Journal of Natural Resource Conservation and Management
Vol. 7, No. 1, pp 64-79, 2026
doi: 10.51396/ANRCM.7.1.2026.64-79

Assessment of soil potassium (K) fractions and their contributions in K uptake of rice as influence by nutrient management practices in an acid Inceptisol of North East India

Seema Bhagowati[1]*, Kulendra Nath Das[2], Kaberi Mahanta[1], Samiran Pathak[1] and Dalim Pathak[1]

[1]AAU - Horticulture Research Station, Assam Agricultural University, Kahikuchi, Guwahati, Assam, India
[2]Department of Soil Science, Assam Agricultural University, Jorhat, Assam, India
**Corresponding author email: seema.bhagowati@aau.ac.in*

Received : March 07, 2026
Revised : April 28, 2026
Accepted : May 02, 2026
Published : June 30, 2026

ABSTRACT

A field experiment was carried out in winter rice for two consecutive growing seasons at demonstration farm of Krishi Vigyan Kendra, Nagaon, Assam Agricultural University, Simaluguri in the Nagaon district of Assam, North East India. Potassium (K) forms and their contribution toward K uptake were found to be affected by chemical fertilizer as well as organic manure use. The treatments of the study were, T_1- Absolute control, T_2- Microbial consortia (Azospirillium + PSB + KSB) @ 4 kg/ha, T_3- RDF (60:20:40:: N: P_2O_5: K_2O), T_4- T_3 + KSB @ 4 kg/ha, T_5- ½ RDF of K as basal + ¼ at 40 DAT + ¼ at 60 DAT, T_6- Potassium nano-fertilizer @ 100 ml/1.2 L of water (10ml/100g), T_7- T_6 + 50% RDF as top dressing at 40 DAT, T_8- ½ RDF of K as basal + Spraying 3% K solution at maximum tillering and panicle initiation stage, T_9- INM Package (50% NP + Full K + 5t/ha Enriched Compost), T_{10} - INM Package (50% NP + Full K + 5t/ha Vermicompost). Water soluble K (WSK) was the lowest among all fractions followed by exchangeable, non exchangeable and lattice K. Highly significant positive correlation values among various forms of K implied the existence of dynamic equilibrium. Yield was always better in INM plots. Grain yield exhibited significant positive correlation with NPK uptake (r = 0.891**, 0.946** and 0.970**), WSK (r = 0.785**) exchangeable K (r = 0.897**). The highest potassium use efficiency (PUE) of 51.96% was found in T_{10} treatment.

Keywords: Rice, Nutrient management, Potassium forms and uptake

INTRODUCTION

Rice (*Oryza sativa*) is a staple food for more than half of the world's population, providing more than 20% of the calories consumed worldwide, especially in East and South Asia, the Middle East, the West Indies and Latin America (Sharif *et al.,* 2014; Fukagawa and Ziska, 2019). It is cultivated worldwide in an area of 172.20 million hectares with an average productivity of 46.9 q ha^{-1} (Rice News Today, 2025). In India, with a production of 152.00 million metric tons and productivity of 43.9 q ha^{-1} rice cultivation covers an area of 52.00 million hectares (Rice News Today, 2025). With the rise of global population global demand of milled rice will increase from 496 million tons in 2020 to 555 million in 2035 approximately. To cover the whole growing population of the world substitute technologies will be required which will enhance the yield per unit land. On the other hand to keep the soil healthy with sustainable crop production a steady supply of N, P and K is must and for this balanced fertilization is need of the hour. The removal of plant nutrients, especially K, is greater under imbalanced fertilizer application in an intensive cropping system (Nava, *et al.,* 2008). But most farmers prefer to apply only nitrogenous fertilizers to crops because either of its immediate visual effects on plants or because of the greater cost of phosphatic and potassic fertilizers, resulting in an imbalanced nutrient consumption ratio (5.2:2.1:1.0) from an ideal ratio of 4:2:1 with respect to nitrogen (N), phosphorus (P), and potassium (K) (Tiwari, 2006). As a consequence, depletion of soil nutrients takes place, and K is one that is most rapidly depleted (Pasricha, 2002). This continuous negative K balance leads to soil K mining resulting loss in soil fertility and sustainability of the cultivated land. Ultimately crop genetic potential is not fully exploited.

Potassium (K) constitutes about 2.1–2.3% of the earth's crust and is the seventh most abundant element in soil (Zorb *et al.,* 2014).Therefore, soil K reserves are generally large (Schroeder, 1978). But bulk of the soil K (90–98%) is present in the mineral's crystal lattice structure for which it is directly not available for plant. To simplify the complex K dynamics in soil, based on its availability in soil, K is generally classified into four types: water-soluble, exchange-able, non-exchangeable and structural forms. Water-soluble K is immediately available for plants and microbes. Exchangeable K is electro-statically bound as an outer-sphere complex to the surfaces of clay minerals and humic substances (Barre *et al.,* 2008). Both fractions are often considered to be easily available for crops but the amount of both pools is very small. Only about 0.1–0.2% and 1–2% of the total K in soil is water soluble and exchangeable K respectively (Sparks, 1987). Non-exchangeable and structural forms are considered to be less or non-available K sources to plant. However, in long term, these pools may also contribute significantly to the plant supply (Pal *et al.*, 2001). But long-term K mining primarily depletes the exchangeable and non-exchangeable K pools in soil, and alters clay minerals to various extents (Das *et al.,* 2022).

Plants absorb K from the environment in two sources: soil and fertilizer (Zörb *et al.,* 2014). With the current increase in yield and multiple cropping index, as well as the unbalance nutrients input in traditional agriculture management practice, soil K has decreased significantly and the overall K balance has shown a deficit (Philp *et al.*, 2021). Potassium not only increases the spikelet number, percentage of filled grains, and 1000-grain weight in rice (Singh and Singh, 2017) but also increases the biotic and abiotic stress tolerance in rice. Appropriate K fertilizer application could promote plant growth and K uptake (Huai *et al.*, 2022). Application of inadequate and imbalanced fertilizer excluding potassic fertilizer is one of the reasons for diminishing K nutrition in paddy fields.

Rice is one of the most important crops in Assam, North East India. Amongst several soil related constraints, high soil acidity especially in the uplands and transitional medium lands limits nutrient availability to the crops (Bhagowati, 2021). Mixed mineralogy of soil and high rainfall of the state also resulted in variations in K status in soil. Although potassium fertilizers were applied potassium deficiency was appearing in Nagaon district of Assam frequently. It indicated that soils may be low in potassium and the applied quantity may not be sufficient to plants demand or potassium is not adequately available to plant due to its complex behaviour in these acid soils of Nagaon district (Dutta and Zaman, 2013).

It was hypothesized, for this study that K application following different nutrient management practices would improve the soil K status and finally augmentation in the yield of rice. A good amount of literature is available on different forms of K under different conditions and soil types; however, there is meager information on the relative contribution to plant K uptake (Horra *et al.,* 2000). Therefore, the present study on "Assessment of potassium use efficiency in transplanted rice" was undertaken to give a specific and clear insight into the impact of K fertilization on availability various potassium forms in soil and their contributions toward yield and potassium uptake in rice.

MATERIALS AND METHODS

The study area

This study was conducted on winter paddy during the rainy seasons of the years 2017-18 and 2018-19 at demonstration farm of Krishi Vigyan Kendra, Assam Agricultural University, Nagaon in the Nagaon district of Assam (Fig. 1) which is located in Latitude 26°357′ N and Longitude 92°640′ E and in an altitude of 50.2 m above mean sea level. The climate of this region is humid, subtropical. The total rainfall received during the crop growth period of 2017-18 was 1249.4 mm and in 2018-19 it was 830.4 mm (Fig. 2). It was observed that the quantity of rainfall was more during the early part of the crop growing season (i.e. from July to September in both the years) than that of later periods. During crop growing period of winter paddy of 2017-18 & 2018-19 the mean maximum temperatures (Max T) varied

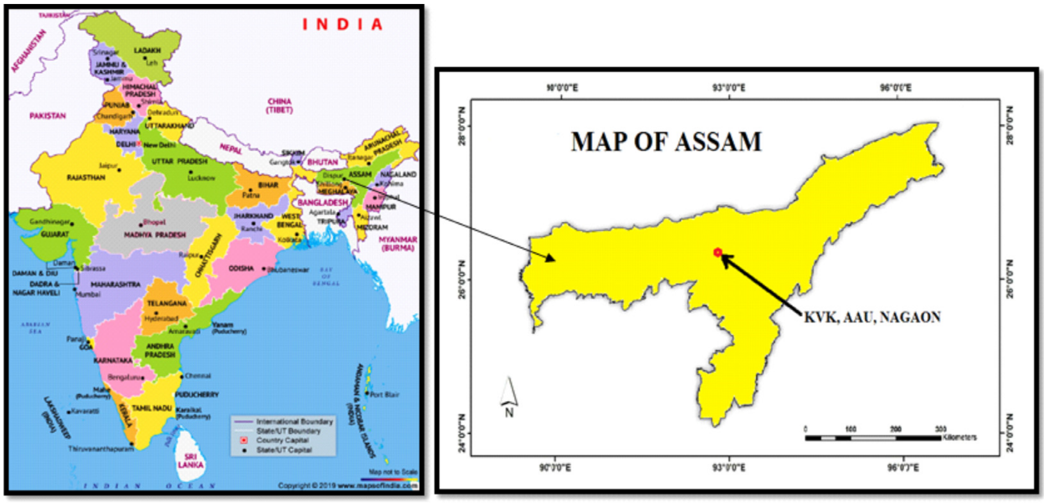

Fig. 1. Location of the experimental site

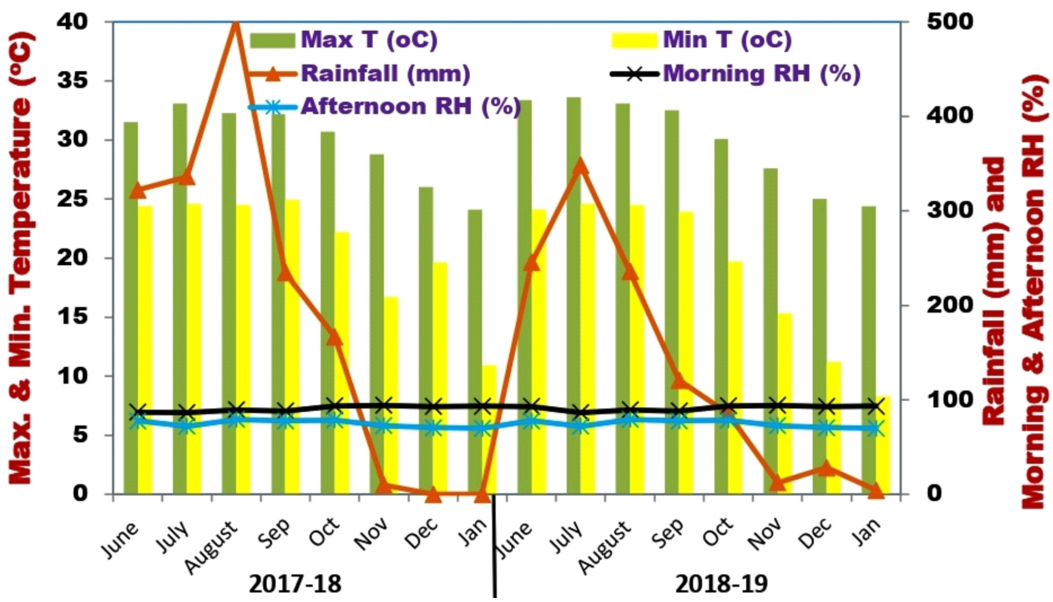

Fig. 2. Meteorological data for the period of field investigation during the years 2017–19 (*Source:* Zonal Research Station, Assam Agricultural University, Shillongani, Nagaon, India)

between 26.0°C to 33.1°C and 25.0°C to 33.6°C respectively (Fig. 2) and mean minimum temperature (Min T) varied between 16.7°C to 24.6°C and 11.2°C to 24.6°C respectively. The variation in mean percent of relative humidity (RH) in the morning hours of 2017-18 was from 94 to 86 and it was 93 to 94 in the morning hours of 2018-19. Likewise, in the evening hours of crop growth period it ranged from 72 to 79 per cent and 72 to 81 per cent respectively during 2017-18 and 2018-19.The experiments were laid out in Randomised Block Design with three replications and ten treatments. The soil of the experimental site was clay loam in texture both in surface {(0-15 cm), (37.81% sand, 25.85% silt and 36.34% clay)} and subsurface layers {(15-30 cm),(33.81%, 26.64% and 39.55%}) and initial pH of the soil measured before starting of the experiment was 4.92 in the upper surface where as in lower surface the pH was 5.14 which ranged from very strongly acidic to strongly acidic in soil reaction.

Experiment details

The field experiment was uniformly laid out for the crop rice (Var. Ranjit) in a randomized block design with three replicates and consists of 10 treatments, composed of different nutrient management options. The ten treatments chosen in this study were T_1- Absolute control, T_2- Microbial consortia (Azospirillium + PSB + KSB) @ 4 kg/ha, T_3- Recommended dose of fertilizers (RDF) @ 60:20:40:: N: P_2O_5: K_2O, T_4- T_3 + Potassium solubilizing bacteria (KSB) @ 4 kg/ha, T_5- ½ RDF of K as basal + ¼ at 40 date of transplanting (DAT) + ¼ at 60 DAT, T_6- Potassium nano-fertilizer @ 100 ml/1.2 L of water (10ml/100g), T_7- T_6 + 50% RDF as top dressing at 40 DAT, T_8- ½ RDF of K as basal + Spraying 3% K solution at maximum tillering and PI stage, T_9- INM Package (50% NP + Full K + 5t/ha Enriched Compost), T_{10} - INM Package (50% NP + Full K + 5t/ha Vermicompost). After land preparation, fertilizers were added to the soil on the day before planting as per treatment details. Nitrogen was applied as urea, P as Single Super Phosphate, K as Muriate of Potash. Twenty five days old seedlings of winter paddy were transplanted during July of 2017 & 2018. Field preparation, seed rate, spacing, cultural operations required and plant protection measures were followed as per the package of practices. The biomass yield was recorded from each plot after harvesting 4 m × 3 m plots for further investigation.

Soil and Plant samplings and Analyses

Three representatives of field-moist surface soil samples (0-20 cm) were collected using soil auger with 5 cm internal diameter before and after the crop harvest. Subsequently soil samples were air-dried, processed, ground and passed through 2 mm sieve and were pooled together to make a composite sample for each treatment and replication ensuing standard protocols. Finally, the samples were preserved in polythene bags which were used for analysis of physico-chemical properties and various forms of K. Initial soil samples collected before initiation of the experiment were also subjected to further soil analysis. The important soil characteristics analyzed were enlisted below (Table 1). Plant samples of grain and straw were digested in a nitric–perchloric digest [10 mL HNO_3: 2 mL perchloric acid ($HClO_4$)], and the final volume was made to 100 mL for determination of K. The concentration of K was measured using a flame photometer after suitable dilutions.

Statistical analysis

The data obtained from different observations during conducting the study were analyzed statistically by using Fisher's method of analysis of variance in Randomized Block Design as outlined by Panse and Sukhatme (1985). The least significant difference (LSD) at $\alpha = 0.05$) was used to compare the treatment means. Significance or non-significance of the variance due to various treatment effects were determined by calculating respective 'F' values. Pearson's correlation was performed to determine the relations between the soil chemical properties and nutrient status with the respective crop yield. Stepwise multiple linear regression analysis was accomplished using R studio to explore the significance and attribution of soil chemical properties and nutrient status in the prediction of crop yield in the sequence.

RESULTS AND DISCUSSION

Forms of K

Water soluble K (WSK)

The knowledge about different forms and availability of K is must while studying the response of crops to K because K supply to crop plants is a complex phenomenon involving relationships among various K fractions in soil (Dotaniya *et al.,* 2023).

As water soluble K is taken away by crops as well as prone to leaching under the influence of high rainfall intensity, its contents in present soil were the lowest among all four fractions (Bhagowati, 2021).

Before establishment of the experiment, the initial water soluble K (Table 1) of the test plot was 9.20 mg kg^{-1} in the upper layer (0 to 15 cm) and 5.40 mg kg^{-1} in the lower layer (15 to 30 cm) of the soil. After completion of the field study by incorporating different treatments consecutively for two years , pooled data on water soluble K in postharvest soil showed that the value of it in the soil ranged from 8.17 mg kg^{-1} to 21.35 mg kg^{-1} (Table 2). The water soluble K was highest with 21.35 mg kg^{-1} in the plot receiving INM Package (50% NP + Full K + 5t/ha Vermicompost) i.e. T_{10} and was the lowest 8.17 mg kg^{-1} in the control plot (Table 1). The amount of water soluble K was low in the treatments T_6 - Potassium nano-fertilizer @ 100 ml/1.2 L of water (10ml/100g) [8.99 mg kg^{-1}], T_7 - T_6 + 50% RDF as top dressing at 40 DAT [10.72 mg kg^{-1}] & T_8 - ½ RDF of K as basal + Spraying 3% K solution at maximum tillering and PI stage [13.12 mg kg^{-1}]. On contrarily, T_2, T_3, T_4, T_5 and T_9 contained higher

Table 1. Initial chemical characteristics of the experimental soils

Soil characteristics	Particulars	Values of soil parameters (depth wise)		Methodology and citation
		0-15 cm	15-30cm	
Soil chemical properties	pH (1:2.5 soil water ratio)	4.92	5.14	Jackson (1973)
	EC (dSm^{-1}) (1:2.5 soil water ratio)	0.19	0.21	Jackson (1973)
	OC (%)	0.91	0.65	Wet digestion method, Walkley and Black (1934)
	CEC (cmol (p+) kg^{-1})	8.40	7.50	Schollenberger and Simon (1945) as outlined by Jackson (1973)
Macronutrients	Av. N (kg ha^{-1})	296.00	183.10	Alkaline potassium permanganate method, Subbiah and Asija (1956)
	Av. P_2O_5(kg ha^{-1})	34.78	24.25	Bray's method, Jackson (1973)
	Av. K_2O (kg ha^{-1})	134.94	113.11	Neutral normal ammonium acetate extraction method, Jackson (1973)
Secondary nutrients	Exch. Ca (cmol (p+) kg^{-1})	2.41	2.30	Complexometric titration method, Jackson (1973)
	Exch. Mg (cmol (p+) kg^{-1})	1.64	1.03	
Different forms of K	Exch-K ($mgkg^{-1}$)	41.00	28.40	Exchangeable K = Available K – Water soluble K
	Water Soluble -K ($mgkg^{-1}$)	9.20	5.40	Grewal and Kanwer(1966)
	Non Exch-K (gkg^{-1})	1.020	1.454	Wood and De Turk (1940)
	Lattice K (gkg^{-1})	8.856	10.222	AEA methodPiper (1966)
	Total K (gkg^{-1})	9.480	10.885	hydrofluoric acid–perchloric acid–nitric acid digestion methodPratt(1965)

Table 2. Status of Water soluble K and Exch. K (mg kg^{-1}) as affected by various treatments in postharvest soil samples

Treatments	Water soluble K			Exch. K		
	2017	2018	Pooled	2017	2018	Pooled
T_1- Absolute control	9.00	7.33	8.17	38.67	36.67	37.67
T_2 - Microbial consortia (Azospirillum + Potassium solubilizing bacteria (PSB) + KSB) @ 4 kg/ha	14.80	15.50	15.15	55.67	55.33	55.50
T_3 - RDF (60:20:40:: N: P_2O_5: K_2O)	18.20	17.00	17.60	60.33	57.00	58.67
T_4 - T_3 + KSB @ 4 kg/ha	20.10	18.17	19.14	59.33	60.67	60.00
T_5 - ½ RDF of K as basal + ¼ at 40 DAT + ¼ at 60 DAT	19.70	20.67	20.19	61.67	62.47	62.07
T_6 - Potassium nano-fertilizer @ 100 ml/1.2 L of water (10ml/100g)	9.30	8.67	8.99	42.67	45.60	44.14
T_7 - T_6 + 50% RDF as top dressing at 40 DAT	10.10	11.33	10.72	45.20	60.67	52.94
T_8 - ½ RDF of K as basal + Spraying 3% K solution at maximum tillering and PI stage	12.70	13.53	13.12	54.67	53.33	54.00
T_9 - INM Package (50% NP + Full K + 5t/ha Enriched Compost)	19.60	20.00	19.80	64.10	65.67	64.89
T_{10} -INM Package (50% NP + Full K +5t/ha Vermicompost)	21.70	22.00	21.35	65.67	66.33	66.00
SED±	3.40	3.70	2.41	4.60	4.62	3.10
CD (5% level)	5.64	5.02	3.60	9.66	9.71	6.50

amount of water soluble K with absolute amount of 15.15 mg kg^{-1}, 17.60, 19.14, 20.19, and 19.80 mg kg^{-1}, respectively, as compared to control plot (Table 2). Water soluble K, in general, was higher in the treatments receiving INM package, microbial consortia and 100% K fertilizer doses.

Water soluble K, in general, was higher in the treatments receiving INM package and 100% K fertilizer doses alone or in combination with KSB. Higher value of this form in the above treatments is the results of readily available K supplied through K fertilizer as well as the amiable edaphic situation created by added organic matter. Sharma *et al.,* (2013) found that incorporation of organic residues collected from lantana (10 to 30 Mg ha^{-1}) over the last 12 years has resulted in a significant build-up of water-soluble K in maximum amount (10 to 32%) among all other K forms studied in Himachal Pradesh. Such an increase in the content of water-soluble K due to addition of organic material has been also reported by Lakaria *et al*., (2012). According to Kumar and Narwal (2016) the increase in water soluble-K content is attributed to the additive effect of this form of K with increasing levels of FYM in soil. Lakaria *et al.,* (2012) reported that application of 100% NPK enhanced water-soluble K concentration significantly in surface soil compared to control treatments under Long-Term Maize (*Zea mays* L.), Wheat (*Triticumaestivum* L.), Cowpea (*Vignaunguiculata* L.) rotation on an Inceptisol. On the other hand, Mesha Nand *et al.,* (2019) found that water soluble potassium was significantly higher in treatments receiving potassium in split application than treatment receiving total potassium as basal. According to Wani *et al.,* (2014), with rising levels of potassium application there was boost in the content of water soluble potassium in soil and it was found slightly more in the treatments where K was applied in two splits as compared to single basal application in wheat crop. Again the study conducted by Ghadam Khani *et al*., (2019) showed that soils treated with *Enterobacter cloacae* Rhizo_33*,* either addition of potassium or not, sustain an elevated amount of exchangeable K (337 mg kg^{-1}) and water soluble K (1·25 and 1·31 meq L^{-1} with and without K application, respectively).

Exchangeable K

The initial exchangeable K content of the experimental plot was 41.00 mg kg^{-1} (Table 1) in the upper layer (0 to 15 cm) of the soil and 28.40 mg kg^{-1} in the lower layer (15 to 30 cm). The concentration of exchangeable K was numerically lesser in sub surface soil as compared to surface soil which may be due to comparatively more weathering, vegetation and supply of K from organic residues in surface layer than in subsurface layers After conducting the experiment by incorporating ten different treatments, the highest value of exchangeable K was found in T_{10} -INM Package (50% NP + Full K + 5t/ha Vermicompost) followed by T_9 - INM Package (50% NP + Full K + 5t/ha Enriched compost), T_5 -½ RDF of K as basal + ¼ at 40 DAT + ¼ at 60 DAT, and T_4- T_3 + KSB @ 4 kg/ha, T_3 - RDF (60:20:40:: N: P_2O_5: K_2O), T_2 - Microbial consortia (Azospirillum + PSB + KSB) @ 4 kg/ha with their respective absolute values of 66.00 mg kg^{-1}, 64.89 mg kg^{-1}, 62.07 mg kg^{-1}, 60.00 mg kg^{-1}, 58.67 mg kg^{-1} and 55.50 mg kg^{-1} and the lowest was in control i.e. 37.67 mg kg^{-1} (Table 2). Exchangeable K corresponded to the amount of chemical K fertilizer applied and also to the INM package including microbial consortia.

According to Wani *et al.,* (2014) all forms of potassium *viz*., water-soluble, exchangeable, available, boiling HNO_3 extractable and lattice increased with increasing levels of potassium and when potassium was applied @ 80 kg K_2O ha^{-1} in two equal splits except for lattice K which was maximum when potassium was applied @ 60 kg K_2O ha^{-1}. Ghadam Khani *et al*., (2019) showed that soils treated with *Enterobacter cloacae* Rhizo_33*,* either receiving potassium or not, maintain a higher amount of exchangeable K (337 mg kg^{-1}) and water soluble K (1·25 and 1·31 meq L^{-1} with and without K application respectively). Basak and Biswas (2009) revealed that treatments receiving mica along with bacterial strain *Bacillus mucilaginosus* enhanced water-soluble K in Alfisols of Hazaribag and Bhubaneswar, India. According to Black (1968) addition of FYM could increase the CEC of the soil, which can hold more exchangeable K and convert K from non exchangeable form to exchangeable form, consequent to mass action effect. Similar finding was also noticed by Mazumdar *et al.* (2014) and Kumar and Narwal (2016).

Non Exchangeable K

Non-exchangeable K is normally considered as slowly released K in soil for the plants under stress condition. The amount of soil non-exchangeable K in the soil before starting of the experiment (Table 1) was 1.020 g kg^{-1} and 1.454 g kg^{-1}in the upper surface (0 to 15 cm) and in the lower surface of the soil (15 to 30 cm) respectively. After conducting the experiment consecutively for two years the two years pooled data (Table 3) showed that maximum amount of non exchangeable K was found in the treatment T_3 (1015.50 mg kg^{-1}) receiving 100% RDF. The non-exchangeable K contents varied from 701.00 mg kg^{-1} to 1015.50 mg kg^{-1} in the different treatments indicating reserve K in the soil possibly because of clay content. On the other hand, plots receiving different K treatments with or without INM (T_2, T_4, T_5, T_6, T_7, T_8, T_9 and T_{10}), the amount of non exchangeable K were found to be decreased than the value recorded under treatment T_3. In general non-exchangeable K was found to be higher in all other treatments compared to the control plot.

But as compared to initial (1.020 mg kg^{-1}) value of non-exchangeable K, lower values were recorded in all the treatments with different levels of potassium in post harvest soils. The possible cause of this might be because of replenishment of water soluble and exchangeable K in soil by release of K from non-exchangeable K and through added fertilizers. The forms of potassium exhibit a dynamic equilibrium among them in the soil. This finding is in accordance with the finding of Swamanna (2015) and Srinivasa *et al.* (2019). Dynamic equilibrium is affected when applied K is either taken up by plants or leached into lower soil horizons or converted into unavailable form. Under this situation, non-exchangeable K plays an important role by releasing K in to exchangeable and solution forms. Similar reports were also made by Rajeevana and Kavitha (2018). It was also observed that non-exchangeable K content was lower in INM treated plots than other treatments. The plausible reason for this could be that in the INM treatment, due to accumulation of organic matter, there would be a shift in CEC sites toward divalent selectivity (Salmon 1964), which would decrease percentage K saturation of the CEC, resulting in the shift of equilibrium of non-exchangeable K ⟵⟶ exchangeable K in favor of the latter, thereby releasing more non-exchangeable K. Similar finding were also noticed by Mazumdar *et al.,* (2014). According to Srinivasa *et al.,* (2019) added FYM might have decreased the fixation of potassium in soil clay lattice by releasing the organic acids during mineralization of FYM and uptake of potassium by crop might be from the fixed portion of soil potassium. Further it can be presumed that the quantity of K released from FYM could not meet out the requirement of the crops (Kumar, 2016).

Lattice K

The initial lattice K content was 8.856 g kg^{-1} in the in the upper surface (0 to15 cm) and 10.222 g kg^{-1} in the lower surface of the soil (15 to30 cm). After two years of conducting the experiment, in the different treatment blocks, the two years pooled data on lattice K ranged from 8736.17 mg $kg^{-1}$to 9155.84 mg kg^{-1} (Table 3). The highest value of lattice K was observed in the plot receiving 100% RDF (60:20:40: N: P_2O_5: K_2O) followed by treatment T_5(9119.67 mg kg^{-1}) where ½ RDF of K as basal + ¼ at 40 DAT + ¼ at 60 DAT was applied. Application of only chemical fertilizers responsible for formation of structural K, hence applied K fertilizer is stored in soil mineral lattice leading to lesser release of K. This finding was in accordance with the finding of Chanu (2015). Lattice K increased in treatments $T_{2,}$ $T_{4,}$ $T_{6,}$ T_7 and T_8 as compared to control. In treatments $T_{6,}$ T_7 and T_8 recommended dose of K was not applied. In the treatments T_2 microbial consortia containing Azospirillum + PSB + KSB @ 4 kg/ha and $T_{4,}$ RDF with K solubilising bacteria were applied. In the treatments T_9 and T_{10} containing INM components the lattice K was found in an increasing order from the initial K. Slight build up in mineral K by addition of organic residue had also been reported by Sharma and Verma (2000) and Divya (2013). Application of higher dose of potassium with vermicompost/ enriched compost might have increased the mineral K in the soil, which may be due to weathering of K bearing minerals by organic acids released during decomposition of organic manures also improves the lattice K content in these plots. These results are in accordance with Kundu *et al.,* (2014).

Sharma *et al.,* (2013) revealed that application of higher dose of potassium with FYM might have increased the mineral K in the soil, which may be due to weathering of K bearing minerals by organic acids released during decomposition of FYM and organic manures also improves the soil structure.

Total K

Before the set up of the experiment, the initial total K of the upper (0 to15 cm) and lower layer (15 to 30 cm) were 9.480 g kg^{-1} and 10.885 g kg^{-1}, respectively. Two years pooled data on the total K content of soils under various treatments varied from 9362.50 mg $kg^{-1}$to 11015.50 mg kg^{-1} (Table 3). The plot receiving INM (T_{10} = 100% NP + Full K + 5 ton/ha Vermicompost) contained the highest value while the control plot exhibited the lowest (Table 3). A significant decrease in the soil total potassium was observed in the control plot. This may be due to lack of external application of potassic fertilizers and large amount of contribution/removal from the lattice clay mineral due to rice cultivation in the plot. But the values of total K in the treatments receiving 100% RDF (T_3) and also T_5 -½ RDF of K as basal + ¼ at 40 DAT + ¼ at 60 DAT were also high in comparison to T_6, T_7 and T_8. In treatments where 100% K fertilizers alone or in combination with INM components were applied for 2 years continuously observed an increase in total K. These treatments are T_9 - INM (100% NP + Full K + 5

Table 3. Status of Non-Exch. K, Lattice K and Total K (mg kg^{-1}) as affected by various treatments in postharvest soil samples

Treatments	Non-exch. K			Lattice K			Total K		
	2017	2018	Pooled	2017	2018	Pooled	2017	2018	Pooled
T_1- Absolute control	784.33	617.67	701.00	8738.67	8733.67	8736.17	9338.33	9386.67	9362.50
T_2 - Microbial consortia (Azospirillum + PSB + KSB) @ 4 kg/ha	819.00	852.33	835.67	8780.00	8763.33	8771.67	9578.00	9565.67	9571.84
T_3 - RDF (60:20:40:: N: P_2O_5: K_2O)	1022.33	1008.67	1015.50	9157.67	9154.00	9155.84	10342.00	10286.33	10314.17
T_4 - T_3 + KSB @ 4 kg/ha	904.67	842.33	873.50	8813.33	8861.67	8837.50	9920.00	9935.00	9927.50
T_5 - ½ RDF of K as basal + ¼ at 40 DAT + ¼ at 60 DAT	919.00	927.00	923.00	9127.67	9111.67	9119.67	10218.33	10209.00	10213.67
T_6 - Potassium nano-fertilizer @ 100 ml/ 1.2 L of water (10ml/100g)	731.33	736.67	734.00	8774.33	8765.67	8770.00	9553.00	9618.33	9585.67
T_7 - T_6 + 50% RDF as top dressing at 40 DAT	749.33	744.00	746.67	8815.00	8805.33	8810.17	9665.30	9619.33	9642.32
T_8 - ½ RDF of K as basal + Spraying 3% K solution at maximum tillering and PI stage	759.67	771.33	765.50	8853.33	8841.67	8847.50	9686.67	9712.00	9699.34
T_9 - INM Package (50% NP + Full K + 5t/ha Enriched Compost)	784.00	780.33	782.17	9085.00	9090.00	9087.50	10991.00	10999.67	10995.34
T_{10} - INM Package (50% NP + Full K +5t/ha Vermicompost)	837.67	830.00	833.84	9106.67	9110.67	9108.67	11008.67	11022.33	11015.50
SED±	49.52	60.74	36.75	48.70	45.37	31.36	66.44	51.73	39.39
CD (at 5% level)	104.05	126.98	77.01	102.31	95.32	65.88	139.58	108.68	82.75

ton/ha Enriched compost [10995.34 mg kg^{-1}], T_3 - 100% RDF [10314.27 mg kg^{-1}], T_5 -½ RDF of K as basal + ¼ at 40 DAT + ¼ at 60 DAT [10213.67 mg kg^{-1}], and T_4 - T_3 + KSB @ 4 kg/ha [9927.50 mg kg^{-1}].

The content of total K increased significantly with annual INM incorporation plots over only half dose of inorganic K fertilizers and nano fertilizers alone or in combination with 50% K fertilizer treated plots or 100% biofertilizer incorporation plot. Similarly, increased levels of fertilizers also brought about significant increase in total K content. As enriched compost/vermicompost and potassic fertilizer contain K, annual applications over the last 2 years might have resulted in buildup of total K in soils (Sharma *et al.,* 2013). Organic manuring is associated with minimizing the losses from leaching by retaining K^+ ion on exchange sites, solubilizing the insoluble component through the action of organic acids released during decomposition and minimizing losses due to fixation in 2:1 minerals. Therefore, applications of vermicompost/enriched compost increase the total K content of the soil. A slight increase in values of total K was observed with the addition of rice straw and FYM reported by Kaur and Benipal (2006). Organic manuring is associated with minimizing the losses from leaching by retaining K^+ ion on exchange sites, solubilizing the insoluble component through the action of organic acids released during decomposition and minimizing losses due to fixation in 2:1 minerals. Therefore, applications of manures increase the total K content of the soil. Similar finding was also noticed by Kumar and Narwal (2016) under long term pearl millet-wheat cropping system.

Increased levels of fertilizers brought about significant increase in total K content *i.e.* in the treatments where application of full dose of recommended fertilizers were done the total K tended to increase in amount. These findings were in accordance with the findings of Chanu (2015).

Table 4. Coefficients of correlation among different forms of potassium, grain yield and K uptake

Forms of K	WSK	Ex K	Av K	Non Ex K	Lattice K	Total K	Grain yield	K uptake
WSK	1							
Ex K	0.947**	1						
Av K	0.978**	0.993**	1					
Non Ex K	0.685*	0.602	0.637*	1				
Lattice K	0.801**	0.769**	0.791**	0.697*	1			
Total K	0.827**	0.826**	0.839**	0.397	0.865**	1		
Grain yield	0.785**	0.897**	0.867**	0.516	0.660*	0.694*	1	
K uptake	0.846**	0.924**	0.908**	0.459	0.722*	0.797**	0.970**	1

Relationship between K Forms

Water soluble K is significantly correlated (Table 4) with exchangeable K (r=0.947**), non-exchangeable K (r=0.685*), total K (r=0.827**) and lattice K (r=.801**). These findings are in agreement with several earlier reports (Saini and Grewal, 2014, Kumar *et al*., 2017 and Dhakad *et al*., 2017). This shows that the water soluble K is governed by exchangeable, non-exchangeable, lattice and total K. On the other hand exchangeable K was found to be highly and significantly correlated (Table 4) with available K (r= 0.993**), non-exchangeable K (r=0.602*),) lattice K (r = 0. 769**) and total K (r = 0.826*). These findings are similar to those of Singh *et al.,* (2001), Gangopadhyay *et al*., (2005), Saini and Grewal (2014). Exchangeable K mostly corresponded to both the INM treatments, as well as amount of chemical K fertilizer applied. As stated earlier, addition of organic matter might have resulted in an increase in organic colloids, which in turn, enhance the cation exchange capacity of the soil, thereby giving a strong sink for K+ (Navneet and Benipal, 2006). Sharma *et al*., (2013) observed 18 to 27% increases in exchangeable K due to addition of organic material (lantana) in soil. The non-exchangeable K was also positively and significantly correlated (Table 4) with available K (r=0.637*), water soluble K (r=0.685*) but correlation is in significant with exchangeable K (r=0.602). Similar results were reported by Kundu *et al.,* (2014) and Bhalerao *et al*., (2018). This means that whenever fixed potassium was released, it moves down, via steps, to available forms, for plant uptake. Total K had significant positive correlation with available K (r=0.839*), water soluble K (r=0.827**), exchangeable K (r=0. 826**) and lattice K (r=0.865**). It showed insignificant but positive correlation with non-exchangeable K (r=0.397). The above relationship revealed that availability of K to crops would be determined by the pools of exchangeable, non-exchangeable and total K. Similar results were also obtained by Yadav *et al.,* (1999) and Kundu *et al.,* (2014). Maximum amount of lattice and total K was recorded in plot receiving 100% K fertilizer along with N & P fertilizers and INM components while lowest was recorded in plots which did not received K fertilizer indicating that the applied K fertilizer is responsible for formation of K lattice. This in turn increased total K in soil.

Inter-relation of different forms of soil potassium

The inter-relationship of various forms of K in soil was interpreted with correlation study amongst them and these values are presented in Table 4 and depicted in Fig. 3 & 4. Perusal of the Pearson coefficient values revealed that a highly significant positive correlation of water soluble K was existed with exchangeable K (r=0.947**), available K (r= 0.978**), non-exchangeable K (r=0.685*) and lattice K (r=0.801*). Similarly, all other forms of soil K *viz.,* exchangeable K, available, non-exchangeable, lattice and the total K were correlated significantly with each other at 1% and 5% level of significance. This indicated their co-existence in dynamic equilibrium in this soil.

The partial contributions of different forms of K in soil, alone or in combination, towards the variability of K forms were computed using stepwise multiple regression analysis and the equations are presented in Table 5. The results showed that the maximum variation in water soluble K was contributed by exchangeable K alone (88.3%) while inclusion of total K and total K + lattice K in the equation could not enhance the contribution markedly. Soil K forms together contributed 88.7% variation towards water soluble K. Similarly, water soluble K contributed 88.3% variation in exchangeable K. Addition of Total K did not changed the contribution markedly while water soluble K + total K + lattice K together contributed

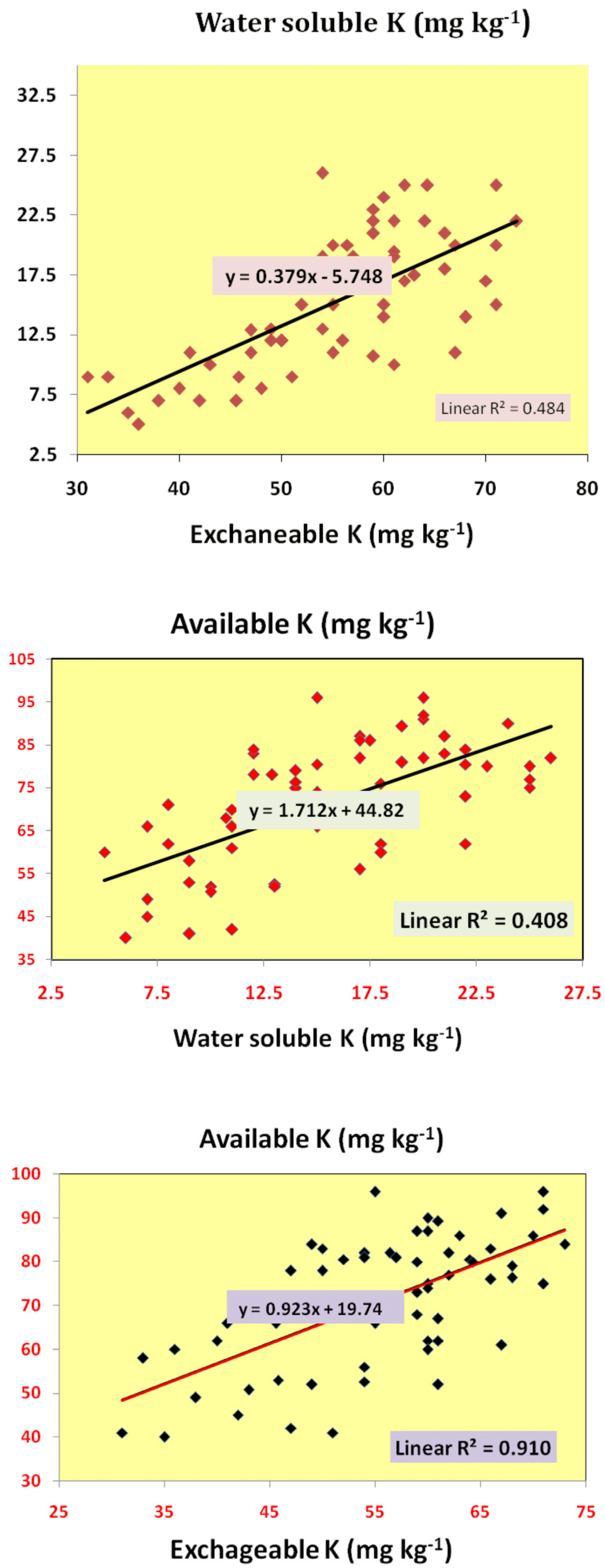

Fig. 3. Correlations amongst various K forms (water soluble, exchangeable-K and available-K)

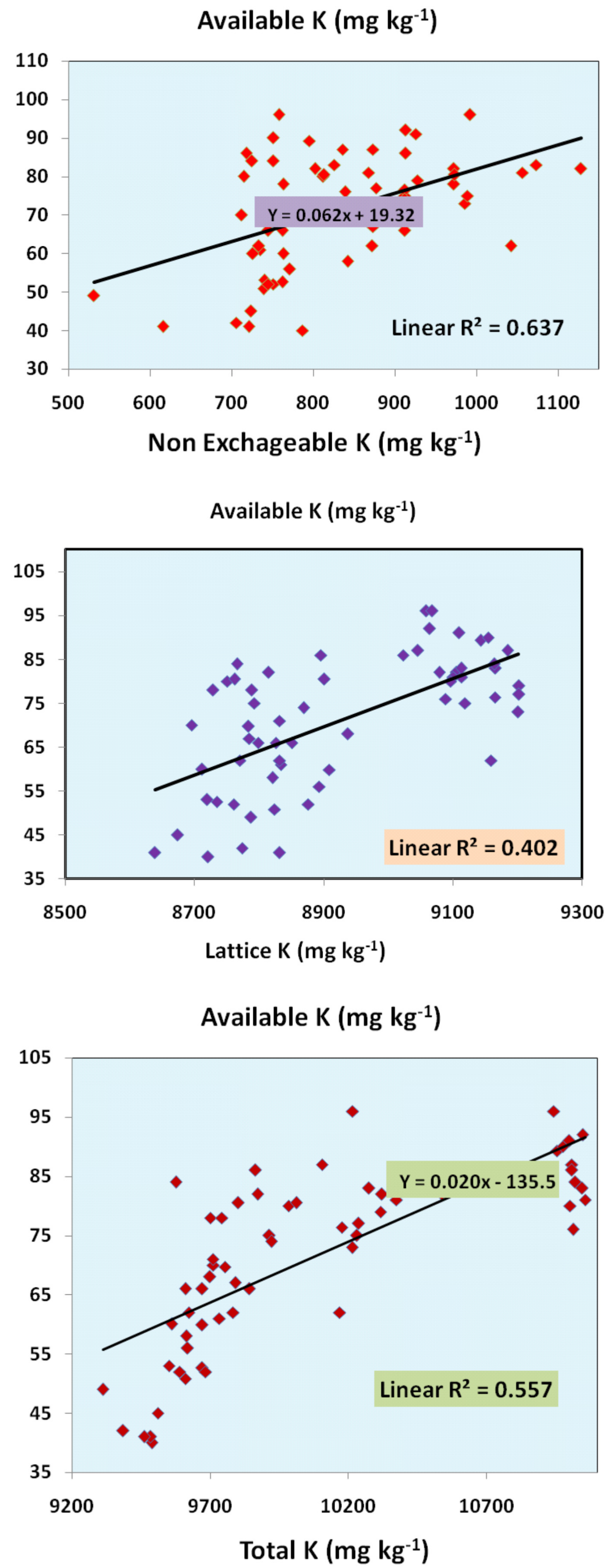

Fig. 4. Correlation amongst various K forms (available-K, Non-exchangeable K, lattice-K and total K)

Table 5. Stepwise multiple regression analysis

Regression equation	R^2
WSK = -13.318 + 0.517*Ex K	0.883
WSK = -21.551+0.453*Ex K +0.001*Total K	0.884
WSK = -53.351+0.438*Ex K + 1.780e-4*Total K +0.005*Lattice K	0.886
WSK = 18.399+0.311*Ex K+0.009*Total K -0.008*Lattice K + 0.018*Non Ex K	0.887
Ex K = 28.858+1.733*WSK	0.883
Ex K = 11.080+1.525*WSK+0.002*Total K	0.884
Ex K = 37.510+1.561*WSK+0.003*Total K -0.009*Lattice K	0.895
Ex K = 30.470+1.599*WSK+0.002*Total K -0.002*Lattice K-0.002*Non Ex K	0.896
Non Ex K = 614.001+13.427*Lattice K	0.403
Non Ex K = -2693.964+0.394*Lattice K+16.795*WSK	0.422
Non Ex K = -2161.191+0.323*Lattice K +1.737*WSK +2.369*Ex K	0.463
Non Ex K = -3027.516+0.634*Lattice K -0.416*Ex K+16.797*WSK -0.204*Total K	0.729
Lattice K = -1538.452+0.002*Total K	0.916
Lattice K = 6421.431+0.249*Total K+10.304*WSK	0.926
Lattice K = 6960.958+0.191*Total K +14.304*WSK-3.208*Ex K	0.941
Lattice K = 5532.577+0.276*Total K-12.377*WSK-0.681*Ex K+1.032*Non Ex K	0.959
Total K = -16721.278+2.998*Lattice K	0.916
Total K = -8138.515+1.958*Lattice K +45.041*WSK	0.921
Total K = -8486.443+1.919*Lattice K+5.339*WSK+23.532*Ex K	0.933
Total K = -12704.245+2.708*Lattice K+56.363*WSK+6.609*Ex K -3.248*Non Ex K	0.940

89.5%. All the forms of K contributed 89.6% variation jointly to exchangeable K.

In case of non-exchangeable K, the highest contribution was obtained from water soluble K *i.e.* 40.3% and the contribution towards the variability improved to 42.2% by addition of water soluble K. Inclusion of exchangeable K in the model improved the variability upto 46.3%; however, all the forms of K collectively contributed about 72.9% towards non-exchangeable K.

In the variability of lattice K, the highest contribution was solely imparted by total K (91.6%) while addition of other forms of K did not contributed much towards lattice K. Combined contribution of various forms of soil K was 95.9%. On the other hand, the lattice K exclusively contributed the maximum contribution of 91.6% towards total K in this soil. No remarkable change was observed in per cent contribution of total K in inclusion of other forms of K. K forms jointly contributed about 94.0% towards total K.

Effect of Potassium management on yield of rice

It is found that the application of different doses of potassium with fertilizers, manures and biofertilizers were effective to maximize the yield and yield components *viz.*, plant height, number of tillers, number of panicle, its length and weight, number of grains per panicle (filled and unfilled), test weight (1000-grain), grain and straw yield of rice (Var. Ranjit). Adoption of INM package (100% NP + Full K + 5 ton /ha vermicompost) are the balance sources of nutrients and it has produced the highest grain and straw yield. Moreover, the yield was considerably higher as compared to that obtained from the no application of the recommended doses of K fertilizer.

The results on Duncan's Multiple Range Test (DMRT) on two years pooled data of grain and straw yield of rice var. Ranjit are presented in Table 6. Perusal of the results revealed that the highest grain yield of 56.22 q ha^{-1} was found in the plot receiving 50% NP + Full K + 5 t/ha Vermicompost (T_{10}) while the lowest of 27.01 q ha^{-1} in the control plot (T_1). Both the yields differed significantly from each other while all other treatments had statistically significant difference either from control or from T_{10}. Treatment T_9 (100% NP + Full K + 5 ton/ha Enriched compost) [54.98 q ha^{-1}] and T_5 - ½ RDF of K as basal + ¼ at 40 DAT + ¼ at 60 DAT [53.88q ha^{-1}], were statistically identical with T_{10}.

As discussed above, the availability of potassium increased throughout the crop growing season under INM practices. The increase in yield with these treatments was attributed to panicle length, grain per panicle and seed weight. Grain yield is a function of number of panicle bearing tillers per hill and grain per panicle besides grain weight (Hasanuzzaman *et*

Table 6. Duncan's Multiple Range Test (DMRT) for grain yield and straw yield

Treatments	Grain Yield (q ha^{-1})			Straw Yield (q ha^{-1})		
	2017	2018	Pooled	2017	2018	Pooled
T_1- Absolute control	27.27	26.75	27.01^f	68.65	72.12	70.39^f
T_2 - Microbial consortia (Azospirillum + PSB + KSB) @ 4 kg/ha	44.85	47.35	46.1^e	118.15	121.82	119.99^{de}
T_3 – RDF (60:20:40::N:P_2O_5: K_2O)	51.3	50.73	51.02^d	127.36	131.15	129.26^c
T_4 - T_3 + KSB @ 4 kg/ha	50.45	53.60	52.03^{cd}	132.95	136.57	134.76^b
T_5 - ½ RDF of K as basal + ¼ at 40 DAT + ¼ at 60 DAT	53.14	54.62	53.88^{abc}	136.32	140.28	138.30^a
T_6 - Potassium nano-fertilizer @ 100 ml/1.2 L of water (10ml/100g)	44.54	46.38	45.46^e	118.85	124.26	121.56^d
T_7 - T_6 + 50% RDF as top dressing at 40 DAT	44.92	47.11	46.02^e	121.5	115.33	118.42^e
T_8 - ½ RDF of K as basal + Spraying 3% K solution at maximum tillering and PI stage	52.44	53.70	53.07^{bcd}	132.06	136.35	134.21^b
T_9 - INM Package (50% NP + Full K + 5t/ha Enriched Compost)	54.85	55.11	54.98^{ab}	137.45	139.17	138.31^a
T_{10} -INM Package (50% NP + Full K +5t/ha Vermicompost)	55.92	56.51	56.22^a	139.05	143.03	141.04^a

Note: Similar alphabet indicates no significant difference between the treatments

al., 2010). These yield attributes were found maximum in the treatment T_{10} followed by T_9. As a result highest grain yield was found in T_{10} followed by T_9. Similar finding was noticed by Iqbal *et al*., (2019). Harish *et al*., (2017) observed highest grain and biological yield in INM practice. Moreover, the increased K supply level promoted the uptake of other nutrient by producing electric gradient across the plasma membrane of root cells which ultimately helped in increasing grain yield. Similar finding was accordance with the finding of Wakeel *et al.,* (2017). According to Choudhary and Suri (2014) and Dass *et al.,* (2017) better performance of rice varieties under INM practice was probably because of good crop establishment and better anchorage of roots.

Perusal of the results of Duncan's Multiple Range Test (DMRT) for of two years pooled data revealed that the straw yield also followed the same pattern as that of grain yield in this experiment (Table 6). The highest straw yield was found in treatment T_{10} - 50% NP + Full K + 5 t/ha Vermicompost (141.04 q ha^{-1}) and control being the lowest straw yielder (70.39 q ha^{-1}).

The straw yield also followed the same pattern as that of grain yield. As discussed above availability of potassium in critical growth stages through different nutrient combination treatments enhanced the straw yield also.

Relation between forms of K, grain yield and K uptake

The results on Duncan's Multiple Range Test (DMRT) for grain yield and NPK uptake of rice var. Ranjit revealed that the highest grain yield of 56.22 q ha^{-1} was found in the plot receiving INM treatment (T_{10} = 50% NP + Full K + Vermicompost @ 5 ton ha^{-1}) while the lowest of 27.01 q ha^{-1} in the control plot (T_1). Both the yields differed significantly from each other while all other treatments had statistically significant difference either from control or fromT_{10} but there was no significant variation amongst them. All they were at par with each other.

The relationship of various fractions of K and K uptake towards grain yield was explained by correlation study (Table 4 and Fig. 5 to 9). Among the different K fractions exchangeable K was the most important K fraction which is highly positive correlated with grain yield (r^2=0.897**). The second most important fraction toward grain yield was water soluble K (r^2=0.785**). Their positive and significant correlation values indicate that amongst all the fractions of K exchangeable K and water soluble K had positive effect to grain yield. This might be due to the accumulation of K through addition of INM

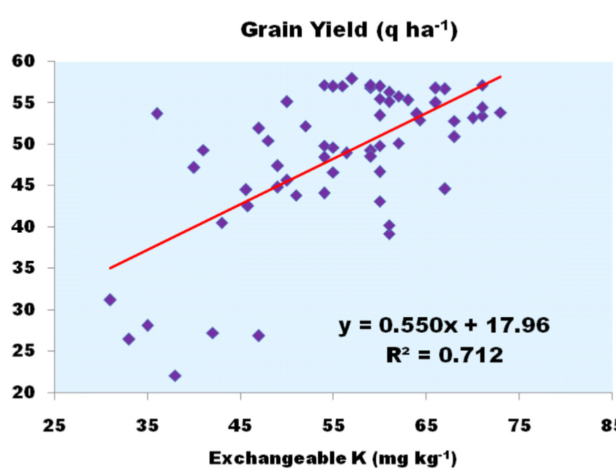

Fig. 5. Correlation plot of exchangeable K – grain yield

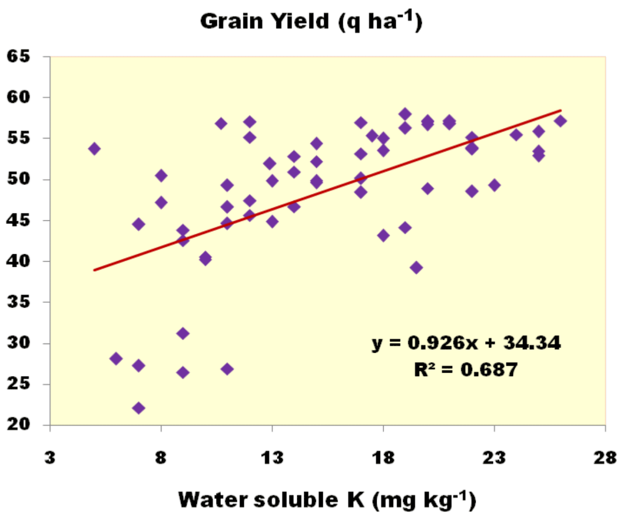

Fig. 6. Correlation plot of water soluble K - grain yield

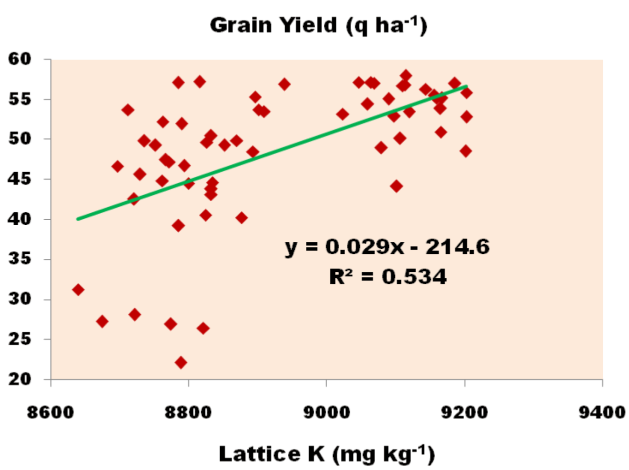

Fig. 7. Correlation plot of Lattice K -grain yield

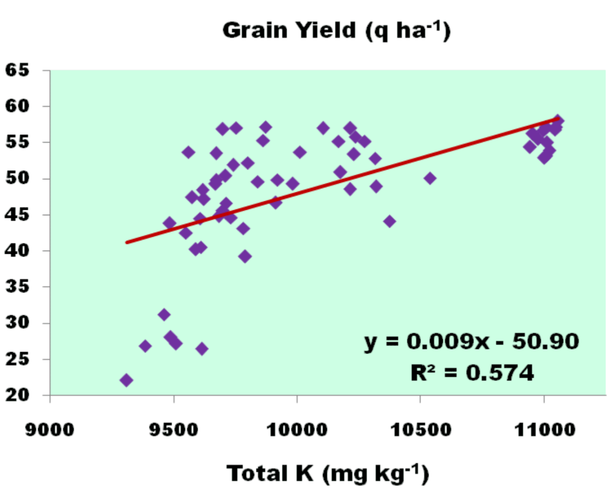

Fig. 8. Correlation plot of Total K –grain yield

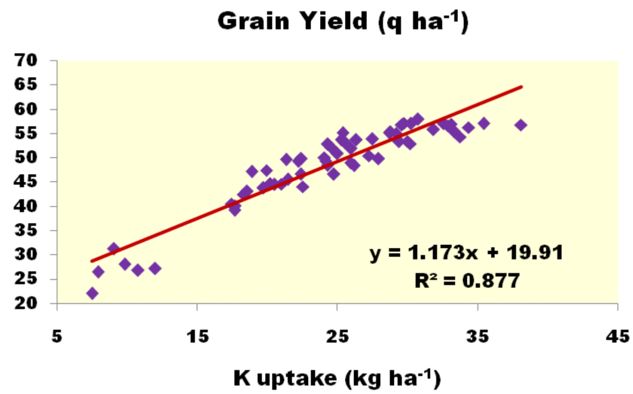

Fig. 9. Correlation plot of K uptake- grain yield

or fertilizer in the different treatment plots. Similar finding was accordance with the finding of Sharma *et al.,* (2013). According to Zhang *et al.,* (2021) contribution of exchangeable K towards plant K uptake would be higher in the soil with straw than the soil without straw and the non-exchangeable K would be the long-term fixed K as a supplement to the potassium pool.

Stepwise multiple regression equations below indicated that exchangeable K was the most important variable contributing towards total variation in grain yield of rice.

Grain yield = - 4.702+0.759*Exch. K, R^2=0.748

Grain yield = -12.862+1.401*Ex K -1.067*WSK, R^2=0.799

CONCLUSION

The information generated in the present study related to the status and distribution of different forms of potassium and its availability in the soil revealed the availability of different forms of K under the influences of varying doses of applied K and INM packages. Again it was noticed that a dynamic equilibrium existed among the different fractions of potassium in these soils.

Finally, it can be concluded that INM Packages were found to be better for maintaining available K status and the resultant crop yield compared to inorganic treatments.

Disclosure statement

The authors declare that they have no conflict of interest.

Funding

The authors did not receive any sort of financial assistance from any funding agency in carrying out this research.

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