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Residue and Potassium Management Strategies to Improve Crop Productivity, Potassium Mobilization, and Assimilation under Zero-Till Maize–Wheat Cropping System

Raghavendra Madar ^{1,*}, Yudh Vir Singh ², Mahesh Chand Meena ², Tapas Kumar Das ², Venkatesh Paramesh ³, Fahed A. Al-Mana ⁴, Mohamed A. Mattar ⁵ and Hosam O. Elansary ^{4,6,7,*}

¹ ICAR-Indian Institute of Soybean Research, Khandwa Road, Indore 452001, Madhya Pradesh, India

² ICAR-Indian Agricultural Research Institute, New Delhi 110012, India; yvsingh63@yahoo.co.in (Y.V.S.); mcmeena@gmail.com (M.C.M.); tkdas64@gmail.com (T.K.D.)

³ ICAR-Central Coastal Agricultural Research Institute, Ela, Old Goa, Goa 403402, India; parameshagron@gmail.com

⁴ Plant Production Department, College of Food and Agricultural Sciences, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia; falman@ksu.edu.sa

⁵ Department of Agricultural Engineering, College of Food and Agriculture Sciences, King Saud University, Riyadh 11451, Saudi Arabia; mmattar@ksu.edu.sa

⁶ Floriculture, Ornamental Horticulture, and Garden Design Department, Faculty of Agriculture (El-Shatby), Alexandria University, Alexandria 21545, Egypt

⁷ Department of Geography, Environmental Management, and Energy Studies, University of Johannesburg, APK campus, Johannesburg 2006, South Africa

* Correspondence: raghavendra4449@gmail.com (R.M.); helansary@ksu.edu.sa (H.O.E.)

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Abstract: Understanding of the potassium (K) nutrient cycle and its microbial transformation of unavailable forms of soil K to plant-available K is crucial in any agroecosystem for strategic nutrient management through inorganic fertilizer, crop residue (CR), and microbial applications. Therefore, the present investigation was undertaken to study the effect of crop residue and K management practices on crop productivity, K mobilization from native soil K-pool, and crop assimilation of K under a zero-till maize–wheat cropping system. The experiment consisted of four residue levels (0, 2, 4, and 6 Mg ha⁻¹) and five K levels (0, 50%, 100%, 150% RDK [recommended dose of K] and 50% RDK + potassium solubilizing bacteria, KSB). Results showed that CR retention at 6.0 Mg ha⁻¹ significantly improved grain yield (of maize by 10.17%; wheat by 9.87%), dry matter accumulation, K uptake and redistribution in native soil K pools (water soluble K (WSK), exchangeable K (EK) and non-exchangeable K (NEK)) at 30 and 60 days after sowing and at harvest as compared to no CR. Among the K management, 50% RDK+KSB reported significantly higher grain yield (of maize by 26.22%; wheat by 24.70%), dry matter accumulation, K uptake, and native K pools (WSK, EK, and NEK) at different growth stages compared to no K. Total K did not differ significantly due to residue and K management. The highest actual change of K reported with 6.0 Mg ha⁻¹ CR (51 kg ha⁻¹) and 50% RDK+KSB (59 kg ha⁻¹) over control. Significant ($p \leq 0.01$) positive correlation was found among grain yield, dry matter accumulation, K uptake, the actual change in K and different native K pools. It can be concluded that retention of 6 Mg ha⁻¹ CR and supply of 50% K through inorganic fertilizer along with seed inoculation of KSB biofertilizers, improved crop growth, productivity by enhancing K assimilation as a consequence of the release of non-exchangeable K and through the application of CR and K treatments under a zero tillage maize–wheat system.

Keywords: conservation agriculture; cropping system; K-balance; K-dynamics; potassium solubilizing bacteria

1. Introduction

The Indo-Gangetic Plain (IGP) of India belongs to a semi-arid agroecosystem, wherein, rice–wheat is the dominant cropping system. Continuous practice of such a system with intensive tillage accompanied by crop residue burning and imbalanced use of fertilizer resulted in soil nutrient deficiency, groundwater depletion, weed problems, soil salinity, and other environmental problems [1,2]. To overcome these problems, successful management of available resources with/without changing the cropping system will play a critical role. Resources such as water, nutrients, and crop residue management are imperative to achieving sustainability. India generates around 620 million tons of crop residues, of which 15.9% of those residues are burnt on the farm itself [3]. This has affected human health due to air pollution and also affected soil health. Recently, the crop residue burning in the IGP region of the country is causing major air pollution in the Northern part of India by reducing the air quality index [4]. Furthermore, the burning of residue resulted in a loss of 25% nitrogen (N), 25% phosphorus (P), 75% potash (K), and 20% sulfur (S) retained in the residues. Potassium (K) is the second most abundant mineral nutrients in crop production and is the third utmost important primary nutrients that affect crop productivity after nitrogen (N) and phosphorus (P) in cereal-based intensive cropping system [5,6]. K deficiency is a worldwide problem since K level depletion is rapid and is reported more often in Asia [7].

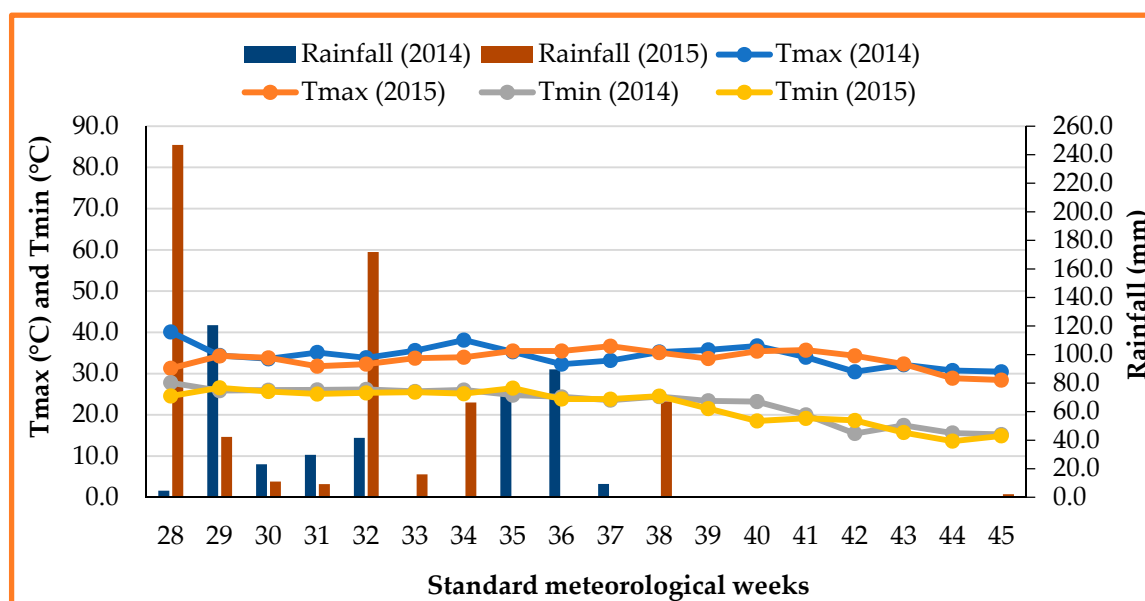
In India, farmers seldom apply K fertilizer and resort to only N and P fertilizers as they consider that these nutrients contribute more to profitable yield and are unaware of the importance of K nutrition in crop production. This practice in intensive cereal–cereal cropping systems has resulted in depletion of available K due to continuous and higher K uptake by crops (1.5 times more K than N) without its replenishing back to soil has resulted in a negative balance of K (69% K) in soil [8]. As such, India does not have any reserve K sources and completely depends on imports from other countries for K fertilizer and incur high foreign exchange. Therefore, the identification of alternative indigenous K fertilizers like potassium solubilizing bacteria (KSB) and crop residue holds prominence in current intensive cropping systems under the semi-arid agro-ecosystem of India. The efficiency of applied K is significantly affected by crop residue retention in soil [9]. It is well documented that K concentration in vegetative tissue is much higher than grain and grain does not accumulate much K. Therefore, replenishing crop residue in the field after harvest of previous crops through conservation tillage practices substantially reduces the K fertilizer input requirement [10]. Hence, straw retention in the field can contribute a considerable amount of plant K to the soil. Moreover, around 90–98% of K in the soil exists in the form of insoluble K-minerals such as feldspar and mica [11] under such situations KSB, belonging to *Bacillus* group facilitates the release of K from bound form to a soluble plant-available form from K bearing minerals in soil [12]. Furthermore, K supply to crops is a complex phenomenon involving relationships among its various chemical forms (water soluble K (WSK), exchangeable K (EK), non-exchangeable K (NEK), and total K (TK)) in native soil. Therefore, the dynamic exchange between these different native soil K pools controls the release of soil K from rapidly and slowly exchangeable forms to plant-available forms under intensive cropping without K application [13]. The rate of K release from soil solid phase to its exchangeable K can significantly affect plant K uptake, and availability of soil K to plants is closely related to its rate of release from the rapidly and slowly exchangeable K pool [14]. The EK and WSK are replenished by the NEK pool when it is solubilized by KSB strains, plant removal, and leaching [15]. Some NEK held in the interlayer of 2:1 type clay mineral could be released relatively easily to provide a substantial portion of K removed by crops during the growing season [16]. Studies also suggested that EK, NEK, and clay mineralogy should be considered together while making K fertilizer recommendation [17]. K availability in sandy loam soils (mainly illite) with

a low degree of K saturation is a complex phenomenon. These soils under a maize–wheat system show medium to high exchangeable K but suffer from K stress, indicating the rate of K uptake by crops does not match with the release by soil. It thus becomes imperative to study the changes in the native soil K pools as influenced by residue and K management practices to determine the fate of applied K by different means to optimize K input. Therefore, the premise of this study is to reorient the residue with potassium interventions under zero tillage in maize–wheat cropping system that may increase K availability by redistribution of native soil K pools for crop assimilation and minimize negative K balance. Therefore, the objectives of this study are to assess: (1) changes in pertinent native soil K-pools, K budgeting; (2) crop growth and K assimilation on crop productivity; (3) relationship between changes in native soil K pools and crop growth, K assimilation, and productivity.

2. Materials and Methods

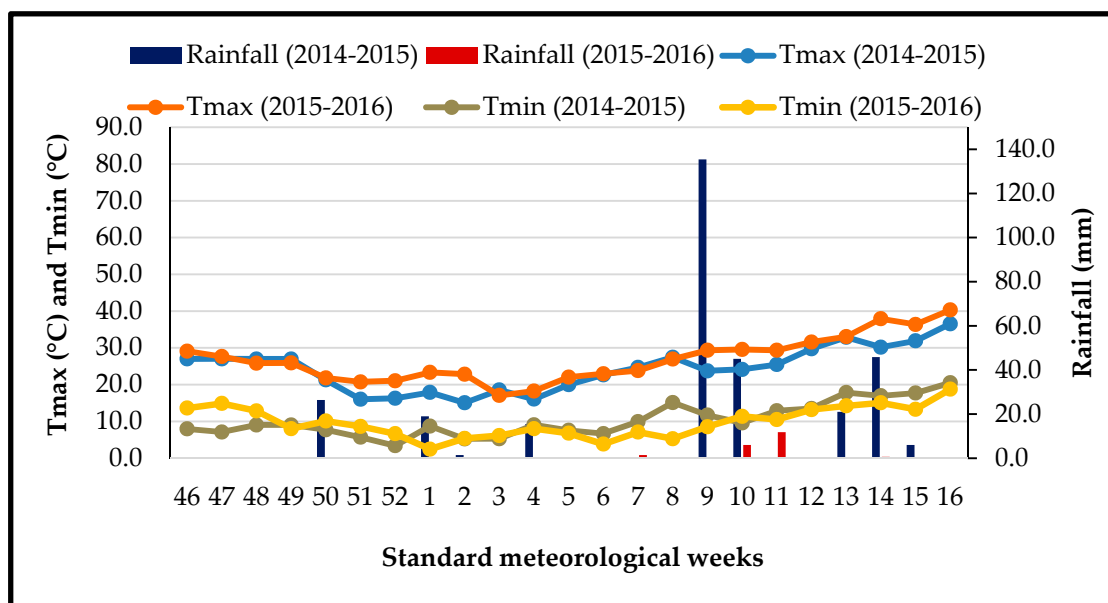
2.1. Experimental Site, Details, and Management

The field experiment was initiated in the rainy season of 2013 to evaluate the effect of different levels of residues of maize and wheat, levels of K application on pertinent soil quality indicators and productivity under the maize–wheat system. The detailed experimental condition and study area have been previously documented [18]. During the rainy season (kharif) of 2014 and 2015, wherein maize was grown, the total rainfall received was 395.4 and 633.10 mm, respectively. However, during the winter season (rabi), when wheat was grown (2014–2015 and 2015–2016) rainfall pattern was erratic and the variations were 315.80 mm and 19.80 mm, respectively. The mean maximum and minimum temperatures during maize growth were (34.27, 33.47 °C), and (22.83, 22.13 °C), respectively during 2014 and 2015. For wheat, the recorded mean maximum and minimum temperature were (26.81, 24.27 °C), and (10.36, 9.77 °C), respectively during 2014–2015 and 2015–2016 (Figure 1a,b). The soil characteristic pertaining to this study is also been elucidated previously [18]. The complete details on the experimental treatments, the following design, and crop management have previously described in detail [18]. The potassium solubilizing bacteria (KSB) belonged to the strain *Bacillus decolorationis*. The N, P, and K added to the soil through crop residue of maize and wheat are also described in the earlier published research [18].



(a)

Figure 1. Cont.



(b)

Figure 1. (a) Weekly meteorological data for the *Kharif* seasons maize crop (2014 and 2015); (b) Weekly meteorological data for the *Rabi* seasons wheat crop (2014–2015 and 2015–2016).

2.2. Plant Sampling and Analysis

Maize plants in quadrant of 0.70×0.70 m rows were selected randomly from the area marked for dry matter accumulation estimation. Plants were uprooted, and above ground, portions were cut for observations at 30 and 60 days after sowing (DAS) and harvest. The sampled plants were first air-dried for three days and then dried in a hot air oven at 65°C for 48 h. Dry weight was expressed in g plant^{-1} . Similarly, for wheat, an area of 0.5 m^2 (0.70×0.70 cm) was taken from the side rows and dry matter accumulation estimated as per the procedure described for maize and was expressed in g m^{-2} . The above-ground biomass was harvested at maturity and grain and straw yield were recorded for each crop (maize, wheat) and expressed as kg ha^{-1} . Representative dry matter of maize and wheat at 30 and 60 DAS, and grain and straw samples at harvest were then subjected to nutrient analysis. Plant potassium content was estimated through the flame photometric method and expressed in percentage (%). The K uptake by both crops was determined by multiplying dry matter, grain/straw yield with their respective nutrient content, and expressed in kg ha^{-1} .

2.3. Soil Sampling and Analysis

Representative soil samples were collected from each plot with the help of tube auger from 0–15 cm soil depth at 30 and 60 DAS, and harvest of maize and wheat crops and soil samples were subjected to the analysis of different soil K fractions. Water-soluble K was extracted using (soil:water: 1:5) as described by Page et al. [19]. Exchangeable K from soil was extracted by shaking neutral normal ammonium acetate for 5 min (1:5) Hanway and Heidel [20]. The HNO_3 extractable K in soil was extracted with 1N boiling HNO_3 1:10 [21]. The K content in different soil extractant was measured flame photometrically. Non-exchangeable K was calculated as the difference between boiling HNO_3 K and available K. Total K was estimated by digestion of soil with hydrofluoric acid in a closed vessel [19].

2.4. K Budget Estimation

For K input contribution through residue, representative samples left after the harvest of each crop were collected from each plot. The varied level of residue (0, 2, 4, and 6 Mg ha^{-1}) retained as per the treatment. All the samples were successively washed thoroughly with tap water, 0.05 M HCL

solution and de-ionized water, and dried at 65 °C in a hot air oven. The dried samples were ground in a stainless-steel Willey mill, wet digestion in 4:1 mixture of nitric and perchloric acid, and total K content were determined photometrically in aqueous extracts. Total K input through crop residue was obtained by multiplying their K content with the quantity recycled in each treatment. Average K input for each plot in different treatment was taken into account for the computation of K input through residue during the study. The K input added through muriate of potash (MoP) fertilizer at different levels (0, 30, 60, 90 kg ha⁻¹ and 30 kg ha⁻¹ + KSB) as per the treatment. The representative samples of rainwater (collected thrice during maize and once during wheat) and irrigation water (thrice during each season) were analyzed for total K content following Page et al. [19]. Total K input through rainfall and irrigation water was computed by multiplying K contents averaged across the seasons with the total amount of rainfall occurred and irrigation water used during the individual season, and finally summing up the seasonal inputs during the study period. The K input through crop residue, fertilizers, rainfall, and irrigation was summed up to work out the total K input under the different treatments. The sum of the final value of an available K_{in} soil and total K uptake by both the crops during experimentation gives the total output of K as per the treatments. The changes in apparent K balance at the end of two years of experimentation was calculated by subtracting the K removal by the crops from that added through different sources. The actual change of the K status in the soil is the difference between the final and initial available K and expressed in kg ha⁻¹. Since reported values of different K input parameters are based on averages across the replications, mean values of total K input, K output, and K balance (apparent and actual change) are reported.

2.5. Determination of Contribution of Different Soil K Pools to Total K

The soil K pools (water-soluble K, exchangeable K, non-exchangeable K) contribution to total K at the end of each cropping cycle was determined by using the following equation.

$$\text{Contribution of soil K pool to total K (\%)} = \frac{\text{Soil K pool whose contribution to total K need to estimate}}{\text{Total K}} \times 100$$

2.6. Statistical Analysis

The data were analyzed by using SAS statistical software (ver. 9.2; SAS Institute, Cary, NC, USA). Two-way analysis of variance (ANOVA) was carried out with the ANOVA procedure in SAS enterprise guide 4.2 and the Fisher least significant differences (LSD) and Tukey's range test were used to separate the treatment means and correlation analysis was carried out through R studio version 3.6.0 [22].

3. Result

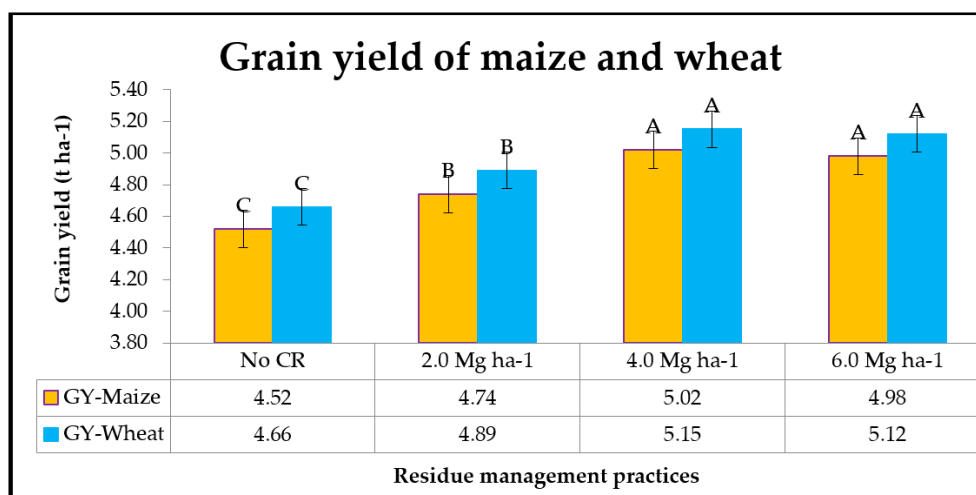
3.1. Crop Growth and Yield of Maize and Wheat as Influenced by Residue and K Management

Application of crop residue at 4.0 and 6 Mg ha⁻¹ CR recorded significantly higher dry matter accumulation at different growth stages (30, 60 DAS and at harvest) and grain yield of maize and wheat over No CR and 2.0 Mg ha⁻¹ CR. Potassium management of 50% RDK+KSB, 100% RDK, and 150% RDK gave significantly higher dry matter accumulation and grain yield in both the crops as compared to No K and 50% RDK (Table 1 and Figure 2a,b). The interaction effect of crop residue and K intervention was found to be non-significant.

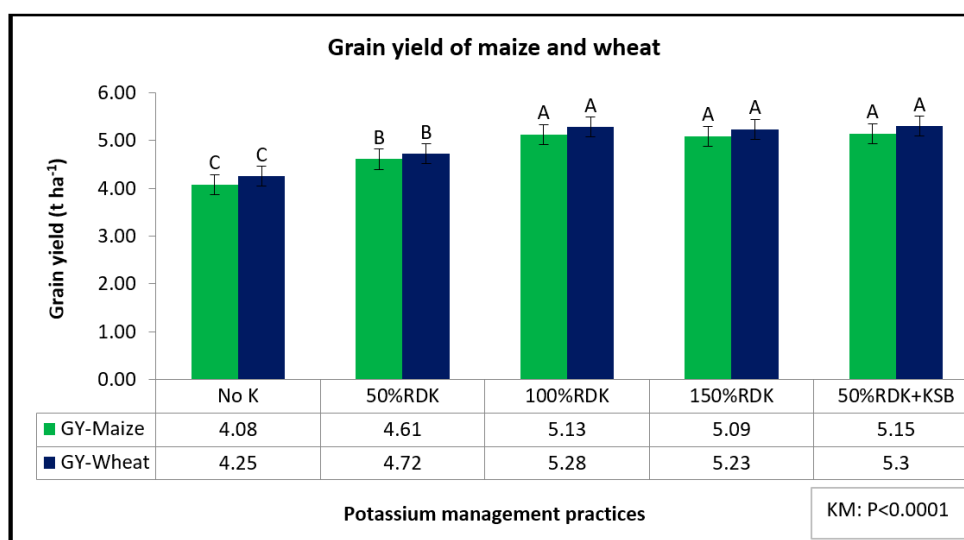
Table 1. Crop residue and potassium management practices on dry matter production of maize and wheat at different crop growth stages in zero tillage maize–wheat system (pooled data of two years).

Crop Residue and K Management	Maize (g plant ⁻¹)														
	30 DAS					60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	19.7 ± 1.0 ^c	21.6 ± 1.1 ^b	23.7 ± 1.2 ^c	23.5 ± 1.2 ^a	22.2 ^B	66.2 ± 4.7 ^b	72.7 ± 3.7 ^b	80.7 ± 4.1 ^b	80.6 ± 0.1 ^b	75.1 ^C	131 ± 19.6 ^b	146 ± 7.4 ^b	164 ± 1.3 ^b	164 ± 8.3 ^b	151 ^C
50%RDK	21.8 ± 1.1 ^{bc}	23.8 ± 1.2 ^b	25.8 ± 1.3 ^{bc}	25.7 ± 1.3 ^a	24.3 ^B	75.1 ± 3.8 ^b	81.7 ± 4.1 ^b	89.7 ± 4.5 ^b	89.5 ± 4.5 ^{ab}	84.0 ^B	155 ± 7.8 ^{ab}	170 ± 8.5 ^{ab}	188 ± 9.4 ^{ab}	187 ± 9.4 ^{ab}	175 ^B
100%RDK	26.7 ± 1.3 ^a	28.7 ± 1.4 ^a	30.8 ± 1.5 ^{ab}	30.6 ± 1.5 ^a	29.2 ^A	92.8 ± 0.1 ^a	99.4 ± 4.9 ^a	107 ± 5.3 ^a	107 ± 0.1 ^a	101 ^A	172 ± 8.6 ^a	187 ± 9.4 ^a	205 ± 10.2 ^a	204 ± 10.2 ^a	192 ^A
150%RDK	26.3 ± 1.4 ^{ab}	28.6 ± 1.4 ^a	30.7 ± 1.5 ^{ab}	30.5 ± 1.5 ^a	29.1 ^A	92.7 ± 4.6 ^a	99.2 ± 4.9 ^a	107 ± 5.3 ^a	107 ± 5.3 ^a	101 ^A	171 ± 8.5 ^a	186 ± 9.3 ^a	204 ± 10.2 ^a	204 ± 0.2 ^a	191 ^A
50%RDK + KSB	28.3 ± 3.0 ^a	30.3 ± 1.5 ^a	32.4 ± 3.6 ^a	32.2 ± 11.6 ^a	30.8 ^A	93.2 ± 4.6 ^a	99.8 ± 5.0 ^a	108 ± 0.9 ^a	107 ± 18.9 ^a	102 ^A	173 ± 0.2 ^a	188 ± 10.5 ^a	208 ± 13.7 ^a	204 ± 14.1 ^a	193 ^A
Mean	24.6 ^B	26.6 ^B	28.7 ^A	28.6 ^A		84.1 ^C	90.6 ^B	98.6 ^A	98.5 ^A		160 ^C	175 ^B	194 ^A	193 ^A	
ANOVA															
CR			0.0022					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			1.00					1.00					1.00		
Wheat (g m ⁻²)															
Crop Residue and K Management	30 DAS					60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	24.6 ± 4.3 ^a	26.8 ± 0.0 ^b	29.3 ± 0.1 ^b	43.4 ± 0.1 ^a	27.5 ^C	114 ± 14.5 ^b	125 ± 6.3 ^b	139 ± 7.0 ^b	139 ± 0.1 ^b	129 ^C	714 ± 36.2 ^b	780 ± 39.3 ^b	864 ± 43.5 ^b	863 ± 43.4 ^b	805 ^C
50%RDK	27.1 ± 1.4 ^a	29.3 ± 1.5 ^{ab}	31.8 ± 1.6 ^{ab}	47.0 ± 1.6 ^a	29.9 ^B	126 ± 6.4 ^{ab}	137 ± 6.9 ^b	152 ± 7.6 ^b	151 ± 7.6 ^{ab}	142 ^B	766 ± 38.5 ^b	832 ± 41.8 ^b	916 ± 46.0 ^{ab}	915 ± 45.9 ^b	857 ^B
100%RDK	29.0 ± 1.4 ^a	31.2 ± 1.6 ^a	33.7 ± 0.1 ^a	49.9 ± 1.7 ^a	31.8 ^{AB}	150 ± 7.5 ^a	161 ± 0.2 ^a	175 ± 8.8 ^a	175 ± 8.8 ^a	166 ^A	892 ± 44.5 ^a	958 ± 47.8 ^a	1042 ± 52.0 ^a	1041 ± 51.9 ^a	983 ^A
150%RDK	28.7 ± 1.4 ^a	30.8 ± 1.5 ^{ab}	33.4 ± 1.7 ^a	49.4 ± 1.7 ^a	31.5 ^{AB}	150 ± 7.5 ^a	161 ± 8.0 ^a	175 ± 8.8 ^a	175 ± 8.7 ^a	165 ^A	890 ± 44.4 ^a	956 ± 47.7 ^a	1040 ± 51.9 ^a	1039 ± 51.8 ^a	981 ^A
50%RDK + KSB	29.4 ± 0.0 ^a	31.6 ± 2.6 ^a	34.1 ± 1.7 ^a	50.2 ± 3.8 ^a	32.2 ^A	151 ± 7.5 ^a	162 ± 8.1 ^a	179 ± 10.2 ^a	176 ± 19.3 ^a	167 ^A	892 ± 44.5 ^a	959 ± 47.8 ^a	1074 ± 103 ^a	1041 ± 51.9 ^a	992 ^A
Mean	27.7 ^C	29.9 ^B	32.5 ^A	32.2 ^A		138 ^C	149 ^B	164 ^A	163 ^A		831 ^C	897 ^B	987 ^A	980 ^A	
ANOVA															
CR			<0.0001					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			1.00					1.00					0.9999		

Data are means of three replicates ± Standard deviation; means with different small and capital letters in the same column and rows differ significantly at $p = 0.05$ according to Fisher LSD and turkey's test. CR: Crop residue, KM: Potassium management, RDK: Recommended dose of potassium, KSB: Potassium solubilizing bacteria. Values under ANOVA are probabilities (p -values) of source of variance.



(a)



(b)

Figure 2. (a) Crop residue management on grain yield of maize and wheat under zero tillage maize–wheat system (pooled data of two years), GY: grain yield, CR: $p < 0.0001$; (b) Potassium management on grain yield of maize and wheat under zero tillage maize–wheat system (pooled data of two years), GY: grain yield.

3.2. Effect on K Assimilation (Uptake) by Maize and Wheat

Crop residue and K management practices showed significant improvement in uptake of K at different growth stages (30 and 60 DAS) in maize stover, wheat straw, and grain+straw/stover at harvest of maize and wheat (Table 2). Among different residue levels highest K uptake in maize stover, wheat straw at 30 and 60 DAS, and at harvest of maize and wheat grain+straw/stover were recorded in 6.0 Mg ha⁻¹ CR as compared to 4.0 and 2.0, Mg ha⁻¹ CR over no residue application. Highest K uptake in grain and straw of maize and wheat at different growth stages were found to be significantly increased with 50% RDK+KSB, 100% RDK, and 150% RDK as against no K application and 50% RDK. The interaction was found to be non-significant.

Table 2. Crop residue and potassium management practices on potassium uptake (kg ha^{-1}) of maize and wheat at different crop growth stages under zero tillage maize–wheat system (pooled data of two years).

Crop Residue and K Management	30 DAS					Maize 60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	1.96 ± 0.4 c	3.01 ± 0.6 b	6.51 ± 0.3 b	7.16 ± 0.9 b	4.66 C	7.3 ± 1.2 c	11.9 ± 2.6 b	21.8 ± 2.6 b	22.4 ± 11.0 b	15.9 C	96.6 ± 10.3 c	113 ± 10.1 b	134 ± 6.5 c	136 ± 3.0 c	120 C
50%RDK	4.62 ± 1.3 bc	6.38 ± 2.4 ab	9.70 ± 1.9 ab	9.54 ± 0.5 ab	7.56 B	14.8 ± 1.9 c	24.3 ± 9.0 ab	41.3 ± 10.1 ab	42.2 ± 2.5 b	30.6 B	116 ± 10.9 bc	141 ± 6.4 a	159 ± 9.0 b	161 ± 6.4 b	144 B
100%RDK	6.58 ± 0.5 ab	9.21 ± 1.7 a	14.7 ± 1.1 ab	15.7 ± 1.1 ab	11.5 A	25.7 ± 0.8 b	41.1 ± 12.2 a	56.8 ± 4.6 a	58.0 ± 4.7 a	45.4 A	144 ± 13.4 ab	160 ± 9.5 a	178 ± 10.8 ab	182 ± 2.8 a	166 A
150%RDK	6.84 ± 1.9 ab	8.86 ± 1.9 a	15.02 ± 1.8 a	16.0 ± 2.0 a	11.7 A	31.8 ± 4.3 b	39.3 ± 4.7 a	57.2 ± 6.2 a	58.4 ± 2.1 a	46.7 A	146 ± 7.7 a	161 ± 8.9 a	180 ± 6.5 ab	184 ± 6.0 a	168 A
50%RDK + KSB	8.71 ± 1.6 a	11.6 ± 2.6 a	16.6 ± 5.5 a	17.4 ± 7.6 a	13.6 A	41.4 ± 5.2 a	43.1 ± 10.9 a	59.3 ± 12.6 a	59.4 ± 16.8 a	50.9 A	152 ± 10.5 a	166 ± 12.4 a	186 ± 10.6 a	190 ± 8.4 a	173 A
Mean	5.74 B	7.82 B	12.5 A	13.2 A		24.2 C	31.9 B	47.3 A	48.2 A		131 C	148 B	168 A	170 A	
Anova															
CR			<0.0001					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			0.8991					0.7171					0.9891		
Crop Residue and K Management	30 DAS					Wheat 60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	0.21 ± 0.0 b	0.40 ± 0.1 b	0.62 ± 0.2 b	0.67 ± 0.1 b	0.48 C	1.87 ± 0.5 b	2.93 ± 0.5 c	3.79 ± 0.8 b	4.15 ± 0.6 b	3.19 C	61.8 ± 30.2 c	70.9 ± 25.0 c	97.4 ± 35.5 b	99.5 ± 19.5 b	82.4 C
50%RDK	0.41 ± 0.1 b	0.69 ± 0.0 b	1.20 ± 0.1 ab	1.25 ± 0.1 ab	0.89 B	2.50 ± 0.2 b	4.91 ± 0.1 b	8.24 ± 2.3 b	8.76 ± 1.0 ab	6.11 B	86.7 ± 5.4 bc	110 ± 12.3 bc	142 ± 14.2 ab	152 ± 10.8 a	122 B
100%RDK	1.11 ± 0.1 a	1.29 ± 0.1 a	1.52 ± 0.2 a	1.56 ± 0.2 a	1.37 A	9.27 ± 0.5 a	11.1 ± 0.0 a	13.2 ± 1.5 a	13.2 ± 0.9 a	11.7 A	113.8 ± 8.1 ab	137 ± 8.2 ab	170 ± 5.7 a	182 ± 9.6 a	151 A
150%RDK	1.15 ± 0.1 a	1.36 ± 0.3 a	1.59 ± 0.3 a	1.54 ± 0.5 ab	1.41 A	9.84 ± 1.8 a	11.4 ± 0.6 a	13.5 ± 2.0 a	13.5 ± 2.7 a	12.1 A	126.7 ± 10.8 ab	150 ± 11.1 a	184 ± 7.3 a	189 ± 6.9 a	162 A
50%RDK + KSB	1.32 ± 0.3 a	1.48 ± 0.3 a	1.64 ± 0.3 a	1.63 ± 0.6 a	1.52 A	10.13 ± 0.6 a	11.8 ± 0.6 a	13.9 ± 1.5 a	13.6 ± 3.0 a	12.4 A	129.7 ± 7.8 a	153 ± 10.0 a	188 ± 10.6 a	192 ± 21.5 a	166 A
Mean	0.84 C	1.04 B	1.31 A	1.34 A		6.72 C	8.42 B	10.5 A	10.6 A		103 C	124 B	156 A	163 A	
ANOVA															
CR			<0.0001					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			0.6559					0.4997					0.8703		

Data are means of three replicates ± Standard deviation; means with different small and capital letters in the same column and rows differ significantly at $P = 0.05$ according to Fisher LSD and turkey's test. CR: Crop residue, KM: Potassium management, RDK: Recommended dose of potassium, KSB: Potassium solubilizing bacteria. Values under ANOVA are probabilities (p -values) of source of variance.

3.3. Soil K Pools under Residue and K Management Practices in the Zero-Till Maize–Wheat System

Soil potassium (K) pools such as water-soluble K (WSK), exchangeable K (EK), and non-exchangeable K (NEK) in the soil at 30 and 60 DAS and at harvest of maize and wheat differed significantly due to variable residue and K management practices (Tables 3–5). Water-soluble K (WSK), exchangeable (EK), and non-exchangeable (NEK) in the soil at different growth stages in the present study were found to be significantly higher with 6.0 Mg ha⁻¹ CR as against control and 2.0 Mg ha⁻¹ CR, and did not significantly vary with 4.0 Mg ha⁻¹ CR. It was found that 150% RDK showed significantly higher WSK, EK, and NEK over control K and 50% RDK at different growth stages of maize and wheat. However, all soil K pools were statistically non-significant with 100% RDK and 50% RDK+KSB except 50% RDK+KSB for NEK. The total K (TK) pool in soil was found to be non-significant due to residue and K management at the end of each maize–wheat cropping cycle (Table 6). However, a slight improvement in TK found with a higher dose of K fertilizer application (150–100% RDK) and CR levels (6.0–4.0 Mg ha⁻¹) over No K, 50% RDK, and 50% RDK+KSB in the soil at the end of cropping cycle. The interaction effect of residue and K fertilization was found significant for WSK (at harvest of maize and wheat) and EK (at harvest of wheat), whereas, NEK and TK interaction effects were found to be non-significant.

3.4. K Budgeting under Zero-Till Maize–Wheat System

Data pertaining to K budgeting (K-input, output, apparent balance, and actual change of K) after two years under residue and K interventions are presented in Table 7. Apparent K balance was found to be negative with residue and K management except control (no-K). However, there was a marked improvement in the actual change of K in the soil due to residue and K management practices. Among CR treatment higher values of actual change in K were found with 6.0 followed by 4.0, 2.0 Mg ha⁻¹ CR and no CR. Among K levels 150% RDK showed the highest change in available K followed by 50% RDK+KSB and 100% RDK. Lowest and negative changes in available K were found with 50% RDK and K control, respectively.

Table 3. Crop residue and potassium management practices on water soluble potassium (kg ha⁻¹) of maize and wheat soil at different crop growth stages under zero tillage maize–wheat system (pooled data of two years).

Crop Residue and K Management	Maize 30 DAS					Maize 60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	19.8 ± 8.0 a	22.7 ± 1.0 b	23.2 ± 1.0 c	23.2 ± 1.0 a	22.3 C	19.8 ± 2.0 b	22.5 ± 1.0 b	23.1 ± 1.0 b	23.1 ± 1.0 b	22.1 C	19.5 ± 2.0 b	22.3 ± 1.0 b	22.9 ± 1.0 c	22.9 ± 1.0 b	21.9 C
50%RDK	23.4 ± 1.0 a	26.1 ± 1.0 ab	26.6 ± 1.0 bc	26.6 ± 1.0 b	25.7 B	23.8 ± 1.0 ab	26.5 ± 1.0 ab	27.1 ± 1.0 b	27.0 ± 1.0 ab	26.1 B	23.5 ± 0.0 ab	27.0 ± 1.0 a	27.6 ± 1.0 b	27.6 ± 1.0 b	26.4 B
100%RDK	24.9 ± 1.0 a	27.6 ± 1.0 a	30.2 ± 1.0 ab	32.2 ± 1.0 a	28.8 A	25.5 ± 1.0 ab	28.2 ± 1.06 a	31.0 ± 1.0 a	32.3 ± 1.0 ab	29.3 A	26.4 ± 1.0 a	29.2 ± 1.0 a	32.9 ± 1.0 a	33.5 ± 1.0 a	30.5 A
150%RDK	25.9 ± 1.0 a	28.6 ± 1.0 a	32.2 ± 1.0 a	34.2 ± 1.0 a	30.2 A	26.5 ± 1.0 a	29.2 ± 1.06 a	32.7 ± 1.0 a	34.7 ± 4.0 a	30.8 A	27.4 ± 1.0 a	30.2 ± 1.0 a	33.1 ± 3.0 a	35.6 ± 2.0 a	31.6 A
50%RDK + KSB	25.9 ± 1.0 a	27.7 ± 1.0 a	30.7 ± 1.0 a	32.5 ± 1.0 a	29.0 A	25.5 ± 1.0 ab	28.2 ± 1.06 a	31.5 ± 1.0 a	32.6 ± 5.0 a	29.5 A	26.5 ± 1.0 a	29.2 ± 1.0 a	33.1 ± 1.0 a	33.9 ± 3.0 a	30.7 A
Mean	23.8 C	26.5 B	28.6 A	29.8 A		24.2 C	26.9 B	29.1 A	30.0 A		24.7 C	27.6 B	29.9 A	30.7 A	
ANOVA															
CR			<0.0001					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			0.4057					0.0889					0.0024		

Crop Residue and K Management	Wheat 30 DAS					Wheat 60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	19.0 ± 1.0 b	21.8 ± 1.0 b	22.4 ± 1.0 c	22.3 ± 1.0 b	21.4 C	18.5 ± 1.0 b	21.3 ± 1.0 b	21.9 ± 1.0 c	21.9 ± 1.0 b	20.9 C	17.9 ± 1.0 b	20.8 ± 1.0 b	21.4 ± 1.0 c	21.4 ± 1.0 c	20.4 C
50%RDK	24.6 ± 1.0 a	27.4 ± 1.0 a	28.0 ± 1.0 b	28.0 ± 1.0 ab	27.0 B	25.2 ± 1.0 a	28.0 ± 1.0 a	28.6 ± 1.0 b	28.5 ± 1.0 ab	27.6 B	25.5 ± 1.0 a	28.5 ± 1.0 a	29.1 ± 1.0 b	29.0 ± 1.0 b	28.0 B
100%RDK	27.0 ± 1.0 a	29.7 ± 1.0 a	32.6 ± 1.0 a	34.2 ± 1.0 a	30.9 A	27.5 ± 1.0 a	30.3 ± 2.0 a	32.9 ± 2.0 a	34.2 ± 1.0 ab	31.3 A	28.1 ± 1.0 a	31.1 ± 2.0 a	34.5 ± 1.0 a	35.9 ± 1.0 a	32.4 A
150%RDK	27.0 ± 1.0 a	30.7 ± 1.0 a	34.3 ± 2.0 a	36.3 ± 2.0 a	32.4 A	28.6 ± 1.0 a	31.4 ± 2.0 a	34.9 ± 2.0 a	36.9 ± 2.0 a	33.0 A	29.1 ± 1.0 a	32.1 ± 2.0 a	35.6 ± 2.0 a	36.8 ± 3.0 a	33.4 A
50%RDK + KSB	28.0 ± 1.0 a	29.8 ± 1.0 a	33.0 ± 1.0 a	34.4 ± 7.0 a	31.1 A	27.6 ± 1.0 a	30.4 ± 2.0 a	33.4 ± 2.0 a	34.8 ± 9.0 a	31.6 A	28.1 ± 2.0 a	31.1 ± 2.0 a	34.6 ± 1.0 a	36.1 ± 1.0 a	32.5 A
Mean	25.1 C	27.9 B	30.1 A	31.1 A		25.5 C	28.3 B	30.3 AB	31.3 A		25.7 C	28.7 B	31.0 A	31.9 A	
ANOVA															
CR			<0.0001					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			0.2986					0.5923					0.0001		

Data are means of three replicates ± Standard deviation; means with different small and capital letters in the same column and rows differ significantly at *p* = 0.05 according to Fisher LSD and turkey's test. CR: Crop residue, KM: Potassium management, RDK: Recommended dose of potassium, KSB: Potassium solubilizing bacteria. Values under ANOVA are probabilities (*p*-values) of source of variance.

Table 4. Crop residue and potassium management practices on exchangeable potassium (kg ha⁻¹) of maize and wheat soil at different crop growth stages under zero tillage maize–wheat system (pooled data of two years).

Crop Residue and K Management	Maize										Wheat				
	30 DAS					60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	203 ± 10.0 b	212 ± 11.0 b	219 ± 11.0 b	335 ± 16.8 b	214 C	203 ± 6.0 b	210 ± 1.0 b	217 ± 11.0 b	330 ± 19.9 b	212 C	202 ± 9.0 b	209 ± 11.0 a	215 ± 12.0 b	331 ± 13.2 b	211 C
50%RDK	233 ± 12.0 ab	241 ± 12.0 ab	248 ± 12.0 ab	370 ± 18.5 ab	243 B	241 ± 12.0 a	248 ± 12.0 a	255 ± 13.0 a	376 ± 18.6 ab	250 B	231 ± 13.0 a	238 ± 12.0 a	244 ± 12.0 ab	362 ± 18.1 ab	239 B
100%RDK	247 ± 11.0 a	255 ± 12.0 a	260 ± 12.0 a	384 ± 20.8 a	255 A	254 ± 13.0 a	261 ± 13.0 a	284 ± 15.0 a	423 ± 16.4 a	271 A	235 ± 12.0 a	241 ± 14.0 a	262 ± 8.0 a	390 ± 15.9 a	250 A
150%RDK	250 ± 12.0 a	259 ± 13.0 a	262 ± 13.0 a	391 ± 19.3 a	259 A	255 ± 11.0 a	263 ± 10.0 a	289 ± 13.0 a	437 ± 18.1 a	276 A	236 ± 9.0 a	244 ± 10.0 a	265 ± 14.0 a	398 ± 17.5 a	253 A
50%RDK + KSB	248 ± 11.0 a	256 ± 12.0 a	261 ± 12.0 a	385 ± 8.40 a	257 A	254 ± 12.0 a	263 ± 12.0 a	287 ± 14.0 a	426 ± 39.5 a	274 A	236 ± 12.0 a	243 ± 13.0 a	263 ± 16.0 a	391 ± 31.1 a	251 A
Mean	236 C	244 B	250 AB	252 A		241 C	249 B	266 A	270 A		228 C	235 B	250 A	251 A	
ANOVA															
CR			<0.0001					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			0.9997					0.0288					0.0391		
Crop Residue and K Management	Maize										Wheat				
	30 DAS					60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	199 ± 5.0 b	208 ± 10.0 b	216 ± 11.0 b	216 ± 11.0 b	209 C	197 ± 10.0 b	204 ± 10.0 b	214 ± 11.0 b	215 ± 11.0 b	207 C	191 ± 6.0 b	199 ± 4.0 b	207 ± 6.0 c	211 ± 6.0 c	202 C
50%RDK	247 ± 7.0 a	255 ± 13.0 b	263 ± 13.0 a	264 ± 13.0 a	257 B	254 ± 13.0 a	261 ± 13.0 a	271 ± 14.0 a	272 ± 14.0 a	264 B	229 ± 4.0 a	240 ± 6.0 a	243 ± 4.0 b	249 ± 4.0 b	240 B
100%RDK	285 ± 13.0 a	266 ± 13.0 a	286 ± 10.0 a	287 ± 7.0 a	274 A	266 ± 13.0 a	272 ± 14.0 a	296 ± 14.0 a	297 ± 15.0 a	283 A	241 ± 4.0 a	250 ± 7.0 a	271 ± 6.0 a	273 ± 6.0 a	259 A
150%RDK	259 ± 8.0 a	268 ± 9.0 a	290 ± 14.0 a	294 ± 17.0 a	278 A	267 ± 8.0 a	275 ± 7.0 a	299 ± 15.0 a	308 ± 16.0 a	287 A	244 ± 3.0 a	251 ± 9.0 a	276 ± 5.0 a	279 ± 7.0 a	263 A
50%RDK + KSB	258 ± 13.0 a	267 ± 13.0 a	287 ± 18.0 a	291 ± 9.0 a	275 A	267 ± 13.0 a	273 ± 14.0 a	298 ± 14.0 a	303 ± 8.0 a	285 A	243 ± 5.0 a	251 ± 7.0 a	272 ± 3.0 a	275 ± 5.0 a	260 A
Mean	244 C	252 B	268 A	270 A		250 C	257 B	276 A	279 A		230 C	238 B	254 A	257 A	
ANOVA															
CR			<0.0001					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			0.1732					0.0304					0.0024		

Data are means of three replicates ± Standard deviation; means with different small and capital letters in the same column and rows differ significantly at $p = 0.05$ according to Fisher LSD and turkey's test. CR: Crop residue, KM: Potassium management, RDK: Recommended dose of potassium, KSB: Potassium solubilizing bacteria. Values under ANOVA are probabilities (p -values) of source of variance.

Table 5. Crop residue and potassium management practices on non-exchangeable potassium (kg ha^{-1}) of maize and wheat soil at different crop growth stages under zero tillage maize–wheat system (pooled data of two years).

Crop Residue and K Management	Maize														
	30 DAS					60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	1492 ± 37.4 a	1534 ± 76.9 a	1558 ± 78.1 a	1560 ± 78.2 a	1536 C	1448 ± 74.6 a	1531 ± 76.8 a	1555 ± 78.0 a	1558 ± 78.1 a	1533 C	1485 ± 37.2 a	1528 ± 76.4 a	1553 ± 77.9 a	1557 ± 78.1 a	1531 C
50%RDK	1550 ± 77.5 a	1592 ± 79.6 a	1615 ± 80.8 a	1618 ± 80.9 a	1593 B	1553 ± 77.7 a	1596 ± 79.8 a	1620 ± 81.1 a	1623 ± 81.2 a	1598 B	1555 ± 77.8 a	1598 ± 79.7 a	1623 ± 81.2 a	1627 ± 81.4 a	1601 B
100%RDK	1607 ± 80.3 a	1649 ± 82.4 a	1672 ± 83.5 a	1691 ± 83.7 a	1655 A	1609 ± 80.4 a	1652 ± 82.5 a	1677 ± 83.8 a	1699 ± 83.9 a	1659 A	1612 ± 80.5 a	1655 ± 82.4 a	1680 ± 83.9 a	1705 ± 84.1 a	1663 A
150%RDK	1612 ± 80.4 a	1657 ± 82.5 a	1683 ± 83.7 a	1712 ± 83.8 a	1666 A	1615 ± 80.6 a	1661 ± 82.7 a	1688 ± 83.9 a	1724 ± 84.1 a	1672 A	1618 ± 80.7 a	1664 ± 82.6 a	1690 ± 84.0 a	1729 ± 84.2 a	1675 A
50%RDK + KSB	1547 ± 77.4 a	1589 ± 79.5 a	1612 ± 80.7 a	1615 ± 80.8 a	1591 B	1550 ± 77.6 a	1593 ± 79.7 a	1618 ± 81.0 a	1621 ± 81.1 a	1596 B	1552 ± 77.7 a	1595 ± 79.6 a	1620 ± 81.1 a	1624 ± 81.3 a	1598 B
Mean	1562 C	1604 B	1628 A	1639 A		1563 C	1607 B	1632 A	1645 A		1565 D	1608 C	1633 B	1648 A	
ANOVA															
CR			<0.0001					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			0.8821					0.7921					0.0336		

Crop Residue and K Management	Wheat														
	30 DAS					60 DAS					At Harvest				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	1484 ± 37.2 a	1527 ± 76.6 a	1550 ± 77.7 a	1556 ± 78.0 a	1529 C	1482 ± 74.3 a	1526 ± 76.5 a	1550 ± 77.7 a	1554 ± 77.9 a	1528 C	1480 ± 74.3 a	1524 ± 76.4 a	1549 ± 77.7 a	1551 ± 77.8 a	1526 C
50%RDK	1560 ± 78.0 a	1603 ± 80.2 a	1626 ± 81.3 a	1631 ± 81.6 a	1605 B	1563 ± 78.2 a	1607 ± 80.4 a	1631 ± 81.6 a	1635 ± 81.8 a	1609 B	1566 ± 78.4 a	1610 ± 80.5 a	1635 ± 81.8 a	1637 ± 81.9 a	1612 B
100%RDK	1616 ± 80.7 a	1659 ± 82.8 a	1682 ± 84.0 a	1706 ± 84.3 a	1665 A	1618 ± 80.8 a	1661 ± 83.0 a	1686 ± 84.2 a	1708 ± 84.4 a	1668 A	1621 ± 81.0 a	1665 ± 83.2 a	1690 ± 84.4 a	1714 ± 81.0 a	1672 A
150%RDK	1621 ± 80.8 a	1667 ± 83.0 a	1692 ± 84.1 a	1732 ± 84.4 a	1678 A	1624 ± 80.9 a	1670 ± 83.1 a	1697 ± 84.3 a	1734 ± 84.5 a	1681 A	1627 ± 81.1 a	1673 ± 83.3 a	1700 ± 84.5 a	1745 ± 80.6 a	1686 A
50%RDK + KSB	1550 ± 77.9 a	1600 ± 80.0 a	1623 ± 81.2 a	1628 ± 81.5 a	1602 B	1561 ± 78.1 a	1605 ± 80.3 a	1629 ± 81.5 a	1633 ± 81.7 a	1607 B	1564 ± 78.2 a	1607 ± 80.4 a	1632 ± 81.7 a	1635 ± 81.8 a	1609 B
Mean	1568 D	1611 C	1635 B	1651 A		1569 C	1614 B	1639 A	1653 A		1572 C	1616 B	1641 A	1656 A	
ANOVA															
CR			<0.0001					<0.0001					<0.0001		
KM			<0.0001					<0.0001					<0.0001		
CR*KM			0.0518					0.7812					0.4844		

Data are means of three replicates ± Standard deviation; means with different small and capital letters in the same column and rows differ significantly at $p = 0.05$ according to Fisher LSD and turkey's test. CR: Crop residue, KM: Potassium management, RDK: Recommended dose of potassium, KSB: Potassium solubilizing bacteria. Values under ANOVA are probabilities (p -values) of source of variance.

Table 6. Crop residue and potassium management practices on total potassium (kg ha^{-1}) at the end of each cropping cycle under zero tillage maize–wheat system.

Crop Residue and K Management	Maize–Wheat Cycle–1					Maize–Wheat Cycle–2				
	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean	No CR	2.0 Mg ha ⁻¹	4.0 Mg ha ⁻¹	6.0 Mg ha ⁻¹	Mean
No K	46,867 ± 2343 a	46,868 ± 2343.4 a	46,881 ± 116 a	46,882 ± 2344 a	46,874 A	46,862 ± 2343.16 a	46,866 ± 2343 a	46,879 ± 2344 a	46,880 ± 2344 a	46,872 A
50%RDK	46,877 ± 2343 a	46,879 ± 2343.9 a	46,891 ± 22.0 a	46,892 ± 2345 a	46,885 A	46,892 ± 2344.56 a	46,896 ± 2344 a	46,909 ± 2345 a	46,910 ± 2345 a	46,901 A
100%RDK	46,989 ± 2344 a	46,890 ± 2344.4 a	46,903 ± 126 a	46,904 ± 2345 a	46,921 A	46,997 ± 2344.71 a	46,899 ± 2344 a	46,912 ± 2345 a	46,913 ± 2346 a	46,930 A
150%RDK	46,891 ± 2344 a	47,092 ± 2344.5 a	47,205 ± 126 a	47,306 ± 2345 a	47,124 A	46,898 ± 2344.86 a	47,105 ± 2345 a	47,220 ± 2345 a	47,321 ± 2346 a	47,136 A
50%RDK + KSB	46,840 ± 2359 a	46,876 ± 2343.8 a	46,889 ± 122 a	46,890 ± 2345 a	46,874 A	46,841 ± 2361.7 a	46,883 ± 2344 a	46,896 ± 2344 a	46,897 ± 2345 a	46,879 A
Mean	46,893 A	46,921 A	46,954 A	46,975 A		46,898 A	46,930 A	46,963 A	46,984 A	
ANOVA										
CR			0.9997					0.9995		
KM			0.9988					0.9978		
CR*KM			1.00					1.00		

Data are means of three replicates ± Standard deviation; means with different small and capital letters in the same column and rows differ significantly at $p = 0.05$ according to Fisher LSD and turkey's test. CR: Crop residue, KM: Potassium management, RDK: Recommended dose of potassium, KSB: Potassium solubilizing bacteria. Values under ANOVA are probabilities (p -values) of source of variance.

Table 7. Potassium budgeting as influenced by crop residue and potassium management in zero tillage maize–wheat system (at the end of two years crop cycle).

Treatment	Input (kg ha ⁻¹)					Output (kg ha ⁻¹)				Apparent Balance (kg ha ⁻¹)	Actual Change (kg ha ⁻¹)
	Initial avail. K in soil	K from Fertilizer	K from Residue	K from irrigation water	K from rain water	Total	Uptake	Final Avail. K in soil	Total		
	(1)	(2)	(3)	(4)	(5)	(1 + 2 + 3 + 4 + 5)	(6)	(7)	(6 + 7)		
	Crop residue management (CRM)										
No CR	245	42	0	18.4	4.20	310	114	264	378	–69	19
2.0 Mg ha ⁻¹	245	42	34	18.4	4.20	343	136	277	412	–69	32
4.0 Mg ha ⁻¹	245	42	72	18.4	4.20	382	170	292	461	–79	47
6.0 Mg ha ⁻¹	245	42	110	18.4	4.20	420	176	296	472	–52	51
	Potassium management (PM)										
No-K	245	0	54	18.4	4.20	322	91	215	305	16	–30
50%-RDK	245	30	54	18.4	4.20	352	134	283	417	–65	38
100%-RDK	245	60	54	18.4	4.20	382	164	303	467	–85	58
150%-RDK	245	90	54	18.4	4.20	412	177	306	482	–71	61
50%-RDK+KSB	245	30	54	18.4	4.20	352	180	304	484	–132	59

CR: Crop residue, RDK: Recommended dose of potassium, KSB: Potassium solubilizing bacteria, K content.

3.5. Soil K Pools Contribution to Total K under Residue and K Management Practices

The data related to different forms of soil K such as WSK, EK, and NEK and their percentage contribution to total K (TK) pool at cropping cycle I and cropping cycle II are presented in Table 8. Contribution of WSK, EK, and NEK among the residue retention at 2.0 to 6.0 Mg ha⁻¹ ranged from 0.059% to 0.066%, 0.493% to 0.539%, and 3.432% to 3.55% in cropping cycle I; and from 0.064% to 0.070%, 0.527% to 0.561%, and 3.457% to 3.550% in cropping cycle II, respectively. These contributions were higher than no CR. Among different K levels (50% RDK, 100% RDK, 150% RDK, and 50% RDK+KSB) contribution of WSK, EK, and NEK ranged between 0.056% to 0.067%, 0.488% to 0.544%, and 3.421% to 3.559% in cropping cycle I; and 0.064% to 0.075%, 0.542% to 0.576%, and 3.468% to 3.599% in cropping cycle II, respectively. The KSB treated plots recorded a slightly lower contribution of NEK to total K over untreated plots in both the cropping cycle.

Table 8. Crop residue and potassium management on percent (%) contribution of different forms of K to total K in zero tillage maize–wheat system.

Treatment	% Contribution of Different Forms of K to Total K					
	WSK		Exch. K		NEK	
	Cropping Cycle I M-W 2014–2015	Cropping Cycle II M-W 2015–2016	Cropping Cycle I M-W 2014–2015	Cropping Cycle II M-W 2015–2016	Cropping Cycle I M-W 2014–2015	Cropping Cycle II M-W 2015–2016
Crop residue management (CRM)						
No CR	0.053	0.057	0.477	0.507	3.345	3.37
2.0 Mg ha ⁻¹ CR	0.059	0.064	0.493	0.527	3.432	3.457
4.0 Mg ha ⁻¹ CR	0.064	0.068	0.532	0.554	3.484	3.515
6.0 Mg ha ⁻¹ CR	0.066	0.07	0.539	0.561	3.515	3.55
Potassium management (PM)						
No K	0.048	0.039	0.447	0.419	3.274	3.251
50% RDK	0.056	0.064	0.488	0.542	3.421	3.468
100% RDK	0.065	0.073	0.534	0.573	3.552	3.587
150% RDK	0.067	0.075	0.544	0.575	3.559	3.599
50% RDK+KSB	0.066	0.073	0.538	0.576	3.413	3.459

Initial: WSK: 0.047%, Exch. K: 0.474%, NEK: 3.318%. CR: Crop residue, RDK: Recommended dose of potassium, KSB: Potassium solubilizing bacteria, WSK: Water soluble potassium, Exch. K: Exchangeable potassium, NEK: Non exchangeable potassium, M-W: Maize–wheat system.

3.6. Correlation between Crop Growth, Yield, K Uptake, and Soil K Pools as a Result of Residue and K Management

Significant and positive correlations (Figure 3) were observed ($p \leq 0.01$ – 0.001) between maize and wheat dry matter accumulation, grain yield and K uptake with different native soil K pools and actual change of K. However, total K pool was not significantly associated with dry matter accumulation, grain yield, K uptake, different native K pools, and actual change of K.

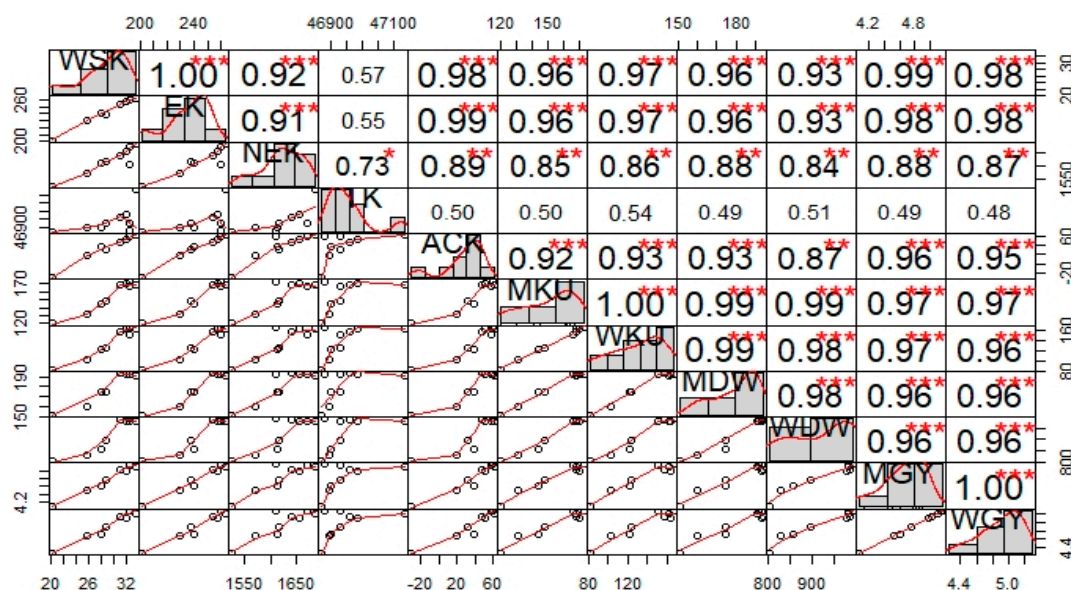


Figure 3. Correlation matrix of maize and wheat yield, K uptake, dry matter, actual K change and native soil K pools (* $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$). WSK: Water Soluble K, EK: Exchangeable K, NEK: Non-Exchangeable K, TK: Total K, ACK: Actual Change in K, MKU: Maize K Uptake, VKU: Wheat K Uptake, MDW: Maize Dry Weight, WDW: Wheat Dry Weight, MGY: Maize Grain Yield, and WGY: Wheat Grain Yield.

4. Discussion

Zero tillage, crop residue (CR) retention coupled with the balanced inorganic nutrient application considered as sustainable agricultural management practices and these practices have a favorable effect on crop growth and yield by improving nutrients (K) dynamics in the intensive cereal-based cropping system. In the present study, the effect of crop residue and K application were found to improve crop growth and yield of maize and wheat under a zero till maize–wheat cropping system. A significant increase in dry matter accumulation and grain yield of maize and wheat were recorded with CR retention at 4 and 6.0 Mg ha⁻¹. This increase in dry matter and yield could be attributed to improvement in soil quality parameters under zero-till residue management practices compared to non-residue retention plots has been reported under a similar agro environment [18,23]. CR retention on soil surface conserves soil water, enhanced nutrient recycling (K) and ensured their long-term availability to improve root growth, leaf area index, and dry matter accumulation with more efficient utilization of other available resources ultimately leading to higher yield as has been previously reported [1].

Application of 50% RDK along with seed inoculation of liquid biofertilizers (KSB) for both maize and wheat resulted in a significant increase in dry matter accumulation and grain yield. Evidence from our study suggested that inorganic K application and inclusion of KSB biofertilizers might have mobilized unavailable forms of soil K pool (non-exchangeable) to plant available K pool (exchangeable and water-soluble K) which might have enhanced K nutrient availability for uptake and assimilation by maize and wheat crops. The inclusion of CR and microbial inoculants might have increased the pertinent soil quality such as organic carbon content, microbial activities, and soil aggregate stability resulting in increased dry matter accumulation and grain yield of maize and wheat under zero tillage environment [18]. Potassium (K) uptake and assimilation at different crop growth stages (30 and 60 DAS and at harvest) in stover/straw, grain+straw of maize, and wheat were significantly influenced by residue and K management practices. The maximum K uptake and assimilation were recorded with 6.0 Mg ha⁻¹ CR as compared to no CR and 2.0 Mg ha⁻¹ CR. This aligns with the findings of Lupwayi et al. [24], wherein crop residue retention increases K content in the straw of wheat and maize as compared to grain. Among the K-management practices highest K uptake and assimilation were

recorded with 50% RDK+KSB, 100% RDK, 150% RDK in stover/straw, grain straw of maize, and wheat at different growth stages. The higher K uptake by increased levels of K application might be due to increased K availability with the addition of a higher dose of K might have improved assimilation of K by maize and wheat as has been reported by Baque et al. [25] and Eldardiry et al. [26]. In addition to this inoculation of KSB might have produced organic acids and capsular polysaccharides which are associated with the solubilization of K minerals in soil [27]. Furthermore, release of K from native pool might have increased the K availability in soils (from non-exchangeable K pool to exchangeable K pool) and thereby increased K uptake and assimilation by the plant [28]. The native soil K pools and their availability in soil depend on mineralogy, soil geochemical conditions, the addition of K fertilizers, crop residue, and tillage practices [29,30].

A significant redistribution in different forms of native soil K pools and with varied residue and K levels at 30 and 60 DAS and harvest of maize and wheat under zero tillage environment revealed that residue retention at 6 Mg ha⁻¹ significantly increased water-soluble K (WSK), exchangeable K (EK), and non-exchangeable K (NK) over no residue applied plots. The increase in these forms of K might be due to higher K concentration in cereal straws (1.2–1.7%) and returning straw to the field could improve available K by 13.33% with concomitant increase in water-soluble K (24.12%), exchangeable K (11.73%), non-exchangeable K (5.34%), and total K (0.18%) than no residue applied plots (% increase over no CR calculated at wheat harvest). These findings are also in consonance with findings of Tejada et al. [31] and Liao et al. [32]. Furthermore, CR releases 90% of their accumulated K in the 52-week incubation period. Therefore, residue K could be expected to contribute to more to plant K supply as and when residue was returned to the soil [5,24]. The organic residues and K application might have resulted in the redistribution among different K pools paving way for increased K mobilization and uptake by crops [33]. Application of K through inorganic fertilizer at different levels from 50% RDK, 50% RDK+KSB, 100% RDK, to 150% RDK significantly improved different forms of K over no K control except by KSB seed inoculated plot for non-exchangeable K at different growth stages of maize and wheat. The successive addition of grades dose of K (50–150% RDK) along with NP fertilizers might have increased different forms of K concentration in soil (0–15 cm) as is evident from improved K uptake and assimilation (Table 2) by maize and wheat at different growth stages. Furthermore, long-term studies conducted by other researchers have also reported that the application of K fertilizers (50-150 RDK% + 100%NP) significantly improved WSK, EK, NK over (No-K) control [34,35]. The seed inoculation of KSB improved different native K pools significantly. This might be due to bacteria solubilize the insoluble silicate minerals by the production of carbon dioxide, proton extrusion, organic acids, and in some cases hydroxyl anion, enzymes, mucilages, siderophores, and gluconate. Organic molecules directly or indirectly enhanced K mineral weathering, and also dissolution of silicate clay minerals, and also made the availability of fixed K in the soil and thereby improved the different forms of K in soil. The microbial inoculation through KSB and its organic acid production decreased non-exchangeable K and can be attributed to solubilization of the native K pool and increases its availability to crops [27,36]. Total K was not significantly influenced due to the different residue and K management practices in both maize and wheat. The presence of K rich minerals like feldspars (orthoclase and microcline), mica, and illite enhanced the total potassium in soil [37]. The negative apparent K balance was observed in all residue and K management practices except control (no K) and was due to continuous depletion of K content in soil because of increased uptake by crops for readily available K and needs to be replenished by adequate inputs of K fertilizers and through residue recycling. Several researchers have reported negative K balance in intensive cereal-based cropping system even with the recommended dose of K and improved slightly with the application of crop residue [29,38,39]. The lower K uptake by crops and depletion of readily available K in the soil after experimentation resulted in positive apparent balance as compared to (no K) control. However, there was an improvement in the actual change of K in soil due to residue (4.0–6.0 Mg ha⁻¹ CR) and K management (150% RDK-50%RDK+KSB) as has been reported by Singh et al. [29] and Raghavendra et al. [40].

The highest negative actual change of K was observed with no K. This may be as a consequence of subsoil or from release of non-exchangeable K [41]. The relationship between growth, yield, and K uptake by maize and wheat with different K pools (WSK, EK, NEK, and TK) in soil under zero tillage maize–wheat system was assessed with correlation study. All the crop parameters (dry matter accumulation, grain yield, and K uptake) were significant ($p \leq 0.01$ – 0.001) and positively correlated with different K pools except total K. The successive addition of K nutrient through different sources such as residue, fertilizer and seed inoculation of KSB strain might have improved the different native K pools except for total K in the soil at different growth stages and increased the availability of K from different pools thereby enhancing K uptake and assimilation by crops that in turn helped in improving crop dry matter accumulation and grain yield and is in concurrence with the findings as has been already reported [42,43]. The contribution of different K pools to the total K pool also differed among native K pools (water-soluble K, WSK; exchangeable K, EK; non-exchangeable K, NEK). The increasing order of different K pools contribution to total K pool ($WSK < EK < NEK$) was observed under the zero-till maize–wheat system. The NEK contributed to a greater extent than WSK and EK towards total K in the soil. The quantity of NEK present in soil was relatively higher than that of other K farms since large portion NEK fixed in clay minerals and not available to crop uptake unless other K pools are depleted. Whereas WSK and EK concentrations in soil were relatively small and are readily available to plant uptake and assimilation, hence their contribution was less to total K. These findings were compared with the findings of Patil and Sonar [44].

The more contribution of soil K pools to total K pool was observed with residue (6 – 4 Mg ha^{-1}) and K fertilizer (150% RDK, 100% RDK, and 50% RDK+KSB) added plots compared to control (no K, 50% RDK, and no residue added) plots. Since additions from the atmosphere and leaching losses of K were negligible and the maintenance of different K forms in soil depends largely on the addition of K through different sources such as crop residue and K fertilizers according to the needs of different crops in the intensive cropping system. Lal et al. [45] reported a much higher increased different native K pools in K fertilizer applied plots. As earlier discussed, vegetative portions (stover/straw) contributed 53–90% of K uptake and assimilation by crops so returning these vegetative portions might replace 70–90% of K removed from the soil by crops and maintain the optimum concentration of different forms of K in soil. Similar findings were reported by Sanyal et al. [46] and Habib et al. [47]. Seed inoculation of KSB decreased NEK contribution to the total K pool. The extra K required by the crops in the sub-optimal K applied plot was supplied from the NEK pool. Furthermore, seed inoculation of KSB stain might have accelerated the weathering of K minerals and solubilization of fixed K by producing organic acids with improved microbial activities in soil.

5. Conclusions

Zero tillage has been advocated to address soil health deterioration and environmental issues. Crop residue retention in any agroecosystem as an important agricultural management strategy not only improves soil quality but also encourages nutrient cycling if properly utilized in crop production process especially under intensive cropping system. Our study established that residue retention (6 Mg ha^{-1}) improved native K soil pools and enhanced growth and yield by augmenting K assimilation of maize and wheat under zero tillage environment. Furthermore, the combined application of inorganic K fertilizer (50% RDK) and seed inoculation of KSB biofertilizer under zero-till maize–wheat system has been found to potentially mobilize native soil K pools (non-exchangeable and total K) through redistribution and might help in improved growth, yield, and K-assimilation by maize and wheat. Upon addition of residue (4 and 6 Mg ha^{-1}), inorganic fertilizer (50% to 150% RDK), and KSB biofertilizer resulting in positive soil K balance through an increased actual change of K over control. Therefore, recycling of K rich cereal residue by returning into the soil (6 Mg ha^{-1}) and combined application of inorganic K fertilizer (50% RDK) with seed inoculation of KSB biofertilizer might be helped to reduce 50% of inorganic K fertilizer requirement. This assumes significance as residue and KSB biofertilizer under zero tillage maize–wheat system supplements inorganic K fertilizer

to meet crop K demand and could be sustainable, vital, and viable options and has larger implications in regions that are prone to residue burning and therefore negative K balance in these soils are of serious concern.

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