 40 kg K ha^{-1}, K$_{60}$ = 60 kg K ha^{-1}, K$_{80}$ = 80 kg K ha^{-1}, K$_{100}$ = 100 kg K ha^{-1}, K$_{120}$ = 120 kg K ha^{-1}; *INUE* internal nutrient use efficiency

total variance (Fig. 4a, b). PCA bi-plot evidently represented observation distribution corresponding to every treatment and the interaction between two main features. Throughout the dataset, N uptake and GY showed the maximum contribution, while PH and GHI showed the least contribution.

4 Discussion

In this study, an insignificant effect of K on the PH was noticed that is in consistent with the findings of Ardakani et al. (2016). Under saline condition, interim stress of K fertilization might be accounted for the reduced PH
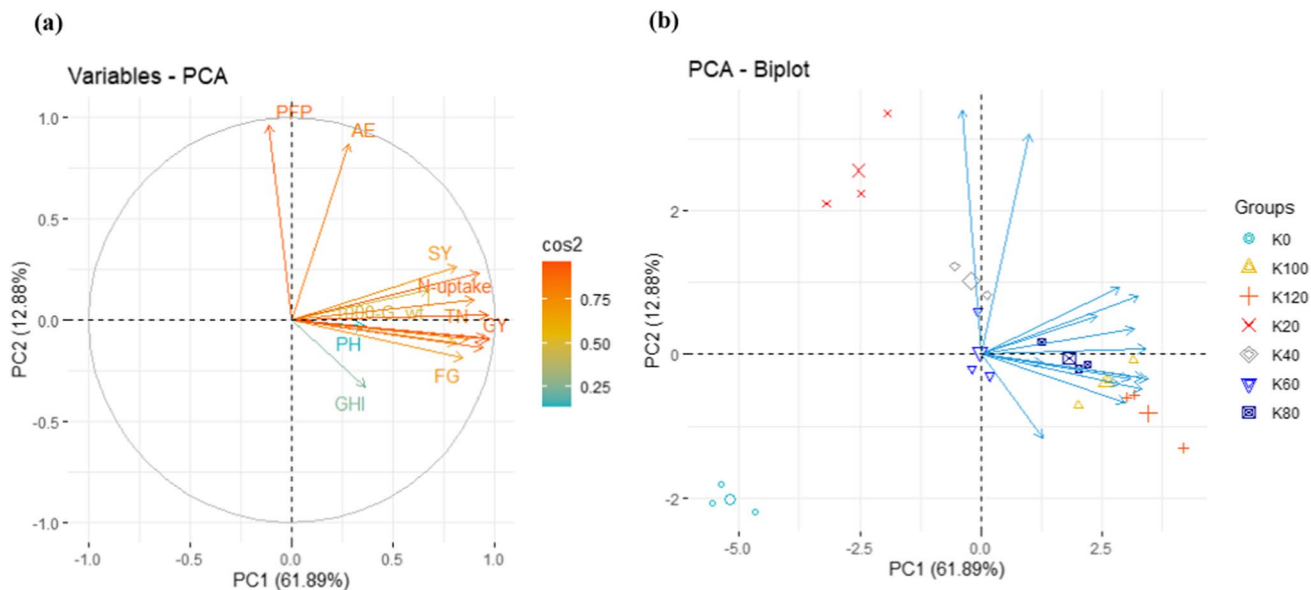
Fig. 4 (a) Variables and (b) bi-plot PCA diagrams demonstrated the performance of K on various growth, yield, and nutrient uptake features of BRRI-47. Here, smaller angles within the vectors depict the greater correlation. In variables PCA red colors are responsible for larger contribution, whereas blue one accounted for less contri- bution. Parameters included: PH, plant height; TN, number of tiller panicle^{-1}; FG, filled grain panicle^{-1}; 1000-G.wt, 1000-grain weight; GY, grain yield; SY, straw yield; GHI, grain harvest index; AE, agronomic use efficiency of K; PFP, partial factor productivity of K; N uptake, nitrogen uptake

(Adhikari et al. 2020). However, a significant effect on rice PH upon K application was obtained by Hartati and Purnomo (2018) that contradicted with our results. The difference in crop salt tolerance mechanisms, soil physiography, or the cropping patterns perhaps was the probable reasons for this contrast finding. The experiment showed a positive effect of K on the TN and PN of rice, which is supported by some previous perusals indicating higher levels of K minimized plant salt stress and increased the effective TN and PN production of rice (Zain and Ismail 2016; Bhagat et al. 2019). Increasing TN and PN per unit plant was one of the factors for rising rice yield (Banerjee et al. 2018). The study implies that rice productivity is collectively regulated by its vegetative growth as the GY noticed to be significantly correlated ($r = 0.74$, $p \leq 0.001$; $r = 0.69$, $p \leq 0.001$) with the TN and PN production, respectively. Adequate K supplies improved N uptake during the growth stages of rice, and this cumulative N uptake increased TN and PN production, which may be due to more N availability that facilitated stomatal movement and cell division of rice plant (Souri and Hatamian 2019; Kundu et al. 2020).

In saline environment, assimilation of CO_2, stomatal opening, and seed production are largely affected by the presence of excess salt ions in nutritional medium (Lima et al. 2020). The FG production of this present study was significantly affected by different K treatment that is identical to the findings reported by Islam et al. (2016). Due to K-mediated carbohydrate metabolism, higher rates of K fertilizer yield huge quantities of starch that facilitated the increasing number of FG production and heavier rice grain (Jiang et al. 2019; Khokhar et al. 2022). In our experiment, the effect of K was indifferent on the UFG and 1000-G. wt. of BRRI-47. Islam and Muttaleb (2016) also found an insignificant effect of K on rice UFG and 1000-G. wt. that is in coherence with our observation. However, a significant response of K on 1000-G. wt. was reported by a number earlier investigations (Hartati and Purnomo 2018; Li et al. 2018). We assumed that these contradict results probably caused by the variations in rice varieties, soil, climate, and cultivation practices, as majority of these studies are conducted in agricultural fields that reflected the farmer's different management conditions. Despite the fact that early rice growth phases are extremely sensitive to salinity impact, as it significantly affected both green and dry rice yield during this stage (Acosta-Motos et al. 2017), we obtained an increase in rice GY and SY with higher K doses. This could be because rice vegetative growth and yield have a clear relationship with photosynthesis rate that improved under the supply of elevated K levels (Zain and Ismail 2016; Kundu et al. 2020). Additionally, potassium is known to promote photosynthetic pigments and enzyme activity that has a

positive effect on K-mediated carbohydrate metabolism and biological activity of plants (Islam et al. 2016). We recorded that application of 100 kg K ha⁻¹ increased the grain yield by 19.13% over the current recommended dose (40 kg K ha⁻¹). This demonstrates the better response of rice in saline soil under increased K supply compared to the traditional practice. Similar to our findings, a significant variation in GY and SY of rice under different K treatments was also documented in some earlier studies (Pal et al. 2019; Mehmood et al. 2020).

DMY of BRRI-47 was significantly higher upon rising K doses. Islam et al. (2015) stated that use of inorganic K fertilizer improved rice plant growth via increasing photosynthetic capability and translocation of photo-assimilate availability of N, P, and K which consequently increased the DMY yield of rice. The result is identical to that of Banerjee et al. (2018) who concluded that K application resulted in greater DMY by increasing net photosynthesis and CO_2 assimilation at heading and ripening phases. AE_K and PFP_K are two indices that represent the efficiencies of added K. The variation in AE_K and PFP_K indices were closely connected with the amount of used fertilizer and the values trend to decrease with the increase in K rates. According to Sarangi et al. (2016), the decrease in AE_K and PFP_K values might be associated the arced return to the transformation of K to grain as the yield approaches the crop canopy at elevated K levels. The present finding is in agreement with some other studies reporting K use efficiency was positively affected by K fertilization (Li et al. 2018; He et al. 2022).

Rice response to external K application largely depends on the amount of time, the sources and mode of fertilizer application, and the relationship of K with other nutrients (Vijayakumar et al. 2019). Potassium supply at higher levels could increase N, K, and P uptake by plant (Dhillon et al. 2019; Kumar et al. 2022). In this study, an increase in macro-nutrient uptake was observed with the rising K doses. The finding is supported by several past investigations mentioning that applied K increased the nutrient acquisition in saline soil by interacting with Na (Kibria et al. 2015; Merwad 2016). In saline soil, K supplementation favors higher stomatal conductance in plants that influenced C absorption and photosynthetic product distribution to the root system (Hou et al. 2019). Therefore, it stimulates the root system growth and development and enhanced the essential nutrient uptake in saline soil. An increase in N, K, P, and S acquisition was observed in this study demonstrating that salinity issue improved with the application of K. In this experiment, 120 kg ha⁻¹ K had showed the maximum K uptake. However, the grain yield at this K level was statistically identical to treatment K_{100} and K_{80}. In this case, the higher K uptake without any significant improvement of yield could lead to luxury consumption of K (Ravichandran and Sriramachandrasekharan 2011).

Salinity tolerance is an intricate mechanism, involving the ability of plant to resist ionic and osmotic stresses produced by highly salinized soil (Chiconato et al. 2019). Consequently, the mitigation measures for salt stress should not emphasize only on reducing the Na^+ buildup in vigorous photosynthetic tissue (Shabala and Cuin 2008) but instead on K^+ homeostasis and the maintenance of a high K^+/Na^+ ratio (Barus et al. 2018). K^+/Na^+ ratio is considered a key factor for assessing crop performance in saline soil (Mohapatra et al. 2021). Under saline condition, the controlled acquisition and translocation of K^+ act as an antagonistic parameter to prevent the buildup of harmful ions like Na^+ and chloride (Cl^-) ions (Kumari et al. 2021). This occurs mostly because of decreased K^+ efflux, which causes significant intracellular retention of K^+ following the exclusion of Na^+ (Gul et al. 2019). Thus, the application of increasing K levels improved the K^+/Na^+ ratio in rice plant, which aids rice's ability to withstand salt stress. Munir et al. (2019) reported that under saline-sodic environment, application of K at higher levels could ameliorate plant physiological and biochemical traits by increasing the K^+/Na^+ ratio in plant tissues that is in line with our present study. An identical effect of K on the K^+/Na^+ ratio of plant was also recorded by Li et al. (2022).

INUE is an important factor for all nutrients to outline a point of recommendation for future development. In our study, "dilution effect" apparently accounted to maximize the IUEN and IUEK in K control pot rather that in K-treated pots. Similar to our findings, Islam and Muttaleb (2016) reported that plants trend to exert the nutrients more efficiently at biochemical level in control pot compared to the pots where the element quantity was relatively high. In this experiment, highly significant correlations between most of the agronomic components and nutrient uptake parameters of rice reflected the greater influence of K fertilization. As a whole, the increasing doses of K fertilizer contributed in lessening salinity stress by ensuring a higher K^+ to Na^+ ratio and significantly enhanced most of the growth, yield, and nutrient uptake traits of rice.

5 Conclusions

The coastal tract of Bangladesh has a very high agricultural potential. But due to salinity issue, the crop productivity in this region cannot able to meet the national average production. The findings of our present investigation imply that the current recommended K rate for rice cultivation (40 kg K ha^{-1}) is insufficient to assist obtainable rice yield potential, and the level might need an improvement to 100 kg K ha^{-1} to maximize the rice productivity and effective nutrient management. Therefore, this project will help to alleviate salinity effect and enhance rice productivity under saline condition. However, optimum K supply

for rice generally varies with the variety, yield target, and fertility status of soil. Conclusively, the study is limited to a single rice variety that does not accurately represent the overall situation. Further research is still needed to establish 100 kg ha^{-1} K as a recommended dose for improving rice production and for managing salinity impact in the coastal belts of Bangladesh.

Declarations

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