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Bio-cover addition, tillage, and bioinoculants affect wheat yield, potassium availability, and quantity-intensity relations in the Himalayan foothills of India

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Abstract

The Himalayan foothills experience heavy rainfall and imbalanced fertilization, particularly with potassium (K). In traditional farming, K fertilization is often low or neglected, resulting in a decline in crop productivity. This study aims to evaluate the impact of bio-cover addition, tillage, and bioinoculants on wheat yield, K availability, and quantity-intensity relations in the Himalayan foothills of India. A field experiment was conducted in a factorial randomized block design with three replications, comprising eight treatment combinations: zero tillage or conventional tillage, no or bio-cover addition and no or seed treatment using bioinoculants in the rice-wheat system. Soil samples were collected from post-wheat plots. The results showed that following zero tillage and bio-inoculation, wheat yields increased by 4% and 11%, respectively. Bio-cover addition with bio-inoculation and tillage with bio-inoculation also increased the yield. However, the three-way interaction of these practices did not notably vary the yield. Among fractions of K, water-soluble K increased in bio-cover addition and decreased in zero tillage practice. Additionally, bioinoculants did not affect this fraction of K. Exchangeable K was higher when combining zero tillage with bio-cover and bioinoculants, whereas non-exchangeable K did not vary with tillage practices and bioinoculants; moreover, bio-cover additions improved this fraction of K. In the case of mineral K and total K, zero tillage and bio-cover addition increased in the soil, except in the deeper layer. Among quantity/intensity parameters, potential buffering capacity was significantly highest when combining zero tillage with bio-cover and bioinoculants, contrasting with the activity ratio, which was highest when combining conventional tillage with bio-cover and no bioinoculants. The correlation study showed that the fractions of K and quantity/intensity parameters were in dynamic equilibrium. Therefore, this study concludes that management practices such as zero tillage, bio-cover addition, and bioinoculants in the Himalayan foothills of India can enhance K availability in the soil. Overall, we recommend that long-term bio-cover additions under zero or conventional tillage with bio-inoculations can improve and maintain K supply in the rice-wheat system.

1. Introduction

Balanced fertilization with macronutrients is crucial for improving crop productivity and produce quality. Among these macronutrients, potassium (K) is one of the most essential, following nitrogen and phosphorus, which significantly impact crop yield and quality (Srinivasarao et al., 2023). Nutrient K can directly influence crop production due to its involvement in several physiological processes, including water relations, enzyme activities, photosynthesis, assimilation, and transport. It also helps control moisture loss from the plant system by regulating stomatal function. Amidst production constraints and yield gaps, imbalanced fertilization is a critical issue in South Asian countries, with a primary focus on N application, leaving plants vulnerable to deficiencies in other essential nutrients, such as phosphorus and potassium. Therefore, proper fertilization management strategies that include K application, either through inorganic or organic sources, are required to sustain crop yield and grain quality (Kumari et al., 2024).

Bio-cover/Crop residue (R) addition can be an alternative management strategy for the K source. According to Rani et al. (2023), R can supplement/substitute for inorganic K sources, which may positively impact K dynamics and contribute to plant growth to some extent (Padbhushan et al., 2023). Zero tillage (ZT) is another effective method that improves soil fertility by enhancing R retention, which positively impacts K levels in the soil (Madar et al. 2020). Bioinoculants are also an important management strategy that enhances K availability by converting insoluble K to soluble fractions in the soil through microbial activity (Madar et al., 2020). Although K on R addition is present in a mineralized form it is available to the plants for uptake. However, there is limited literature on how this R interacts with other bioinoculants and impacts K availability and its fractions.

Potassium is a dynamic nutrient that exists in the soil in different distinct fractions that include soil solution K, exchangeable K, non-exchangeable K, and structural or mineral K. These different fractions maintain a dynamic balance, and a decrease in any particular fraction is likely to cause the equilibrium to shift in favour of replenishing it (Lalitha and Dakshinamurthy, 2014; Kumari et al., 2024). Among these, soil solution K is the most readily available fraction for plant uptake and represents only a small fraction of the total K in soil (Bell et al., 2021). As a component of mineral structures, K is predominantly present in non-exchangeable or fixed fractions and only a small amount is found in soil solution and/or exchangeable K (Pasricha, 2002). When soil solution K and exchangeable K are depleted, non-exchangeable K, which serves as a reserve source of K, becomes available and can significantly influence soil fertility (Sui et al., 2017). However, under a long-run intensive cropping system, the exchangeable K may not be a reliable indicator of the K-supplying power of the soil (Islam et al., 2017). As crops take up readily available or exchangeable K, non-exchangeable K is released by the soil gradually, replenishing the available K pool. The Quantity/Intensity (Q/I) relationship is important to provide insights into the K-supplying capacity of soils. Plant K absorption depends on the quantity, intensity, and removal rate by crops, which can be modelled using the activity ratio at equilibrium, labile K, potential buffering capacity, and the free energy change from K exchange equilibrium. This can be determined using Q/I isotherms. The activity ratio of K, developed by Beckett (1964), is one of the acceptable measurements for evaluating K dynamics and its availability. This ratio accounts for the chemical potential of labile K, as well as the potential of labile (calcium + magnesium) in the same soil, while also considering the soil's buffering capacity.

The Himalayan foothills receive heavy precipitation (> 3000 mm) and have a limited window for introducing legumes. There have been limited long-term studies on management strategies, such as ZT, R addition, and bioinoculants, in the rice-wheat system of this region, particularly regarding their impact on nutrient availability, especially potassium (K). In this study, we hypothesized that the availability and dynamics of K vary according to different management strategies and soil types. The objective of this investigation is to evaluate the impact of long-term tillage, R addition, and bioinoculants on wheat yield, soil K fractions, and Q/I relationship in the foothills of the Himalayas of India.

2. Materials and methods

2.1. Experimental details, soil, and climate

This study was conducted on a permanent plot trial for long-term partial conservation agriculture, which was established in 2006 under the rice-wheat cropping system (Fig. 1). The present study is the 15th crop cycle grown under the wheat crop in the winter season. The field is located at 26°19' N, 89°23' E, 43 m above mean sea level, at the Research Farm of the Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar, West Bengal, India. This region receives >3000 mm of rainfall annually, with approximately 80% of it occurring between June and October. The winter season is cold, while the summer is mild. The average minimum and maximum temperatures are 19°C and 30°C, respectively.

The soils in this area are composed of alluvial sediments, resulting from heavy rainfall, which causes a significant loss of base-fractioning cations, such as calcium and magnesium ions, through percolating water. In general, the soils in this region have a gritty texture and acidic conditions. According to the soil fertility classification of West Bengal province, soils are moderate to less fertile, with medium to high levels of total nitrogen and organic carbon, high levels of total phosphorus, and medium to low levels of potassium (K) (Sinha, 2013).

2.2. Treatment details, crop and nutrient management

Initially, in the experiment, each of the three treatment components (tillage, bio-cover (R) and bioinoculants (B)) had two levels. Tillage levels were zero tillage (ZT) and conventional tillage (CT); bio-cover addition (R1) and no bio-cover addition (R0) and addition of bioinoculants (B1) and no bioinoculants (B0). Therefore, a total of eight treatment combinations are available, namely: ZTR0B0, ZTR0B1, ZTR1B0, ZTR1B1, CTR0B0, CTR0B1, CTR1B0, and CTR1B1. A total of 24 plots were prepared by replicating each treatment three times and arranged in a randomized block design.

After harvesting, rice straw was left in the residue-treated plots at 3 t ha^{-1} on a sun-dried basis for in-situ application in both zero-till and conventionally tilled plots. *Azotobacter* spp. and *Pseudomonas* spp. (phosphate solubilizer) @ 5 g kg^{-1} of wheat seed was treated with a talc-based formulation of gum acacia. Wheat variety PBW-343 was shown in the field using a zero-till seed cum fertilizer drill for both the CT and ZT plots with a seed rate of 105 kg ha^{-1}. Fertilizers were applied in the ratio of nitrogen: phosphorus: K at 120:60:60 kg ha^{-1}. Irrigation was carried out on the 21st and 42nd days after sowing, along with fertilization during the vegetative stage (Half nitrogen and total phosphorus and total K) and at crown root initiation (Half nitrogen). Intercultural operations, such as manual weeding/herbicide application and pesticide application, were performed in CT/ZT plots. Harvesting of the wheat crop was done in March month and wheat yield was recorded (5 m x 5 m crop cut) and calculated at 12% moisture level. Harvested grain and straw samples were oven-dried at 65°C for 2 days. Dried samples were digested in acid, diluted and analyzed for plant

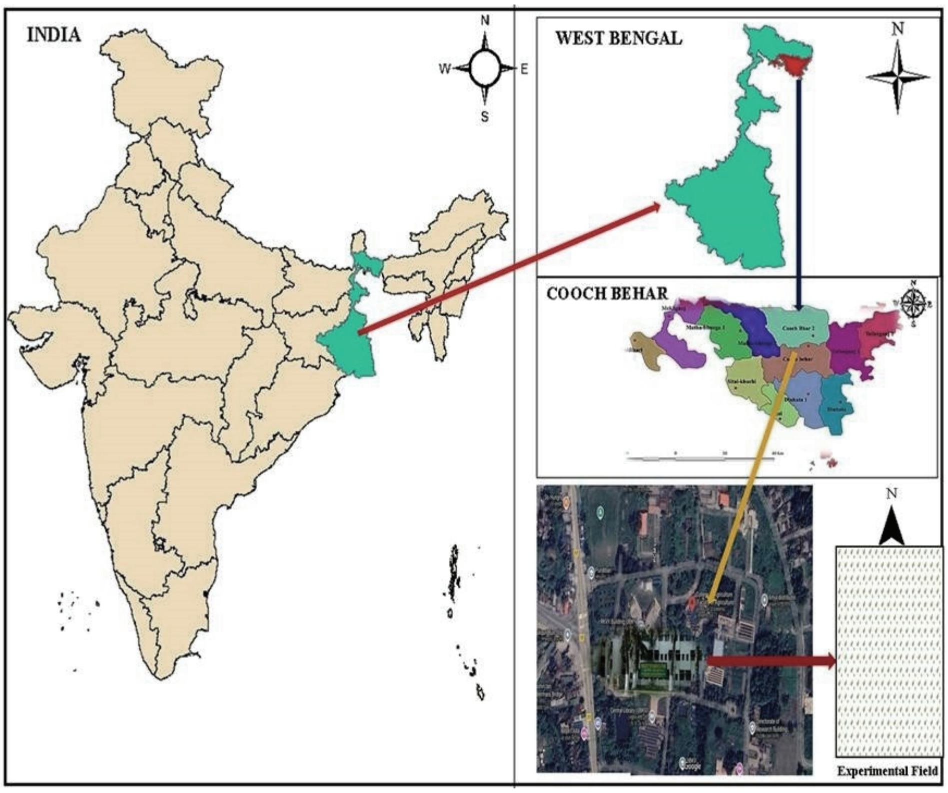

Fig. 1. Location map of the study area at UBKV, Coochbehar, West Bengal, India

K using flame photometer. Plant K uptake was calculated by multiplying K content and dry matter. K use efficiency measured using partial factor productivity and reciprocal internal use efficiency of K is given below:

Partial factor productivity of K (kg grain kg^{-1} K added) =

$$= \frac{\text{Grain yield (kg ha}^{-1}\text{)}}{\text{Total K added (kg ha}^{-1}\text{)}}$$

Reciprocal internal use efficiency of K (kg Mg^{-1} grain yield) =

$$= \frac{\text{K uptake (kg ha}^{-1}\text{)}}{\text{Grain yield (Mg ha}^{-1}\text{)}}$$

2.3. Soil sampling, processing, and analysis

The soil samples for analysis were collected from depths of 0–10, 10–20, and 20–40 cm in each treated experimental plot, immediately after harvesting the wheat crop. Prepare a composite soil sample for each treatment plot and homogenise repeatedly until a final weight of 500 g was achieved, after eliminating all stubbles, residues, root biomass, and extraneous materials. Before the analysis, the soil samples were carefully stored in airtight polythene containers after being air-dried at room temperature, pulverized in a wooden mortar, sieved through a 2-mm sieve, and preserved.

Soil pH and electrical conductivity were determined using a glass electrode (Jackson, 1973). Soil organic carbon was determined using the Walkley and Black (1934) wet digestion method. Water-soluble K was extracted from the soil water solution in a ratio of 1:5 and measured using a flame photometer (Jackson, 1973). Exchangeable K was extracted by mixing soil with 1N ammonium acetate in a 1:5 ratio. The solution was stirred for 30 minutes, filtered and the K content was measured using a flame photometer (Hanway and Heidal, 1952). Non-exchangeable K was determined using a 1:10 ratio of soil and 1N HNO_3, and the mixture was boiled for 10 minutes. Then filtered the solution in a 25 ml volumetric flask, and made volume up to 25 ml. If the sample readings were outside the calibrated range, then dilute them. Non-exchangeable K was estimated by the difference between available K and nitric acid extractable K (Wood and DeTurk 1941). Total K was estimated through acid digestion using hydrofluoric acid (48%) and perchloric acid (72%) followed by flame photometer (Jackson, 1973).

To determine the Q/I parameters of K, the procedure described by Beckett (1964) was followed. A 5 g soil sample was weighed and placed in a conical flask. Then, 50 ml graded K ion solutions at concentrations of 0, 2, 4, 6, 8, 10, and 20 mg kg^{-1} were added to the soil. The solutions were shaken on a shaker for about 30 minutes and then filtered through filter paper. The aliquot was analysed for K^+ concentration using a flame photometer. Moreover, calcium and magnesium ions were measured using the Versanate titration method. In this method, 3 ml of the aliquot was transferred to a measuring cylinder, diluted with distilled water to make up the volume 10 ml and placed in a conical flask. 15 ml buffer solution and 10 drops of reagents (Triethylamine, Hydroxyl amine chloride, and Eriochrome Block-T) were added. The solution was then titrated with EDTA, and the appearance of a blue colour indicated the endpoint. After filtration, the remaining soil in funnels was treated with 100 ml Ammonium acetate to find the leachate K.

$$AR = \frac{aK}{\sqrt{a}(Ca + Mg)}$$

$$AR = \frac{fK}{\sqrt{f}(Ca + Mg)} x \frac{cK}{\sqrt{c}(Ca + Mg)}$$

Here, AR – Activity ration of K, aK = K's activity (moles L^{-1}), a (Ca + Mg) = Activity coefficient of Ca + Mg, fK = Activity coefficient of K, f (Ca + Mg) = Activity coefficient of Ca + Mg, cK = Concentration of K (moles L^{-1}), c (Ca + Mg) = Concentration of Ca + Mg (moles L^{-1}), Δ K was estimated at the difference between the concentration of K^+ added to the soil in the extracted solution and K^+ in the leachates. It was expressed in cmol (p^+) kg^{-1}. Specifically, the concentration ratio (KX) was also measured. Potential buffering capacity (PBC) was calculated using the following equation:

$$PBC = \frac{KL}{AR}$$

Where, KL is 'labile K' and AR is the 'activity ratio of K'

2.4. Statistical analysis

The data collected from the study were analysed using ANOVA for a factorial randomized block design. The mean values were compared with the least significant difference (LSD) and standard error at 5% probability level (Steel and Torrie, 1980) using Microsoft Excel and OPSTAT software. Correlation and regression analysis were done using SPSS 20 to evaluate the relationship among the variables.

3. Results

3.1. Fractions of potassium

3.1.1. Water-soluble potassium

Among tillage practices, conventional tillage (CT) had a higher water-soluble K by 10.5% in the soil layer of 0–10 cm compared to zero tillage (ZT) and *statistically similar to* the soil layers of 10–20 cm and 20–40 cm (Fig. 2). In the case of bio-cover addition (R) improved this fraction of K by 21–37% with increasing trend downward layers. The interaction effect of tillage and R significantly changed the amount of water-soluble K up to 20 cm, was highest in CTR1 followed by ZTR1, CTR0 and lowest in ZTR0 in the soil layer 0–10 cm, while in the subsurface layers, it was highest in the treatment ZTR1 followed by CTR1, CTR0 and lowest in ZTR0 (Fig. 2). The interaction effect of R and bioinoculants (B) significantly increased the amount of water-soluble K up to 0–10 cm and further *statisti-*

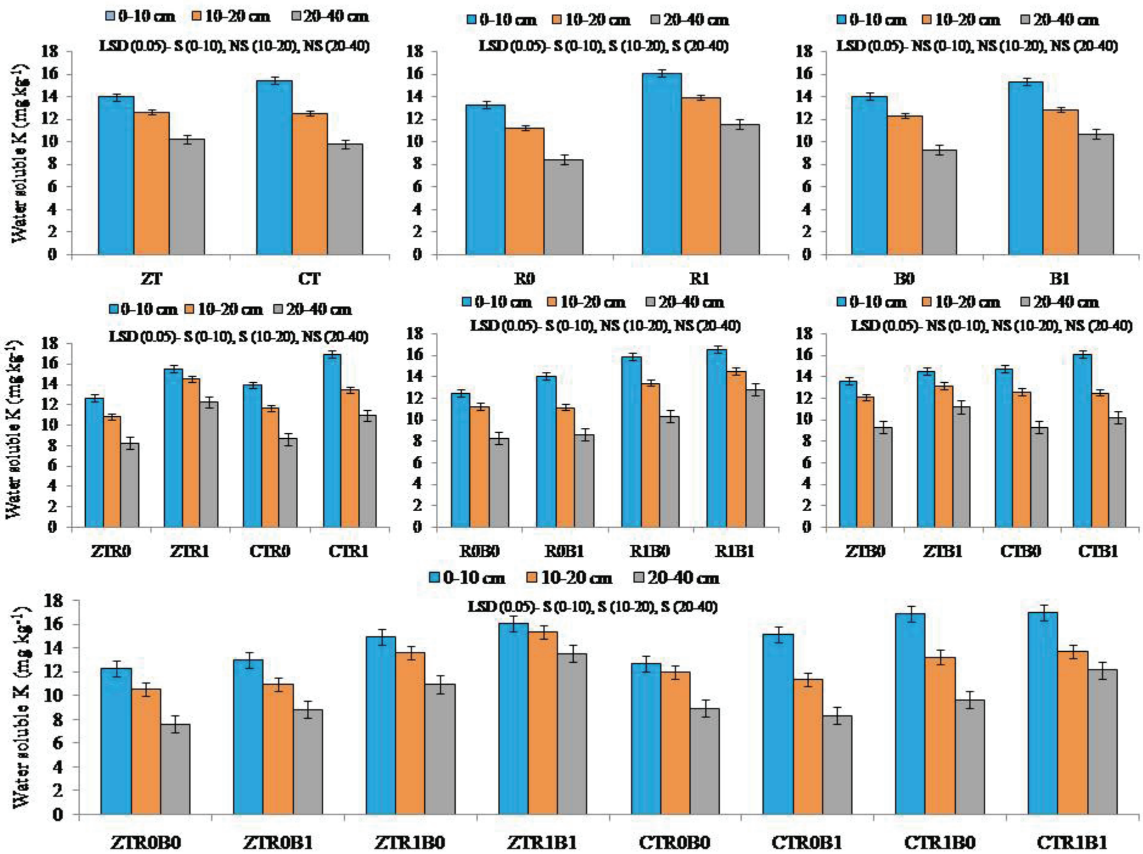

Fig. 2. Effect of tillage, bio-cover addition, and bioinoculants on water-soluble potassium (mg kg^{-1}) in post-wheat soil after 15^{th} crop cycle (ZT – Zero tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without), LSD – Least significant difference, S – Significant, NS – Non-significant)

cally similar from the soil depths from 10–20 cm and 20–40 cm. The highest water-soluble K was in R1B1 compared to other treatment combinations. There was no impact on the interactive effect of tillage and B inoculation. Combining all three management practices, the highest water-soluble K was observed in the treatment CTR1B1, followed by CTR1B0, ZTR1B1, CTR0B1, ZTR1B0, ZTR0B1, and CTR0B0, with the lowest value in ZTR0B0. However, in the soil layers of 10–20 cm and 20–40 cm, the highest water-soluble K was in the treatment ZTR1B1, and it declined with increasing soil depths.

3.1.2. Exchangeable potassium

Zero tillage was higher in exchangeable K compared to CT by 5% in the soil layer 0–10 cm, and deeper layers did not show variation among tillage practices (Fig. 3). Bio-cover addition improved this K fraction. The highest exchangeable K due to R addition was found in the surface layer, followed by the subsurface layers, which increased by 5–35% across all depths. Similarly, B inoculation increased the fraction in all the soil layers in a decreasing trend by 3, 4, and 15% in the soil depths of 0–10, 10–20, and 20–40 cm, respectively. The two-way interactions had a significant influence on exchangeable K. In the 0–10 cm soil layer, the highest exchangeable K was found in treatment ZTR1B1, followed by ZTR1B0, CTR1B1, ZTR0B1, CTR1B0, ZTR0B0, and CTR0B1, with the lowest value in CTR0B0. Similarly, in the soil layers of 10–20 cm and 20–40 cm, the highest exchangeable K was in the treatment ZTR1B1, and it declined with increasing soil depths (Fig. 3).

3.1.3. Non-exchangeable potassium

In this study, tillage practices and B inoculation did not affect the non-exchangeable K. Residue addition increased the amount of non-exchangeable K in the soil irrespective of soil depths (Fig. 4). The trend of non-exchangeable K in the soil layers was 20–40 cm> 10–20 cm>0–10 cm. Two-way and three-way interactive effects of tillage, R addition, and B inoculation did not result in a change in the amount of non-exchangeable K in the soil (Fig. 4).

3.1.4. Mineral potassium

Among tillage practices, ZT had higher mineral K than in the CT practice, irrespective of the studied soil layers. The increase of mineral K in the treatment ZT over CT in the soil was 12.5, 4 and 4% in the soil depths 0–10 cm, 10–20 cm and 20–40 cm, respectively (Fig. 5). Bio-cover addition improved this fraction of K up to 20 cm significantly and *statistically similar* at the lower depth over without R addition. Bioinoculants did not affect the concentration of K. The interaction of tillage and

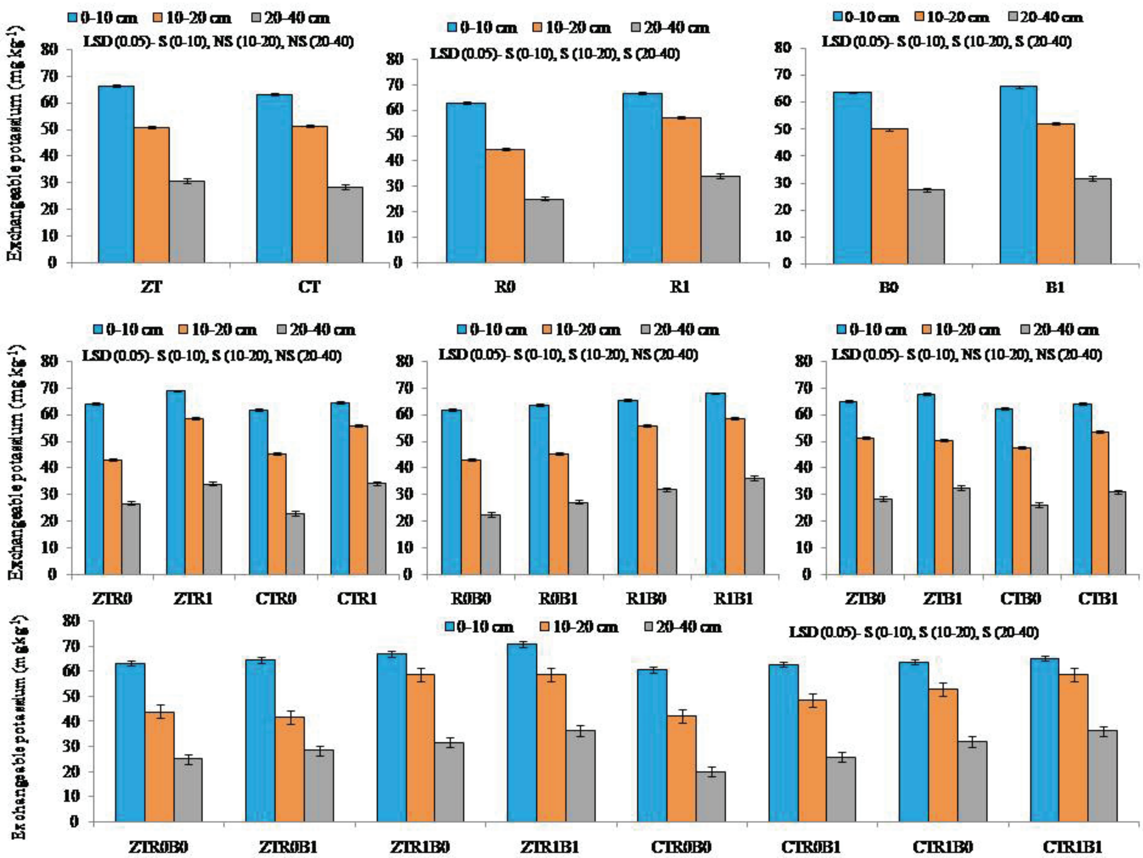

Fig. 3. Effect of tillage, bio-cover addition, and bioinoculants on exchangeable potassium (mg kg^{-1}) in post-wheat soil after 15th crop cycle (ZT – Zero tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without), LSD – Least significant difference, S – Significant, NS – Non-significant)

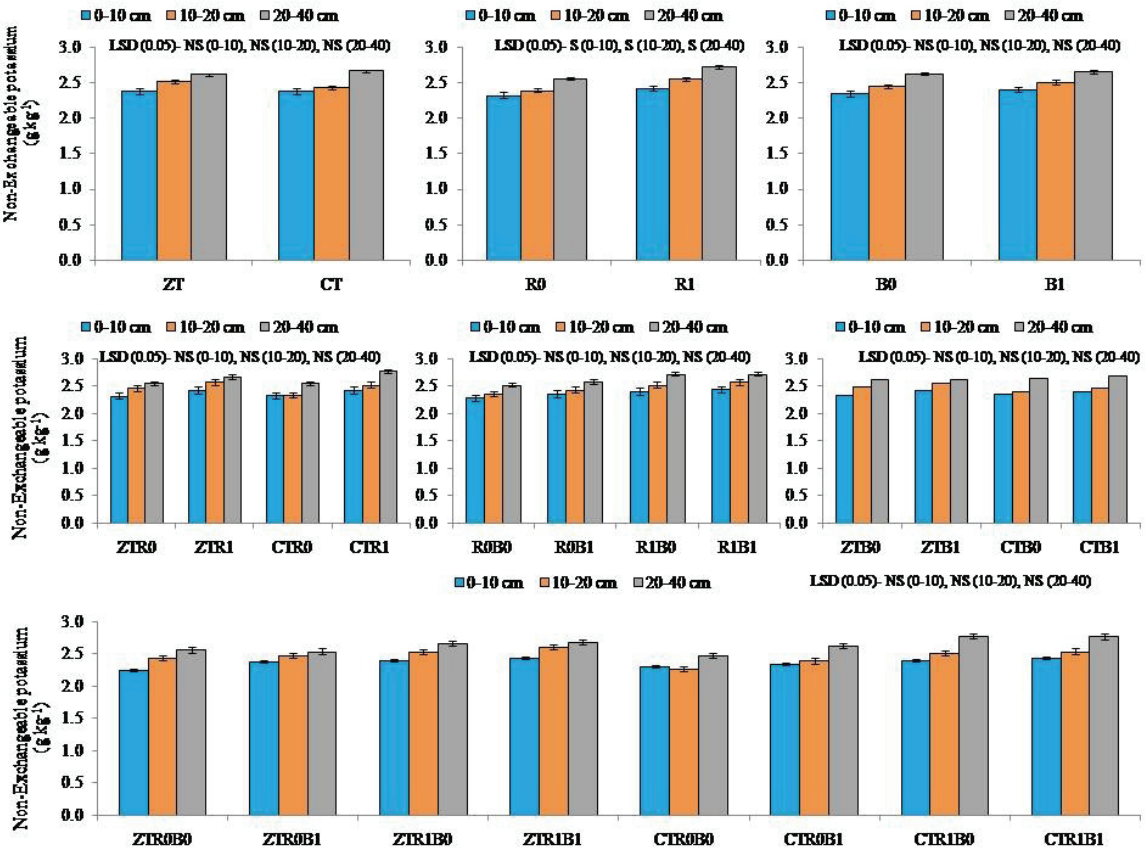

Fig. 4. Effect of tillage, bio-cover addition, and bioinoculants on non-exchangeable potassium (mg kg^{-1}) in post-wheat soil after the 15th crop cycle (ZT – Zero-tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without), LSD – Least significant difference, S – Significant, NS – Non-significant)

R affected the mineral K up to 20 cm. It was highest in ZTR1, followed the ZTR0 and CTR1 and lowest in CTR0 while in the subsurface layers (20–40 cm), mineral K was non-significant (Fig. 5). Data obtained from three-way interaction effects, in soil layers 0–10 cm and 10–20 cm, the highest mineral K was in the treatment ZTR1B1 followed by ZTR1B0, ZTR0B0, ZTR0B1, CTR1B1, CTR1B0, and CTR0B1 and lowest in CTR0B0, however, no impact was in the lower soil depth of 20–40 cm (Fig. 5).

3.1.5. Total potassium

The increase of total K in the treatment ZT over CT in the soil was 9, 4, and 3% in the soil depths of 0–10 cm, 10–20 cm, and 20–40 cm, respectively (Fig. 6). In the case of R management, R addition significantly improved this fraction of K up to 20 cm significantly. While inoculation with B had significantly improved total K up to 10 cm, and further, there was no impact in the lower depths relative to no B. The interaction effect of tillage and R affected total K up to 20 cm. It was highest in ZTR1 followed by ZTR0, CTR1 and lowest in CTR0 in the soil layers 0–10 and 10–20 cm, while in the subsurface layers (20–40 cm), total K recorded non-significantly (Fig. 6). There was no impact on the interactive effects of R addition and B inoculation, however, the combined impact of tillage and B inoculation varied the total K up to 10 cm and further changed non-significantly. Data obtained from the three-way interaction showed a variation in total K up to 20 cm. In the 0–10 cm soil layer, the highest total K concentration was observed in treatment ZTR1B1, followed by ZTR1B0, ZTR0B0, ZTR0B1, CTR1B1, CTR1B0, and CTR0B1, with the lowest value in CTR0B0. A similar trend was observed in the 10–20 cm depth range; however, no impact was observed in the lower soil depth of 20–40 cm (Fig. 6).

3.2. Wheat yield, potassium uptake and potassium use efficiency

On comparing the wheat yield after the 15^{th} crop cycle, among tillage practices, a higher yield was in ZT (3.55 t ha^{-1}) over the CT (3.41 t ha^{-1}) (Table 1). In the case of R addition, there was no variation in grain yield. Continuous B addition significantly increased the grain yield (3.66 t ha^{-1}) over the one without B (3.30 t ha^{-1}), respectively. The interaction effects of R addition and B inoculation, and tillage and B, had a significant influence on wheat yield. The yield trend differed from that of the previous year due to weather abnormalities and heavy rainfall that affected wheat yields during the study period. A three-way interaction did not reveal a variation in grain yield. Among tillage practices, ZT had a higher K uptake by wheat straw than CT (Table 2). Biofertilizer inoculation increased K uptake by both straw and grain. The combined effect of R addition and B influenced K uptake by straw. Similarly, a combination of tillage and B affect-

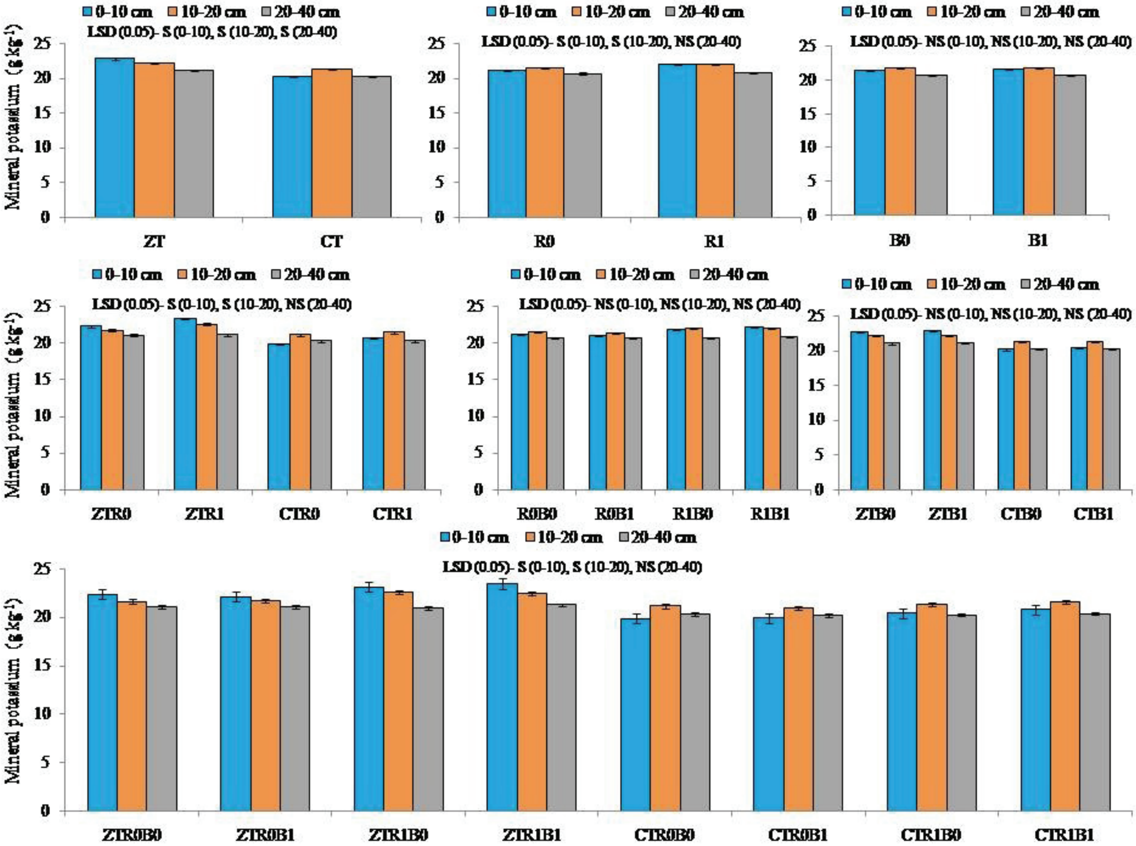

Fig. 5. Effect of tillage, bio-cover addition, and bioinoculants on mineral potassium (g kg^{-1}) in post-wheat soil after the 15th crop cycle ((ZT – Zero-tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without), LSD – Least significant difference, S – Significant, NS – Non-significant)

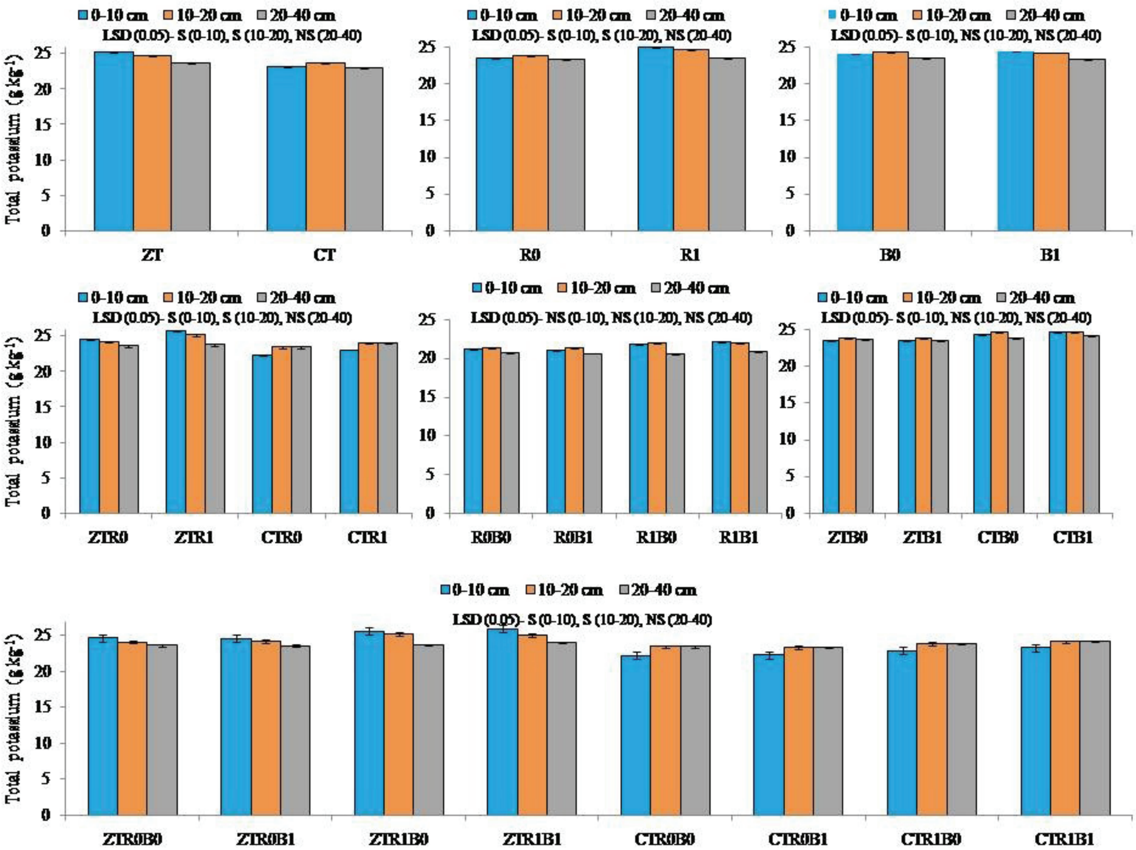

Fig. 6. Effect of tillage, bio-cover addition, and bioinoculants on total potassium (g kg^{-1}) in post-wheat soil after the 15th crop cycle (ZT – Zero-tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without), LSD – Least significant difference, S – Significant, NS – Non-significant)

Table 1
Effect of tillage, bio-cover addition, and bioinoculants on wheat yield (t ha^{-1}) in after the 15^{th} crop cycle

Wheat yield (t ha^{-1})							
ZT	3.55	R0	3.48	B0	3.30	ZTR0B0	3.15
CT	3.41	R1	3.47	B1	3.66	ZTR0B1	3.93
SE (m)	0.04		0.04		0.04	ZTR1B0	3.41
LSD (0.05)	0.11		NS		0.11	ZTR1B1	3.71
ZTR0	3.54	R0B0	3.77	ZTB0	3.82	CTR0B0	3.25
ZTR1	3.56	R0B1	3.20	ZTB1	3.28	CTR0B1	3.60
CTR0	3.43	R1B0	3.56	CTB0	3.51	CTR1B0	3.37
CTR1	3.39	R1B1	3.39	CTB1	3.31	CTR1B1	3.41
SE (m)	0.05		0.06		0.06		0.09
LSD (0.05)	NS		0.15		0.15		NS

(ZT – Zero-tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without), SE (m) – mean standard error, LSD – Least significant difference, NS – Non-significant)

Table 2
Effect of tillage, bio-cover addition, and bioinoculants on wheat potassium uptake (kg ha^{-1}) in after 15^{th} crop cycle

Wheat potassium uptake (kg ha^{-1})											
	Straw	Grain		Straw	Grain		Straw	Grain		Straw	Grain
ZT	30	19	R0	26	17	B0	25	17	ZTR0B0	30	17
CT	23	17	R1	28	18	B1	29	19	ZTR0B1	30	20
SE (m)	0.8	0.5		0.8	0.5		0.8	0.5	ZTR1B0	25	20
LSD (0.05)	2.4	NS		NS	NS		2.4	1.6	ZTR1B1	36	21
ZTR0	30	18	R0B0	22	16	ZTB0	26	17	CTR0B0	21	16
ZTR1	31	19	R0B1	25	18	ZTB1	32	20	CTR0B1	22	17
CTR0	21	16	R1B0	28	17	CTB0	24	17	CTR1B0	23	19
CTR1	26	18	R1B1	33	19	CTB1	25	17	CTR1B1	28	18
SE (m)	1.1	1.1		1.1	1.1		1.1	1.1		1.6	1.1
LSD (0.05)	NS	NS		3.45	NS		NS	3.4		NS	NS

(ZT – Zero-tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without), SE (m) – mean standard error, LSD – Least significant difference, NS – Non-significant)

ed K uptake by grain. A three-way interaction did not reveal a significant variation in plant K uptake. Potassium use efficiency is measured and shown as partial factor productivity and reciprocal internal use efficiency of K in Fig. 7. Increasing trend of partial factor productivity of K was ZTR0B1> CTR0B1> CTR0B0> ZTR0B0> ZTR1B1> ZTR1B0~ CTR1B1>CTR1B0 and decreasing trend of reciprocal internal use efficiency of K was CTR0B0~ CTR0B1< ZTR1B0~ CTR1B0<ZTR0B1~ CTR1B1<ZTR0B0<ZTR1B1.

3.3. Pearson correlation matrix and regression analysis of wheat yield, soil properties and fractions of potassium

Results revealed that wheat yield was positive and significantly correlated to exchangeable K and non-exchangeable K (Table 3). The soil properties, such as pH, were highly negatively correlated with exchangeable K, organic carbon, and water-soluble K, and they were positively and significantly correlated with non-exchangeable K. Organic carbon was positively and significantly correlated with all fractions of K, except for non-exchangeable K, which was negatively and significantly correlated. Water-soluble K was positive and significantly correlated with exchangeable and total K. Exchangeable K was negative and highly correlated with non-exchangeable K and positively and significantly correlated with mineral K and total K. Mineral K was positively and highly significantly related to total K (Table 3).

The regression analysis shown in Table 4 indicates that yield was the dependent variable, while soil properties and fractions of K were the independent variables. The regression analysis predicts the yield shown in Equation 1.

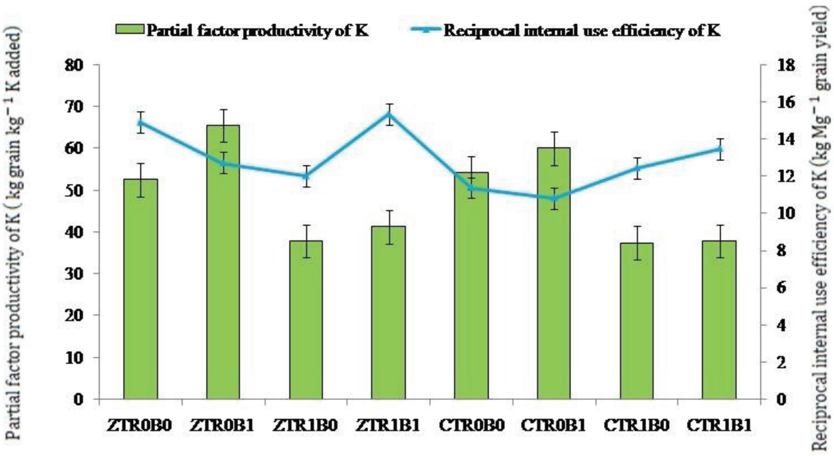

Fig. 7. Effect of tillage, residue bio-cover addition, and bioinoculants on potassium use efficiency in post-wheat soil after the 15th crop cycle (ZT – Zero-tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without), Bars represent mean value and error bars represent standard error

Table 3
Pearson correlation matrix (wheat yield, pH, organic carbon, fractions of potassium)

	pH	Organic carbon	Water soluble-K	Exchangeable K	Non-exchangeable K	Mineral K	Total K
Yield	0.319	0.067	0.145	0.443*	0.539*	0.266	0.211
pH	1.000	(–)0.661**	(–)0.440*	(–)0.575**	0.746**	0.182	0.080
Organic carbon		1.000	0.730**	0.925**	(–)0.707**	0.437*	0.440*
Water soluble-K			1.000	0.860**	(–)0.292	0.322	0.445*
Exchangeable K				1.000	(–)0.571**	0.483*	0.509*
Non-exchangeable K					1.000	(–)0.176	(–)0.104
Mineral K						1.000	0.914**

* Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

Table 4
Regression analysis (wheat yield, pH, organic carbon, fractions of potassium)

Dependent variable	Independent variable	Regression coefficient (b)	Standard error	Lower Confidential limit (95%)	Upper Confidential limit (95%)
Yield	Intercept	2.04	1.95	–2.09	6.17
	pH	0.19	0.35	–0.56	0.94
	Organic carbon	–0.33	0.68	–1.76	1.11
	Water soluble potassium	0.02	0.06	–0.10	0.13
	Exchangeable potassium	0.01	0.02	–0.03	0.04
	Non-exchangeable potassium	–0.15	0.85	–1.94	1.65
	Mineral potassium	0.01	0.23	–0.47	0.50
	Total potassium	0.00	0.19	–0.39	0.40

Wheat yield = 2.04 + 0.19* pH – 0.33 * organic carbon + 0.02 * water soluble K+ 0.01 * exchangeable K– 0.15 * * non-exchangeable K+ 0.01 * mineral K + 0.00 * total K, $R^2 = 0.37$ Equation 1

3.4. Quantity and intensity relationship

3.4.1. Potential buffering capacity (PBC)

Tillage, R addition, and B had a significant variation in PBC (Table 5; Supplementary Fig. S1). In the soil depth 0–10 cm, the highest value of PBC in ZTR1B1 and the lowest value found in CTR0B0. In soil depth 10–20 cm, PBC was significantly higher in the treatment ZTR1B1 compared to the lowest value of PBC in CTR0B1. In the soil layer 20–40 cm, the highest PBC was in CTR1B1, and the lowest PBC was in CTR1B0.

3.4.2. Activity ratio (AR)

In the soil depth 0–10 cm, the highest value of AR was in CTR1B1, and the lowest value was in CTR0B0 (Table 5; Supplementary Fig. S1). At a soil depth of 10–20 cm, AR was significantly higher in the treatment CTR0B0 compared to the lowest value of AR in ZTR1B1. A similar trend was observed in the soil layer 20–40 cm.

3.4.3. Labile potassium (KL)

At a soil depth of 0–10 cm, the highest value of KL was observed in ZTR0B0, ZTR0B1, CTR1B0, and CTR1B1, while the lowest value was found in CTR0B0 and CTR0B1 (Table 5). At a soil depth of 10–20 cm, KL was significantly higher in the treatments CTR1B0 and CTR1B1compared to the lowest value in ZTR0B0, CTR0B0, and CTR0B1. In the 20–40 cm soil layer, the highest KL was observed in CTR0B1, while the lowest KL was found in ZTR0B0 and CTR1B0.

3.4.4. Specifically held potassium (KX)

At a soil depth of 0–10 cm, the highest value of KX was observed in ZTR1B1, and the lowest value was found in CTR0B0. At a soil depth of 10–20 cm, KX was significantly higher in treatment CTR1B1 compared to the lowest value of KX in CTR1B0. In the soil layer 20–40 cm, the highest KX was observed in CTR1B1, and the lowest KX was observed in ZTR1B1 (Table 5).

Table 5
Effect of tillage, bio-cover addition, and bioinoculants on Quantity-Intensity parameters in post-wheat soil depths (0–10 cm, 10–20 cm and 20–40 cm) after the 15th crop cycle

Treatments	PBC [cmol kg^{-1} (mol L^{-1})$^{-1/2}$]	AR X 10^{-3} [(mol L^{-1})$^{1/2}$×10^{-3}]	KL (cmol (p+) kg^{-1})	KX (cmol (p+) kg^{-1})	±ΔK X 10^{-3} (cmol (p+) kg^{-1})	CR X 10^{-3}
			0–10 cm			
ZTR0B0	56.18	3.08	0.16	145.00	5.17	2.87
ZTR0B1	55.67	3.09	0.16	146.20	5.40	2.86
ZTR1B0	57.02	3.01	0.15	155.68	5.12	2.88
ZTR1B1	63.07	2.97	0.15	163.58	5.12	2.88
CTR0B0	45.50	3.27	0.14	120.92	3.26	3.05
CTR0B1	45.83	3.26	0.14	121.33	3.39	3.13
CTR1B0	47.43	3.29	0.16	131.04	2.65	3.21
CTR1B1	48.79	3.24	0.16	131.41	2.59	3.07
SE (m)	0.55	0.03	0.002	1.42	0.04	0.03
LSD (0.05)	1.64	0.09	0.01	4.25	0.12	0.10
			10–20 cm			
ZTR0B0	52.12	2.79	0.14	98.63	3.08	2.60
ZTR0B1	60.37	2.70	0.16	134.89	3.70	2.37
ZTR1B0	65.89	2.65	0.15	124.59	2.58	2.33
ZTR1B1	66.96	2.64	0.15	122.12	2.93	2.55
CTR0B0	46.68	3.44	0.14	126.19	4.20	3.20
CTR0B1	43.50	3.40	0.14	140.32	4.19	3.21
CTR1B0	43.63	3.60	0.17	97.26	3.26	3.19
CTR1B1	44.36	3.62	0.17	144.88	3.40	3.37
SE (m)	0.61	0.03	0.002	1.18	0.15	0.03
LSD (0.05)	1.82	0.10	0.01	3.53	0.46	0.08

Table 5 – continue

Treatments	PBC [cmol kg⁻¹ (mol L⁻¹)⁻¹/²]	AR X 10⁻³ [(mol L⁻¹)¹/²×10⁻³]	KL (cmol (p+) kg⁻¹)	KX (cmol (p+) kg⁻¹)	±ΔK X 10⁻³ (cmol (p+) kg⁻¹)	CR X 10⁻³
			20–40 cm			
ZTR0B0	57.69	2.33	0.12	91.62	1.16	2.17
ZTR0B1	60.18	2.32	0.14	108.99	1.32	2.23
ZTR1B0	62.94	2.30	0.15	84.76	1.31	2.15
ZTR1B1	65.78	2.29	0.15	82.24	1.23	2.19
CTR0B0	56.09	2.88	0.15	116.68	0.27	2.68
CTR0B1	62.30	2.77	0.17	130.29	0.27	2.58
CTR1B0	51.42	2.71	0.12	91.84	1.02	2.53
CTR1B1	67.77	2.67	0.18	136.62	0.90	2.49
SE (m)	0.61	0.03	0.002	1.12	0.02	0.02
LSD (0.05)	1.87	0.10	0.005	3.35	0.07	0.07

PBC – Potential buffering capacity, AR – Activity ratio, KL – Labile potassium, KX – Specifically held K, ΔK – Difference in the concentration of K^+ added in soil that is in extracted solution and K^+ in leachates, CR – Concentration ratio, SE (m) – mean standard error, LSD – Least significant difference) (ZT – Zero-tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without)

3.4.5. Difference in the concentration of K+ added in soil that is in the extracted solution and K^+ in the leachates (ΔK)

In the soil depth 0–10 cm, the highest value ΔK was observed in ZTR0B1, and the lowest value was in CTR1B1. In soil depth 10–20 cm, ΔK was significantly higher in the treatment CTR0B0 compared to the lowest value in ZTR1B0 (Table 5). In the soil layer 20–40 cm, the highest ΔK was recorded in ZTR0B1and the lowest ΔK was in CTR0B0 and CTR0B1.

3.4.6. Concentration ratio (CR)

At a soil depth of 0–10 cm, the highest value of CR was observed in CTR1B0, and the lowest value was in ZTR0B1. At a soil depth of 10–20 cm, CR was significantly higher in treatment CTR1B1 compared to the lowest value in ZTR1B0. In the soil layer 20–40 cm, the highest CR was recorded in CTR0B0, and the lowest CR was in ZTR1B0.

3.5. Pearson correlation matrix of quantity-intensity parameters

Data on the correlation matrix among Q/I parameters is presented in Table 6, which indicates that exchangeable K was positively and significantly correlated with PBC and KX, and negatively and significantly correlated with AR. PBC was positively and significantly correlated with KX and ΔK, and negatively and significantly correlated with AR and CR. AR is negatively correlated with KX and ΔK and positively and significantly correlated

Table 6
Pearson correlation matrix (Quantity-Intensity-parameters)

	EXK	PBC	AR	KL	KX	ΔK	CR
EXK	1.000	0.820*	(–)0.761*	0.200	0.856**	0.464	(-)0.472
PBC		1.000	(–)0.973**	0.298	0.981**	0.854**	(–)0.851**
AR^K			1.000	(–)0.167	(–)0.961**	(–)0.908**	0.905**
KL				1.000	0.334	0.130	(–)0.184
KX					1.000	0.806*	(–)0.798*
ΔK						1.000	(–)0.938**

PBC – Potential buffering capacity, AR – Activity ratio, KL – Labile potassium, KX – Specifically held K, ΔK – Difference in the concentration of K^+ added in soil that is in extracted solution and K^+ in leachates and CR – Concentration ratio
* Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

to CR. KX is positively and significantly correlated with ΔK and negatively and significantly correlated with CR. ΔK is negative and highly significantly correlated with CR.

4. Discussion

The introduction of zero tillage (ZT) over conventional tillage (CT), bio-cover incorporation/mulching, and bioinoculants (B) in the area has resulted in higher crop productivity and improved soil quality (Padbhushan et al., 2023). A limited number of studies have reported on the impact of these management practices on soil K dynamics in the Himalayan foothills of India, which is one of the essential elements for soil and plant sustainability. This study reported the effects of agricultural practices (tillage, R, and B) on fractions of K, crop yield, K uptake, and quantity-intensity relations in the Himalayan foothills of India.

4.1. Effect of management practices on fractions of potassium in soil

The water-soluble fraction of K is one of the readily available fractions of soil K present in a small proportion of the total K. It is immediately taken up by the plants for their growth and development. The water-soluble K concentration in the soil depends on weathering, R return, clay transformation, and the previous crops sown in the field (Kumar et al., 2022; Kumari et al., 2024). Adding R released labile K from organic residues and increased water-soluble K. Additionally, R addition facilitates both solubilization and chelation, thereby increasing the concentration of water-soluble K. Considering the main effects, water-soluble K was observed to be higher in CT than in ZT up to a 20 cm soil layer, which may be attributed to greater leaching losses in ZT. These findings were also similar to the results of Sarkar et al. (2013), Habib et al. (2014), Meena and Biswas (2014), and Das et al. (2019). Ranganathan and Satyanarayan (1980) and Sharma et al. (2023) reported that tillage and R addition affected water-soluble K content, which decreased with increasing soil depths. Upward translocation of water-soluble K from the lower soil layers to the surface could occur due to capillary rise.

Exchangeable K is also a readily available fraction of K, immediately available for plant uptake, after water-soluble K (Kumar et al., 2022; Kumari et al., 2024). Water-soluble K and some parts of the exchangeable K fraction, the available K, are determined by the ammonium acetate method. The results revealed that long-term intensive cultivation using a rice-wheat cropping system with altered management practices can vary the amount of exchangeable K in post-wheat soil. Lakaria et al. (2012) reported a similar range of exchangeable K in their study. Dhanorkar et al. (1994) observed a similar trend with tillage practices, suggesting that the movement of K to the exchange site is mediated by the higher cation exchange capacity of the soil, which increases when performing ZT over CT practices. Kumari et al. (2017) found that the addition of R resulted in an increase in the exchangeable K content of the soil. Adding R, K fixation was observed due to its continuous addition with potassic fertilizers (Sepehya, 2011; Majumdar et al., 2014). The additional supply of organic source manures increases the cation exchange capacity of the soil and hence can hold more exchangeable K and finally convert K from the non-exchangeable fraction to the exchangeable fraction (Black et al., 1968; Deubel et al., 2011; Dhanorkar et al., 1994; Sharma et al., 2009). The results of this study were similar to the findings reported by Santhy et al. (1998), Singh and Singh (2001), Sawarkar et al. (2013), and Meena and Biswas (2014).

Non-exchangeable K is not an instantly available fraction of K in the soil for plants. The plant utilizes this fraction of K when non-exchangeable K is unavailable for the long-crop growing period (Kumar et al., 2022). Meena and Biswas (2014), Jatav et al. (2010), and Sharma et al. (2013) also reported similar results, indicating that the regular application of organic sources increased the non-exchangeable K fraction. Song and Huang (1988) reported that the increase in non-exchangeable K in the soil during the use of organic sources is due to the release of K from K-containing primary minerals (biotite, muscovite) due to dissolution with organic acids produced because of the degradation of organic sources. The sum-up contribution of water-soluble K, exchangeable K, and non-exchangeable K for this study was <10% of the total K, irrespective of the treatment combinations.

Mineral K or structural K is one of the fractions of K bound to the structure of the rock-fractioning minerals. Typical examples of mineral K include K-feldspar, orthoclase, microcline, and mica (biotite and muscovite). The fraction of K changes over time through long-term intensive cultivation and human disturbances resulting from management practices. Intensive cultivation and long-term management affected the mineral K. Singh and Singh (2001) reported similar findings.

Total K is the sum of all fractions of K in which mineral K constitutes the Major portion of >90% of the total K. Change in total K concentration is not a short-duration process but requires a long period (Kumar et al., 2022). This statement is also disclosed through this study, where after the 15^{th} crop cycle, the concentration of total K was changed with treatments. Total K is not a crucial parameter for understanding plant K uptake; however, it provides information about the Soil K reservoir. In this study, tillage has been shown to influence total K, as reported by Singh and Singh (2001). The correlation study suggested that fractions of K are related to one another, and a similar result was reported by Kumari et al. (2024).

4.2. Effect of management practices on crop yield, potassium uptake and potassium use efficiency

The grain yield was improved following the addition of ZT and B. The Combination of tillage and R addition did not influence the yield, but the combination of R addition and B, and tillage and B, had increased the yield. Similarly, Dixit et al. (2019) observed the positive impacts of ZT on wheat yield over five years of cultivation. The higher yield of wheat in ZT is due to the compound effects of additional nutrients held in the system (Kaschuk et al., 2010), lesser weed population (Chauhan et al., 2007), improved soil physical health, better water regimes, and improved nutrient use efficiency compared to CT (Jat et al., 2013;

Singh et al., 2016). Potassium uptake was generally consistent with the yield data. We observed that ZT had a higher K uptake by wheat straw than CT, and crop residue and biofertilizer inoculation support wheat K uptake, which is eco-friendly, nutrient-rich, and easily biodegradable and therefore, releases K. These organic materials enhanced microbial action for a rapid decomposition phenomenon and improved root growth for better wheat K uptake. Among K use efficiency, the partial factor productivity was lower for treatments supplied with R and higher for those supplied with B. The reciprocal internal use efficiency of K increased with ZT over CT, R, and B.

4.3. Effect of management practices on quantity-intensity parameters

Potential buffering capacity (PBC) measures the ability of soil to resist the change with given K. PBC suggests that higher values in soil maintain the higher availability in soil at the time of stress of K, while lower values of PBC mean lower ability to maintain the availability in stress (Wang et al., 2004). The strong K buffering capacity also suggests that the soil has a higher ability to retain K and resist changes in K levels (Al-Zubaidi et al., 2008). A higher value in ZT-based systems was observed due to its R retention in soil (Kumar et al., 2022). Zero tillage had a higher PBC than permanent raised beds and CT. The results of Suttanukool, Darunsontaya, and Jindaluang (2019) are compatible with the range of PBC. Tillage, R, and B were significant variations in the activity ratio (AR). An accurate estimation of the K^+ availability in soil is by the AR in equilibrium solutions. These variations in the AR in soils could be attributed to variations in the K^+ concentrations of equilibrating solutions, the contents of calcium and/or magnesium, and, most likely, to variations in the soils' mineralogical composition (Yawson et al., 2011). The results were corroborated by Kumar et al. (2022), who found lower values in the ZT-based system compared to the CT-based system due to the organic matter content, which causes fractions to chelate with available nutrients and become unavailable to plants at specific periods. The higher values of KL than that of the ammonium acetate extractable K^+ suggest that K^+ should primarily be produced via solubility or diffusion mechanisms rather than exchange in certain of these soils (Abaslou and Abtahi, 2008). The finding was well in concurrence with Panda and Patra (2018) and Kumar et al. (2022). These results observed higher values in the case of the ZT system than in CT and it might be due to the availability of K. It was observed that greater values with a negative sign mean greater release of K in soil solution. The magnitude of concentration ratio (CR) provides a clue as to the kind of exchange sites involved in the reaction (Barbayiannis et al., 1996). The CR value depends on the available K values in the soil. The higher the available K are the greater the CR of the soil. Higher values give insight into soils representing better K^+ intensity. Due to the presence of basic cations in the long-term experiment, the CR was lower in the ZT than in the CT. These results conformed to Kumar et al. (2022). K^+ is adsorbed on planar sites if the CR values are greater than 0.01, and if they are less than 0.001, K^+ is absorbed at high-affinity (specific) sites (Sparks and Liebhardt, 1981).

Overall, this study indicates that to optimize wheat yield and achieve economic benefits, it is essential to effectively improve and maintain K supply. An insufficient supply of K leads to significant losses in wheat yield and quality, whereas a sufficient K supply results in high wheat yields, improved quality, and ultimately, resilience to environmental stresses.

5. Conclusions

We evaluated three agricultural practices (tillage, bio-cover addition and bioinoculants) and their impact on wheat production and soil potassium (K) sustainability. We concluded that wheat yields are influenced by the following agricultural practices. Additionally, zero tillage (ZT) and the addition of bio-inoculants to bio-cover enhanced the availability of K, whereas the use of bioinoculants had a minimal impact. Specifically, ZT improved all fractions of K except for water-soluble K. Bio-cover addition increased all fractions of K as well as total K. In contrast, bioinoculants had a minimal effect on K fractions. Among the treatment combinations studied, ZTR1B1 had in the highest levels of both fractions of K and total K, showing best recommended treatment for enhancing K availability in soil and plant. Additionally, the various fractions of K were found to be interrelated, signifying that they exist in a dynamic equilibrium. The relationships among quantity-intensity parameters further assist in evaluating the supplying power of K. Higher potential buffering capacity values suggest a lower concentration of K in the soil solution. The findings of quantity-intensity parameters supported our recommendation that the treatment ZTR1B1 had the highest K-supplying capacity.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Abhas Kumar Sinha – Conceptualization, Funding acquisition, Supervision. **Anusha Pabbu** – Data curation, Investigation, Visualization, Writing – original draft. **Gopal Kumar** – Validation. **Achin Kumar** – Writing – review & editing. **Rajeev Padbhushan** – Methodology, Writing – original draft, Writing – review & editing. All authors read and approved the final manuscript.

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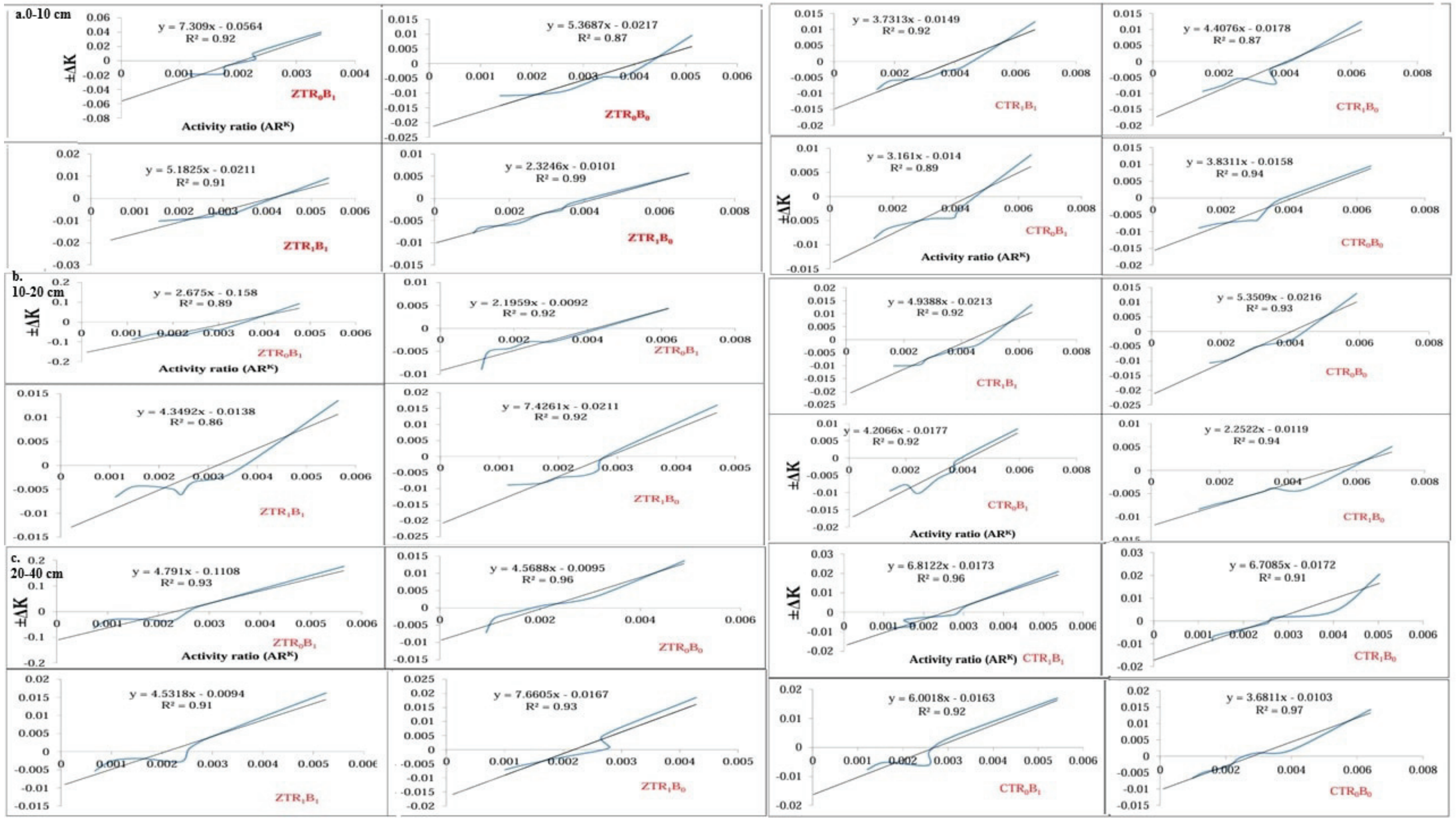

Supplementary Fig. S1. Effect of tillage, bio-cover addition, and bioinoculants on Quantity-Intensity parameters in post-wheat soil depths (0–10 cm, 10–20 cm and 20–40 cm) after the 15th crop cycle (ZT – Zero tillage, CT – Conventional tillage, R – Bio-cover (1 – with and 0 – without), B – Bioinoculants (1 – with and 0 – without))