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ORIGINAL ARTICLE

Conservation agriculture improves yield and potassium balance in intensive rice systems

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Abstract Intensive rice-based systems are mining soil potassium (K) due to negative K balances. Conservation Agriculture (CA) practices may increase yield and economic return of rice-based systems but there is limited understanding of their effects on K pools and balances. This study evaluated crop productivity and K input–output balances under contrasting rice-based intensive cropping and long-term CA. The comprised three factors- (a) soil disturbance (strip planting, SP and conventional tillage, CT); (b) residue retention (low, LR, 20 cm by plant height and high, HR, 50 cm) and; (c) K application-100% K (recommended dose, RD), 50–75% K of RD (low dose, LD), and 125–150% K of RD (high dose, HD). The long-term experiment initiated in 2010 and soil samples were collected in 2018 after 24th crop and 2020 after 30th crop of triple cropping system. The K balances for the 2018 cropping cycle were negative, ranging from − 47 to − 82 kg ha^{-1} yr^{-1}. In the 2020 cycle, when the high K dose was increased from 125 to 150% of RD, the negative K balance was significantly reduced in SP-HR-HD (− 19 kg ha^{-1} yr^{-1}) while 23–35% higher cropping system yield was achieved. Leaching was a significant K loss pathway. Overall results indicate that minimum soil disturbance and increased crop residue retention had significant positive effects on cropping system yield and K balance. However, to achieve neutral K balance in intensive rice-based cropping systems, increased

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recycling of K from crop residue, higher doses of K addition or lower K losses are needed.

Keywords Conservation agriculture · K balance · Residue retention · Strip planting · K fertilizer · System yield

Introduction

Sustainable crop production in the Eastern Gangetic Plain (EGP) based on high cropping intensity in rice-based cropping systems has become increasingly important for regional food security and poverty alleviation (Parvin et al. 2017). In order to produce more food annually in a limited area, the most important option after increasing the cropping intensity on the same piece of land is to increase the production efficiency of the individual crops by using optimum management practices (Mondal et al. 2015). Rice in Bangladesh is mostly planted on puddled soil after intensive tillage, followed by removal of up to 80% of crop stubble, followed by cultivation and planting of the one or two more crops in the intensive rice-based systems. While puddling softens the soil, reduces water and nutrient loss through percolation, and limits weed occurrence (Humphreys et al. 2005), it causes aggregate breakdown, macropore destruction and sub-surface compaction (Sharma et al. 2005), which adversely affects the succeeding dryland crop (Sharma et al. 2005). Furthermore, repeated puddling of soil for rice and intensive tillage for dryland non-rice crops in the long-term use results in a decline in soil organic carbon (SOC) (Six et al. 2004; Shibu et al. 2010), negatively affecting cation exchange capacity and increasing the risk of K leaching loss (Munodawafa 2011; Suman et al. 2019).

Straw is frequently removed from fields as a source of cooking fuel, for animal feed and to prepare fields for the next crop in these highly intensified cropping systems. As a result of these practices, the K status of Asian soils has rapidly deteriorated (Dobermann et al. 2002). High yielding varieties with a short growing season also increase K demand from the soil. Most intensively farmed areas in Bangladesh have a high level of K mining (removal of 130–165 kg K ha^{-1} yr^{-1}) (Islam 2008). To avoid depletion of the soil's stores, K fertilizer rates should be determined not only by soil tests and crop responses, but also by the amount of K withdrawn by harvested crops. Quantitative estimates of K balance can aid in the development of a sound fertilizer recommendation program for sustaining high levels of crop output while also ensuring the soil's long-term fertility and productivity.

As a novel soil management practice, the combination of strip planting and increased crop residue retention, known as Conservation Agriculture (CA), is effective in increasing food output but also in enhancing soil health (Bell et al. 2019). Our recent research also showed that compared to the conventional practices, both strip planting and increased residue retention increased soil K levels in all fractions down to a depth of 30 cm in these intensive rice-based cropping systems (Islam et.al. 2023). This suggests that these practices could be an effective strategy to reverse negative K balances and decrease the amount of K fertilizer required, therefore providing economic benefits (Tiwari 2007, Islam et.al. 2023). However, the impacts of the components of CA on K input–output balance and thus K fertilizer recommendation for better yields in these systems are still not clear. The present study was undertaken to assess the impact of CA practices in a rice-based cropping pattern on: (i) K inputs and outputs and partial K balance in soil; (ii) cropping system productivity, and; (iii) K fertilizer requirements.

Materials and methods

Site description

Location, morphological characteristics and classification of the experiment soil

The experiment was conducted at Alipur, Durgapur, Rajshahi in northwest Bangladesh (24° 29′ 02.0″ N Latitude and in 88° 46′ 53.7″ E Longitude). The Calcareous Grey Flood Plain soil was classified as a Typic Haplaquept from the Arial/Sara soil series (Huq and Shoaib 2013; USDA 2014), occurring on the High Ganges River Flood Plain (Brammer et al. 1988). The site was moderately well drained (water can drain gradually after heavy rainfall or seasonal inundation). The initial and final soil nutrient status of the experimental soil by depth are given in Table 1.

Table 1 Initial (2018) and final soil nutrient status (2020) during the study

Factors and treatments	BD (g cm^{-3})		pH (H_2O)		TN (%)		SOC (%)		Exch K (mg kg^{-1} soil)		Extr P (mg kg^{-1})		Extr S (mg kg^{-1})	
Depth × year														
Depths (cm)	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020
0–5	1.34	1.33	6.49	6.55	0.16	0.17	1.23	1.26	39.9	36.6	30.7	32.2	17.5	15.9
5–15	1.37	1.36	6.53	6.59	0.07	0.07	0.69	0.70	43.8	40.5	18.8	20.8	16.1	14.6
15–30	–	–	6.55	6.66	0.07	0.07	0.39	0.37	43.3	40.1	7.8	8.4	11.0	10.6
30–45	–	–	6.66	6.77	0.06	0.06	0.26	0.24	42.4	39.2	6.1	6.9	8.8	8.3
45–60	–	–	6.63	–	0.06	–	0.19	–	36.6	–	5.8	–	6.9	–
LSD (0.05)	–		0.29		0.02		0.08		5.58		4.36		2.71	
Level of sig	ns		***		***		**		***		***		***	

SOC soil organic carbon, *TN* total nitrogen, *Exch K* exchangeable potassium, *Extr P* extractable phosphorus and *Extr S* extractable sulfur, *BD* bulk density

*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$, ns = not significant

Details of the experimentat site were previously reported by Alam et al. (2016, 2018).

Weather during crop growing periods

Weather data of the experimental years (2019 and 2020) were presented in App. suppl. A. Table 2. Total annual rainfall was 1224 and 1414 mm, of which 90–95% was received during the Kharif (monsoon) season from May to October, when relative humidity was 82–92% and 85–91% in 2019 and 2020, respectively. Highest monthly average maximum temperature was 36.1 °C in May and 34.7 °C in June, while lowest monthly average minimum temperatures were 10.2 °C and 11.4 °C in January during 2019 and 2020, respectively. Maximum average sunshine hours per day were 7.84 in March and 8.08 in November and maximum monthly total evapotranspiration was 65.8 mm in May and 66.2 mm in April, while minimum values were 31.7 mm in December and 24.1 mm in January during 2019 and 2020, respectively.

Experiment design, crops management and sample collection

An experiment on the annual Lentil-T. Aus rice-T. Aman rice cropping pattern was undertaken with three factors: (A) level of soil disturbance (strip planting = SP and conventional = CT), (B) level of residue retention (low, LR = 20 cm of cereal stubble and high, HR = 50 cm) and (C) K application rate – recommended dose (RD = 188 kg K ha^{-1}), low dose (LD = 50% or 75% K of RD), and high dose (HD = 125 or 150% K of RD). The initial two factors (A and B) were first applied in 2010 as described by Islam et al. (2023). In 2018 after 24 crops, the K treatments were added as third factor (C) and continued for two years (6 crops). During the first cropping year, K application rates were set at 75%, 100% and 125% of RD, whereas in the subsequent year, the rates were adjusted to 50%, 100% and 150% of RD. The experiment was a split-split plot design where tillage was the main plot, residues were subplots, and K doses were sub-subplots with the plots size 2 m × 7 m, four replications, and three crops per year in a diversified cropping sequence (Suppl. A. Table 1). In SP, the seeds or seedlings were sown/transplanted in 3 cm wide strips separated by 27 cm of undisturbed soil for lentil and 17 cm for rice crop using a Versatile Multi-Crop Planter (VMP). Conventional tillage was done by 3–4 passes of a rotary tiller. Low residue involved keeping about 20 cm of the standing rice crop stubble in the field during harvesting of cereal crops. High residue involved keeping 50 cm of standing rice stubble during harvesting. However, 100% of lentil residue was returned to the same plot of all treatments after harvest. In the SP system, the crop residue was mostly retained as standing stubble or on the soil surface while the same amount of residue was incorporated into the soil by repeated rotary tillage in the CT system.

All intercultural operations for each crop and fertilizer recommendation were performed according to Fertilizer Recommendation Guide (FRG 2018) during cropping periods. Data of the yield and yield contributing characters were collected from each crop. Details about crops are given in Suppl. A. Table 3.

Soil sample collection and analysis

Composite soil samples were collected by an auger (5 cm diameter) from 0 to 5, 5 to 15, 15 to 30, 30 to 45 and 45 to 60 cm depths from each replicated plot after the harvest of 24 and 30 crops (in 2018 and 2020, repectively). There were nine auger holes per plot for each composite sample. For the determination of mean soil BD, two depths (0–15 and 5–15 cm) were collected by a core sampler (5 cm diameter) from two places per plot (Black 1965). The collected soil samples were air dried at room temperature, mixed thoroughly, crushed and sieved with a 10-mesh sieve. Before crushing, stones, visible roots and insects were removed. Exchangeable K was determined by shaking the soil with NH_4OAc solution (1:10 ratio) and adjusting to pH 7 (Knudsen et al. 1982). Soil organic carbon was determined by the Walkley and Black (1934) method. The soil pH was analyzed using standard methods suggested by Chapman (1965). The amount of total N was determined by Semi-micro Kjeldahl method (Bremner and Mulvaney 1982) and extractable P was determined by the Olsen method (Olsen and Sommers 1982). Soil S was extracted by calcium chloride (0.15%) solution (Williams and Steinbergs 1959).

Plant sample collection and analysis

After sowing, three 1.5 m^2 quadrats in each subplot were pre-marked by bamboo sticks for all required data collection. Five plants of each quadrat and 15 plants in total of each sub-plot were labelled. The grain and straw samples of lentil and rice were collected from the pre-identified area of each sub-sub-plot after harvest of each crop. The harvested crop was threshed, cleaned and air dried at room temperature. After drying, the straw samples were chopped into 3–4 cm size and then kept in polyethylene bags and a 10 g sub-sample was taken from each treatment for oven drying. Then, the grain and straw samples were dried in an oven at about 65 °C for 48 h and then ground by a grinding mill to pass through a 40-mesh sieve.

Oven-dry ground plant samples weighing 0.5 g (grain and straw) were weighed into digestion tubes. Plant samples were digested in a di-acid mixture (HNO_3: $HClO_4 = 2:1$) and determination of K concentration in the extract was by flame photometer (Knudsen et al. 1982).

Water sample collection and analysis

Irrigation water volume was measured by a flow meter connected to a pump extracting water from a deep tube-well. Rain water was measured and collected by placing a rain gauge near the experiment. Leaching water was measured and collected at 40 cm depth by establishing four lysimeters of 20 cm diameter (two in SP and two in CT) in the 100% K dose plots. Leaching water was collected every day at 11 am during the rice growing period. After collection of water samples, they were immediately carried to the laboratory and stored in a cool box at + 4–6° C temperature until the samples were analyzed for K concentration.

Rice equivalent yield (REY)

Total system productivity was calculated as the summation of individual (component) crop yields of each cropping cycle. The productivity was also compared by calculating the economic rice equivalent yield (REY) using formula given by Ahlawat and Sharma (1993), where.

$$\mathrm{REY}\left(\mathrm{Mg\ ha^{-1}}\right) = \frac{\mathrm{Yield\ of\ each\ crop}\left(\mathrm{Mg\ ha^{-1}}\right)\times\mathrm{Economic\ value\ of\ respective\ crop}\left(\mathrm{Tk\ Mg^{-1}}\right)}{\mathrm{Price\ of\ rice\ grain}\left(\mathrm{Tk\ Mg^{-1}}\right)}$$

Estimation of potassium balance

After completion of the lentil-rice-rice cropping pattern for two years, K balance was estimated by using following input–output formula, where

$$\text{K Balance} = \left(K_{org} + K_{fer} + K_{dep} + K_{iri}\right) - \left(K_{cro} + K_{lea}\right)$$

Input–output flows:

Input pathways	Output pathways
K_{org} = Organic sources (eg. residues)	K_{cro} = Crop produce and residues
K_{fer} = Fertilizers	K_{lea} = Leaching
K_{dep} = Natural deposition (eg. rain water)	
K_{iri} = Irrigation water supply	

Statistical analysis

Significance of treatment effects on the crop productivity, K input, output and balance were determined by analysis of variance (ANOVA) of the Split-Split Plot design. Soil depth effect was determined by ANOVA for a Repeated Measures Design for soil K and others physiochemical properties. Treatment means were separated by Duncan's Multiple Range Test (DMRT) using the statistical package Statistix 10 at 5% level of significance.

Results

Component crop yield and system yield

Lentil yield

The lentil yield in 2019 cropping year was significantly influenced by the interaction of tillage, residue retention and K dose (Table 2). Compared to farmers' current practice (CT-LR-RD), SP with either residue level increased the lentil yield by 22% when the high doses of K was applied and by 12–19% when recommend does of K was applied. The yield from CT-HR-HD was also 12% higher than that from farmers' current practice (Fig. 1a).

In 2020, tillage and the interaction of residue retention and K dose significantly influenced lentil yield (Table 2). The lentil yield was 16% higher in SP than in CT (Suppl. A. and Table 8) and 13%, 9% and 7% higher in HR-HD, HR-RD and LR-HD than in LR-RD, respectively (Fig. 1b). It was even 5% higher in HR-LD than LR-RD (Fig. 1b).

Transplanted (T.) Aus rice yield

In 2019, T. Aus yield was significantly influenced by the interaction of tillage × residue retention (Table 2), because yield in SP-HR was 12% higher than in CT-LR, while there was no difference between other treatments (Fig. 1c). In addition, it was significantly influenced by the interaction of residue retention × K does (Table 2). More specifically, the yield was 17%, 10% and 11% higher in HR-HD, HR-RD and LR-HD, respectively, than in LR-RD. Even LD of K with HR

Table 2 Level of significance of crop yields of the lentil-T. Aus rice-T. Aman rice system in 2019 and 2020

Factors and treatments	Grain yield (Mg ha^{-1})						System REY (Mg ha^{-1})	
	Lentil		T. Aus rice		T. Aman rice			
	2019	2020	2019	2020	2019	2020	2019	2020
	Level of significance							
Tillage (T)	*	*	ns	ns	ns	ns	*	*
Residue (R)	**	***	**	**	*	***	***	***
K dose (K)	***	***	***	***	***	***	***	***
T×R	ns	ns	**	ns	ns	ns	ns	ns
T×K	ns	ns	ns	***	*	ns	ns	**
R×K	ns	*	*	ns	ns	ns	ns	ns
T×R× K	*	ns	ns	*	*	*	*	**

*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$, ns = not significant

had smilar yield of T. Aus rice to the LR- RD treatment. On the other hand, LR-LD decreased T. Aus rice yield by 8% relative to LR-RD. (Fig. 1d).

Tillage, residue retention, K dose and their interaction significantly influenced the T. Aus yield in 2020 (Table 2). T. Aus yield was about 38%, 24%, 17% and 8% higher in SP-HR-HD, SP-HR-RD, SP-LR-HD and SP-LR-RD, respectively, than in CT-LR-RD (farmer's current practice) (Fig. 1e). Even a 9% yield increase was found in SP-HR-LD relative to CT-LR-RD. On the other hand, T. Aus yield was about 20%, 14%, 10% and 9% higher in CT-HR-HD, CT-HR-RD, CT-LR-HD and CT-HR-LD, respectively, than in CT-LR-RD. About 6% yield decreased was obtained in CT-LR when K dose decreased from RD to LD (Fig. 1e).

Transplanted Aman rice yield

Tillage, residue retention, K dose and their interaction significantly influenced T. Aman rice yield in both cropping seasons (Table 2). In 2019, compared to farmer's practice (CT-LR-RD), T. Aman yield was about 12–27% higher in all the treatments with high dose of K and 18% higher in SP-HR-RD treatment, but there was no significant difference with other treatments (Fig. 2a). In 2020, T. Aman yield was about 12–34% higher in all the treaments than in CT-LR-RD, with the exception of the treatments of CT-LR-LD and SP-LR-LD (Fig. 2b).

System REY

Tillage, residue retention, K dose, and their interactions significantly influenced REY in both years (Table 2). In 2019, REY was significantly increased by the high dose of K, being 23%, 15%, 14% and 8% higher in SP-HR, SP-LR, CT-HR, and CT-LR, respectively, than the farmer practice (CT-LR-RD). However, the yield in CT-LR-LD was 9% lower than in CT-LR-RD (Fig. 2c).

In 2020, compared to farmer's practice (CT-LR-RD), all the treatments with recommended K and higher doses of K had 11–35% higher REY, regardless of tillage practice or residue retention level. Even when the low dose of K was applied, the REY was still 17%, 9% and 5% higher in SP-HR, CT-HR, and SP-LR, respectively, than farmer practice (Fig. 2d). However, a 6% decrease in REY in CT-LR-LD was found relative to CT-LR-RD (Fig. 2d).

Potassium budget in soil

Potassium added through crop residue (K_{org})

Tillage, residue retention, K dose, and their interactions significantly influenced total K added during the first crop cycle (Table 3). Compared to farmer's current practice, the total K addition was significantly higher with high residue retention and with higher K dose, being 143–191% and 117–150% higher in SP and CT treaments, repectively. For the treatments with low residue retention, there was 14–17% higher K inputs in treatments with high K dose than in CT-LR-RD, but no significant difference with other LR treatments (Fig. 3a).

In the 2nd crop cycle, tillage, and the interaction of residue retention and K dose significantly influenced the amount of K added to soil through residue by T. Aus and T. Aman rice (Table 4). The total K added by residue was 21.6% higher in SP (73.3 kg ha^{-1} yr^{-1}) than in CT (60.3 kg ha^{-1} yr^{-1}) (Table 4). The total K addition was significantly higher in HR treatments and increased with K dose. When K dose increased from LD to HD, the amount of K added by residue was increased from 35 to 42 kg ha^{-1} yr^{-1} in LR, but from 86 to 103 kg ha^{-1} yr^{-1} in HR (Fig. 4a).

Potassium added through irrigation (K_{iri}), rain water (K_{dep}) and fertilizer (K_{fert}) in soil

In 2019, the total irrigation water added to the field was about 7.73 million L ha^{-1} yr^{-1} in both SP and CT tillage systems (Suppl. A. and Table 7). About 12.6 kg K ha^{-1} yr^{-1} was added in SP and CT systems through irrigation water with the K concentration ranging from 1.43 to 1.82 mg L^{-1}. The total rain water added to the soil was about 12.3 million L ha^{-1} yr^{-1} (Suppl. A. and Table 7). The K concentration of rain water ranged from 0.72 to 1.17 mg L^{-1} and about 9.0 kg K ha^{-1} yr^{-1} was added to soil through rain water. The total K added by fertilizer to the soil was 71 kg ha^{-1} yr^{-1} in LD, 94 kg ha^{-1} yr^{-1} in RD and 118 kg ha^{-1} yr^{-1} in HD (Table 3).

In 2020, about 12.7 kg ha^{-1} yr^{-1} K was added in both SP and CT systems in soil through irrigation water due to a smaller volume of water added than

Table 3 Effects of tillage, residue retention and K dose on K outputs, K inputs and K balance in soil during 2019 in the Lentil-T. Aus rice-T. Aman rice cropping pattern

Factor and treatments		K outputs							K inputs						K balance (kg ha^{-1} yr^{-1})
		K uptake (kg ha^{-1})					Total K uptake by crops (K_{cro})	K loss by leaching (K_{lea})	Total K output (kg ha^{-1} yr^{-1}) (K outputs)	K addition (kg ha^{-1} yr^{-1})				Total K addition (kg ha^{-1} yr^{-1}) (K inputs)	
		Lentil	T. Aus rice		T. Aman rice										
		Grain	Grain	Straw	Grain	Straw				Residue (K_{org})	Rain water (K_{dep})	Irrigation water (K_{iri})	Fertilizer (K_{fert})		
Tillage	CT	21.2	16.5	77.6	17.5	82.1	215	28	242	60.7	9	12.6	94	176	−66
	SP	22.8	18.1	79.5	17.8	81.3	220	26	246	67.7	9	12.6	94	183	−63
	LSD (0.05)	–	1.51	–	–	–	–		–	0.6				0.3	–
Residue retention	LR	21.4	15.9	74.8	17	79.5	209	27	236	37.9	9	12.6	94	153	−83
	HR	22.6	18.7	82.3	18.3	83.9	226	27	253	90.5	9	12.6	94	206	−47
	LSD (0.05)	0.9	1.4	4.8	0.9	3.3	5.6		6	3.4				3	4.8
K dose	LD	20.3	15.5	72.7	15.2	73.9	198	27	225	58.6	9	12.6	71	151	−74
	RD	22.1	17.2	79.5	17.9	81.3	218	27	245	64.6	9	12.6	94	180	−65
	HD	23.7	19.2	83.4	19.8	89.9	236	27	263	69.3	9	12.6	118	209	−54
	LSD (0.05)	0.8	0.9	1.7	1.2	3	3		3	1.4	–	–	–	1	2.25
Level of significance	Tillage (T)	ns	*	ns	ns	ns	ns	–	ns	***	–	–	–	**	ns
	Residue(R)	*	**	**	*	*	***	–	***	***	–	–	–	***	***
	K Dose (K)	***	***	***	***	***	***	–	***	***	–	–	–	***	***
	T×R	*	ns	*	ns	ns	*	–	*	*	–	–	–	*	ns
	T×K	ns	ns	ns	ns	ns	ns	–	ns	ns	–	–	–	ns	ns
	R×K	ns	ns	*	ns	ns	*	–	*	***	–	–	–	**	**
	T×R×K	**	ns	*	ns	ns	ns	–	ns	*	–	–	–	*	ns

CT conventional tillage, *SP* strip planting, *LR* low residue retention, *HR* high residue retention, *LD* 75% dose of K, *RD* recommended K dose, *HD* 125% of RD of K

$*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, ns = not significant

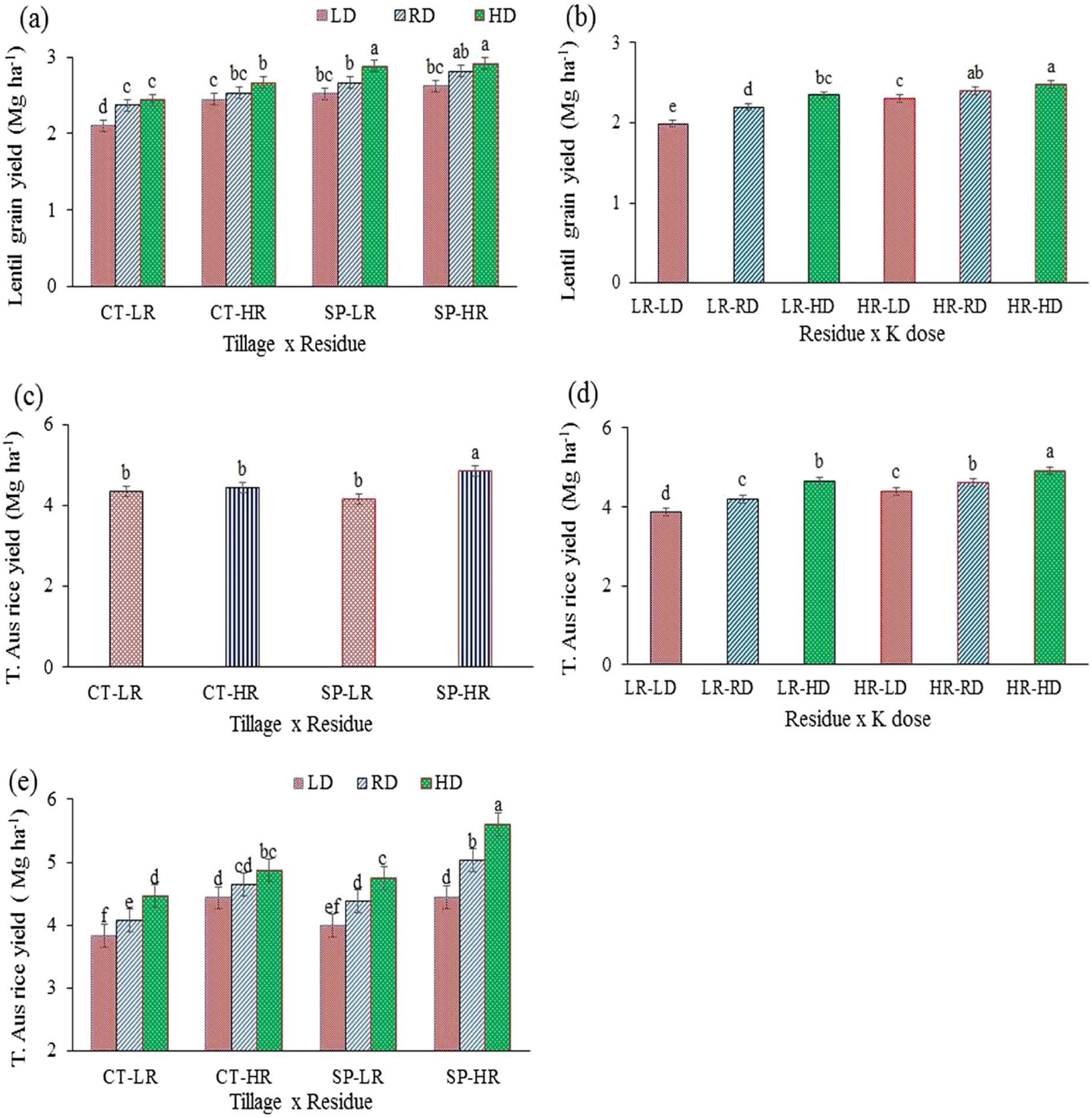

Fig. 1 Lentil grain yield (**a** during 2019 and **b** during 2020), T. Aus rice yield (**c** and **d** during 2019 and **e** during 2020) as affected by tillage, residue and K dose treatments; treatment means followed by the same letter are not significantly different. (SP-strip planting and CT-conventional tillage; HR-high residue and LR-low residue; HD-high K dose, RD-recommended K dose and LD-low K dose. Error bars represent SE ($P < 0.05$); means (n = 4) shown)

in 2019 (Suppl. A. and Table 7). By contrast, more rain fell in 2020 (Suppl. A. and Table 7) and so about 12.8 kg ha^{-1} yr^{-1} K was added in soil through rain water. Due to adjustments in the LD and HD K rates, the total K added by fertilizer to the soil in 2020 was 47 kg ha^{-1} yr^{-1} in LD, 94 kg ha^{-1} yr^{-1} in RD and 141 kg ha^{-1} yr^{-1} in HD of K (Table 4).

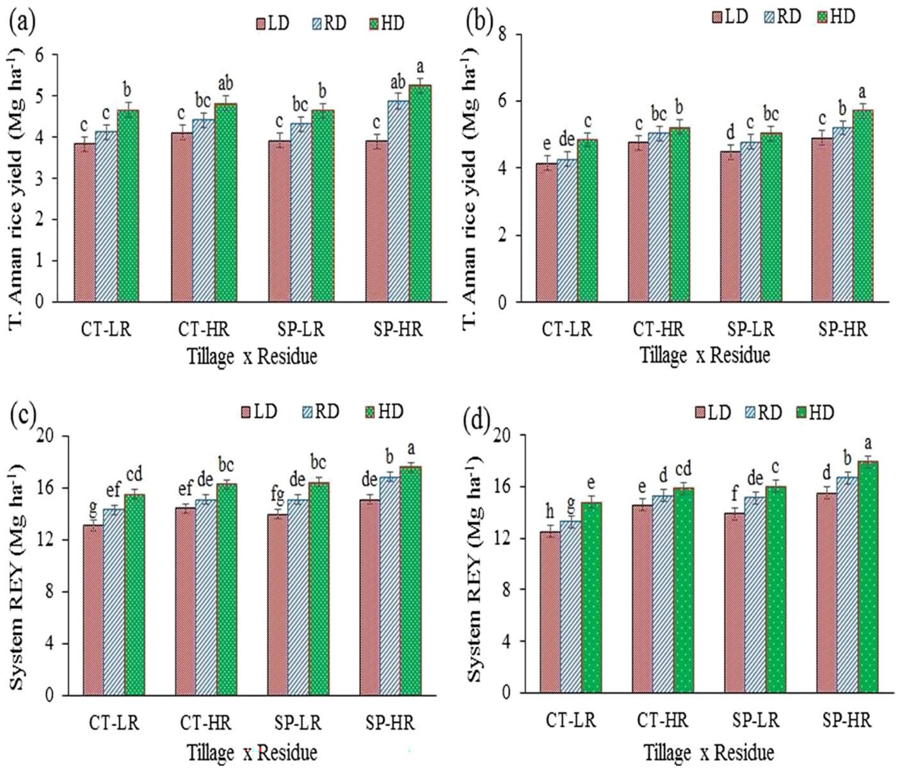

Fig. 2 Rice (T. Aman) yield (**a** during 2019 and **b** during 2020) and annual rice equivalent yield (REY) (**c** during 2019 and **d** during 2020) as affected by tillage, residue and K dose treatments. (SP-strip planting and CT-conventional tillage; HR-high residue and LR-low residue; HD-high K dose, RD-recommended K dose and LD-low K dose. Error bars represent SE ($P<0.05$); means (n = 4) shown)

Total K added in soil (K inputs)

Tillage, residue retention, K dose, and the interactions significantly influenced the total amount of K added to soil in the lentil-rice-rice system during the first crop cycle (Table 3). Total K input increased with the increasing doses of K, while at a given K dose it was significantly higher in SP-HR than CT-HR but similar between SP-LR and CT-LR. The K input was about 20% higher in LR-HD treatments, but about 17% less in LR-LD treatments, than in LR-RD, regardless of tillage (Fig. 3b).

During the 2nd crop cycle, tillage, residue retention, K dose, and the interaction of residue retention × K dose significantly influenced the amount of total K added in soil (Table 4). The K addition in the SP system was 7% higher than in CT. The total K input increased with the increasing K dose, with a greater change in HR than in LR. Moreover, there was 37% more total K addition in HR-RD than in LR-RD (Fig. 4b).

Potassium loss by leaching water (K_{lea})

In the 1st crop cycle, the water loss by leaching was about 8.7 million L ha^{-1} yr^{-1} in CT and 9.2 million L ha^{-1} yr^{-1}in SP (Suppl. A. and Table 7). The mean K concentration of leachate water was 3.15 mg L^{-1} in CT and 2.85 mg L^{-1} in SP, therefore about 27.5 kg K ha^{-1} yr^{-1} from CT and 26.3 kg K ha^{-1} yr^{-1} from SP were lost through leaching water (Table 3).

In the 2nd crop cycle, the loss of leaching water from surface soil was about 10.9 million L ha^{-1} yr^{-1} in CT and 10.4 million L ha^{-1} yr^{-1} in SP (Suppl. A. and Table 7). The mean K concentration of leachate water was 2.85 mg L^{-1} in CT and 2.60 mg L^{-1} in SP. About 29.6 kg K ha^{-1} yr^{-1} from CT and 28.4 kg K ha^{-1} yr^{-1} from SP losses occurred from the soil by leaching (Table 4).

Potassium removal by crops (K_{cro}) and total output from soil (K outputs)

In the 1st crop cycle, residue retention and K dose had a large impact on total K uptake by crops as well as total soil K output (Table 3). In HR paired with

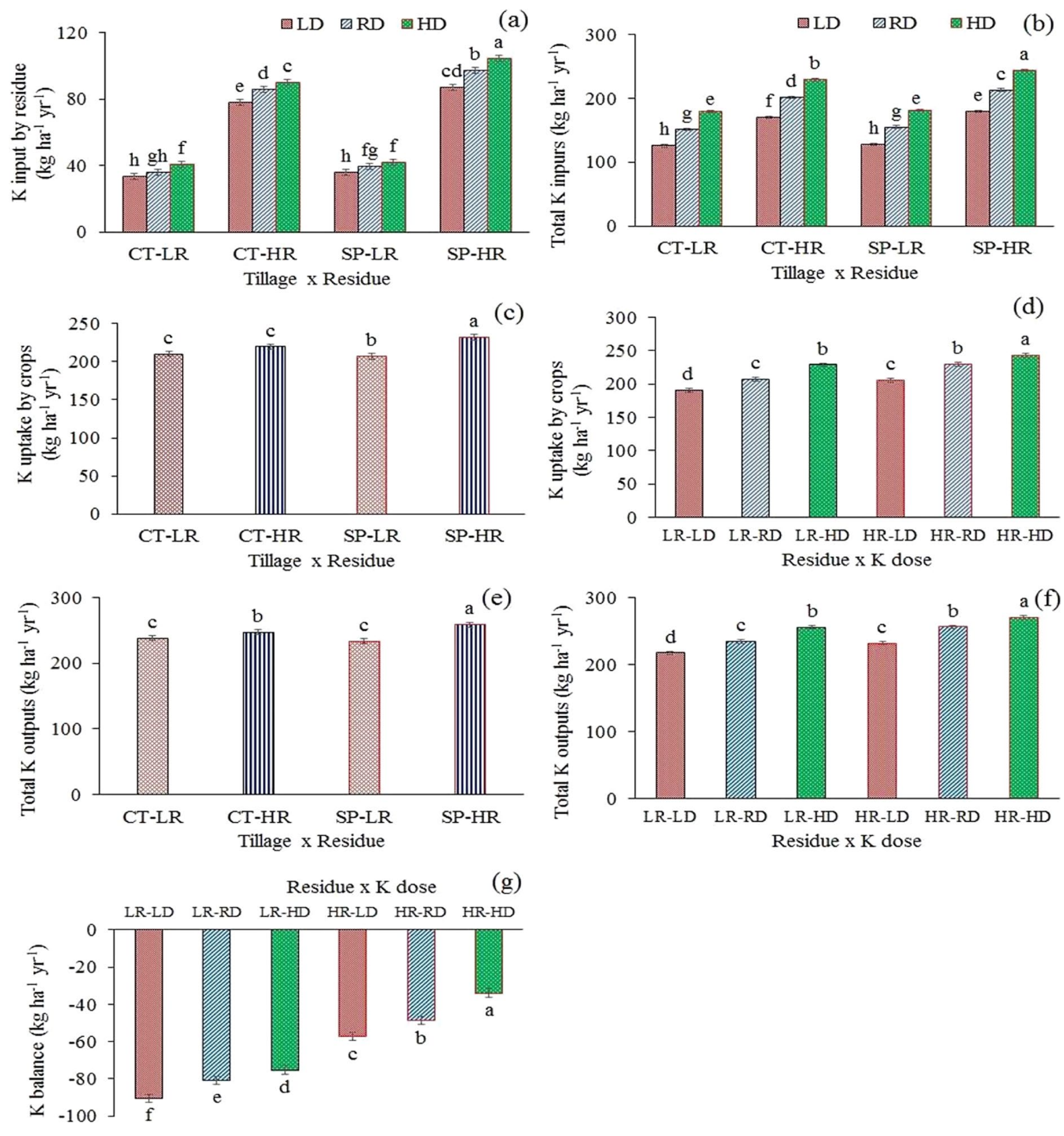

Fig. 3 K input by crop residue (**a**), total K input (**b**), K uptake by crops (**c** and **d**), total K outputs (**e** and **f**) and K balance in soil (**g**) as affected by tillage, residue and K dose treatments during the 1st crop cycle; treatment means followed by the same letter are not significantly different. (SP-strip planting and CT-conventional tillage; HR-high residue and LR-low residue; HD-high K dose, RD-recommended K dose and LD-low K dose. Error bars represent SE ($P < 0.05$); means ($n = 4$) shown)

CT or SP, total K uptake increased by 9% in SP-HR and by 4% in CT-HR relative to CT-LR, respectively (Fig. 3c). The total K uptake increased by 10.6% more in HR-RD than in LR-RD. The total K uptake in LD, coupled with LR and HR, was reduced due to the lower yield; it resulted in 8% and 1% lower total K uptake in LR-LD and HR-LD, respectively, compared to LR-RD. In HD of K paired with LR or HR, total K

Table 4 Effects of tillage, residue retention and K dose on K outputs, K inputs and K balance in soil during 2020 in Lentil-T. Aus rice-T. Aman rice cropping pattern

Factor and treatments		K outputs								K inputs					K balance (kg ha^{-1} yr^{-1})
		K uptake (kg ha^{-1})					Total K uptake by crops (K_{cro})	K loss by leaching (K_{lea})	Total K output (kg ha^{-1} yr^{-1}) (K outputs)	K addition (kg ha^{-1} yr^{-1})				Total K addition (kg ha^{-1} yr^{-1}) (K inputs)	
		Lentil	T. Aus rice		T. Aman rice										
		Grain	Grain	Straw	Grain	Straw				Residue (K_{org})	Rain water (K_{dep})	Irrigation water (K_{iri})	Fertilizer (K_{fert})		
Tillage	CT	18.7	16.9	83.8	20	89.8	229	30	259	60.3	12.8	12.7	94	180	− 79
	SP	21.8	19	83.8	20.1	87.7	232	28	261	73.3	12.8	12.7	94	193	− 68
	LSD (0.05)	1.5		–	–	–	–		11	7				7	9
Residue retention	LR	19.3	16.9	78.9	19.1	82.4	217	29	246	38.4	12.8	12.7	94	158	− 88
	HR	21.2	18.9	88.7	20.9	95	245	29	274	95.2	12.8	12.7	94	215	− 59
	LSD (0.05)	–	–	7.3	1.6	3.5	11		11	4				4	9
K dose	LD	18.3	15.8	75.8	18	81	209	29	238	60.3	12.8	12.7	47	133	− 105
	RD	20.6	18.3	84.6	19.6	89.2	232	29	261	67.6	12.8	12.7	94	187	− 74
	HD	21.9	19.7	91	22.4	95.9	251	29	280	72.4	12.8	12.7	141	239	− 41
	LSD (0.05)	0.7	1	1.8	1.2	2	4.4		4.4	1.9	–	–	–	1.9	5.2
Level of significance	Tillage (T)	*	ns	ns	ns	ns	ns	–	ns	*	–	–	–	*	*
	Residue(R)	ns	ns	**	*	***	**	–	**	***	–	–	–	***	***
	K Dose (K)	***	***	***	***	***	***	–	***	***	–	–	–	***	***
	T×R	ns	ns	ns	ns	ns	ns	–	ns	ns	–	–	–	ns	ns
	T×K	ns	ns	ns	ns	*	ns	–	ns	ns	–	–	–	ns	ns
	R×K	*	ns	ns	ns	ns	ns	–	ns	***	–	–	–	***	ns
	T×R×K	ns	ns	ns	*	*	*	–	*	ns	–	–	–	ns	*

CT conventional tillage, *SP* strip planting, *LR* low residue retention, *HR* high residue retention, *LD* 50% dose of K, *RD* recommended K dose, *HD* 150% of RD of K

*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$, ns = not significant

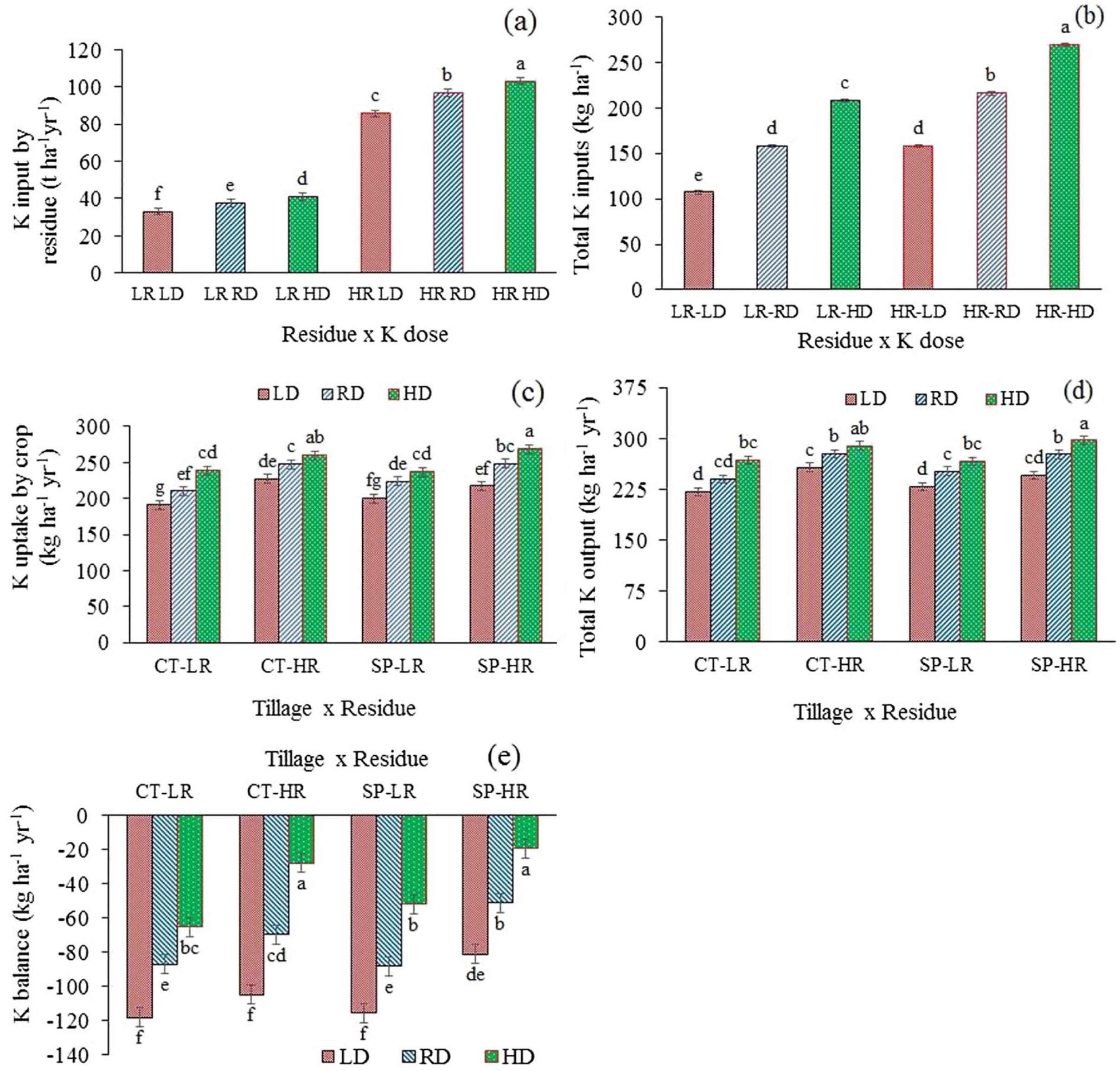

Fig. 4 K input by crop residue (**a**), total K input (**b**), K uptake by crops (**c**), total K output (**d**) and K balance in soil (**e**) as affected by tillage, residue and K dose treatments during the 2nd crop cycle; treatment means followed by the same letter are not significantly different. (SP-strip planting and CT-conventional tillage; HR-high residue and LR-low residue; HD-high K dose, RD-recommended K dose and LD-low K dose. Error bars represent SE ($P < 0.05$); means (n = 4) shown)

uptake by crops increased by 17% and 11%, respectively, in comparison to LR-RD (Fig. 3d).

In the 1st cropping year, similar trends were seen in the total K output. The total K output increased by 10.3% more in SP-HR and 4.5% more in CT-HR than in CT-LR, respectively (Fig. 3e). Due to the lower yield, the total K output in LD was decreased when combined with LR or HR, resulting in 7% and 1% less total K output in LR-LD and HR-LD, respectively, than in LR-RD. Compared to LR-RD, total K output in HD of K paired with LR or HR increased by 15% and 9%, respectively (Fig. 3f).

In the 2nd crop cycle, residue retention, K dose, and the interaction effect of tillage, residue retention, and K dose had significant influences on total K upake by crops (Table 4). The K uptake by crops significantly increased with increasing K feriliser doses and was higher in HR than LR treatments, with the exception that no difference occurred between SP-HR-LD and SP-LR-LD. For a given residue retention and K dose, there was no significant difference between CT and SP treaments. Compared to farmer's practice (CT-LR-RD), the total K uptake was 13–28% higher in the all treatments with RD or HD (except SP-LR-RD), but it was similar to or lower than in treaments with LD (Fig. 4c).

Similar trends were observed for total K output. Overall, the total K output was higher in HR than LR treatments and increased with the increasing K doses, while the increment was bigger in HR than LR treaments. For a given residue retention and K dose, there was no significant difference between CT and SP treaments. The total K output from farmer's practice (CT-LR-RD) was similar to all the treatments, with the exception of the four treatments with high residue plus RD or HD of K which had 15–24% higher K outputs (Fig. 4d).

Potassium balance in soil (K balance)

In the 1st crop cycle, the interaction of residue retention and K dose had significant effects on K balance in soil in the lentil-rice-rice system (Table 3). The K balances were negative, in the range − 47 to − 82 kg ha^{-1} yr^{-1} for residue levels and − 55 to − 74 kg ha^{-1} yr^{-1} for K doses (Table 3). The negative K balance was significantly reduced in HR-HD followed by HR-RD, HR-LD, LR-HD and LR-RD (Fig. 3g). The negative K balance was reduced by 29–58% in HR with LD, RD and HD followed by 7% in LR-HD than in LR-RD (Fig. 3g).

In the 2nd crop cycle, total K balances were negative in all the treatment combinations and significantly influenced by the interaction effect of tillage, residue retention, and K dose (Table 4). Total K balance increased with the increasing dose of K, while the increase was bigger in HR than LR treaments, and at a given K dose it was significantly higher in SP-HR than CT-HR but similar between SP-LR and CT-LR. The magnitude of the negative total K balance was reduced by 78% in SP-HR-HD and by 68% in CT-HR-HD when compared with the current farmer's practice (CT-LR-RD) (Fig. 4e).

Total potassium stock in soils

In both year, tillage, residue retention and their interaction have a significant influence on the total K stock in soils (Suppl. A. and Table 4). In 2018, the higher soil K (11.2 Mg ha^{-1}) stock was obtained from SP

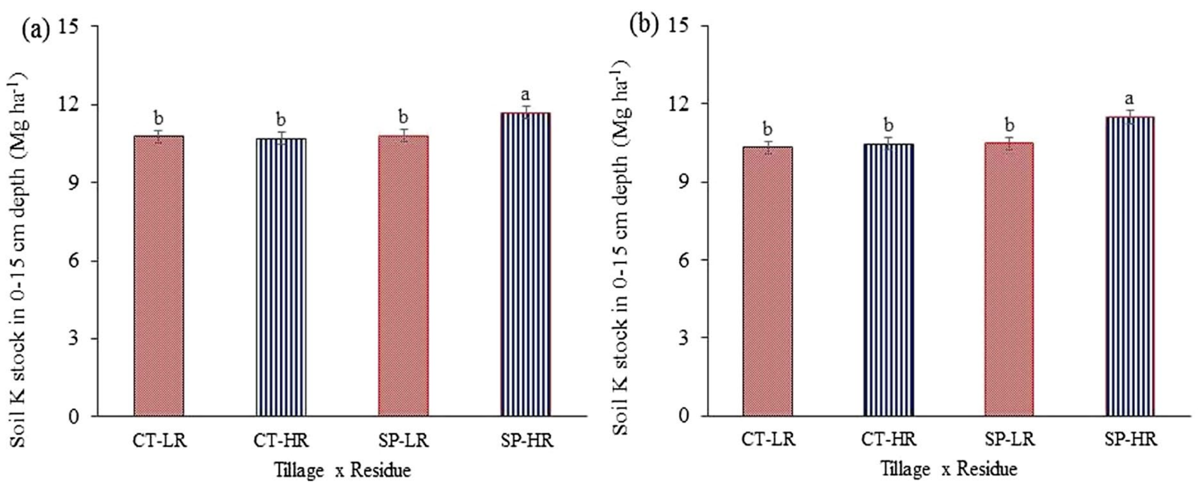

Fig. 5 Soil K stock in 0–15 cm depth (a) during 2018 and soil K stock (b) during 2020 as affected by tillage and residue; treatment means followed by the same letter are not significantly different. (SP-strip planting and CT-conventional tillage; HR-high residue and LR-low residue. Error bars represent SE (P < 0.05). Means (n = 4) shown). Total K stock estimated from total K concentrations and bulk density

with HR than others that were statistically similar (Fig. 5a).

In 2020, tillage, residue retention and soil depth had a significant influence on the total K stock in soils (Suppl. A. and Table 4). The SP-HR treated plots contained higher (11.5 Mg ha^{-1}) K stock than other treatments that were statistically similar (Fig. 5b).

Discussion

Only the combination of minimum soil disturbance and increased crop residue retention and 50% more K (SP-HR-HD) than the current recommendation achieved close to neutral K balance. While the influence of minimum soil disturbance on K balance was only about 11 kg K ha^{-1} yr^{-1}, increased crop residue retention, even at only 50-cm of available rice stubble, achieved a more substantial reversal of negative K balance (29 kg K ha^{-1} yr^{-1}) (Table 4). More importantly, the decrease in negative K balance occurred despite a 10–12% higher system yield. By contrast, the K balance was highly negative in the current practice of conventional tillage and low crop residue retention in the lentil-rice-rice cropping pattern which compromises the sustainability of the current practices. The conventional management practices thus cause continuous K depletion in soils. This result is consistent with our previous paper that showed conventional tillage and low crop residue significantly decreased soil K fractions in the top 30 cm relative to reduced soil disturbance and increased residue retention (Islam et.al. 2023). Given that farmers in this region under-fertilise with K relative to recommendations (Islam et al. 2022a, b), the negative K balance on farmers' fields will likely exceed the values reported here. However, even a 50% increase in K fertilizer was unable to correct the negative K balance, or the depletion of K stocks in soil over the two-year period. In the following discussion, we first examine factors contributing to negative K balance and then to the impacts on cropping system productivity.

Changing K balance in the lentil-T. Aus rice-T. Aman rice cropping pattern

Higher K dose along with CA practices almost corrected the negative K balance mainly due to the increased K added by fertiliser despite a small increase in K removal by crops. Tillage did not affect K balance in the first year, but it did in the second year, mainly due to the increased K addition by crop residue. The 50 cm crop residue retention reduced the negative K balance in both years. It also increased the K recycling through the rice straw by an amount greater than the increased K output. Total K inputs by rain water and irrigation which were not affected by any treatments accounted for small proportions of K input. In two separate years, 2019 and 2020, atmospheric deposition of K into soil by rainwater relative to total K input was 4.9 and 6.6% in SP and 5.1 and 7.1% in CT, respectively. In the case of irrigation, 6.6–6.9 and 6.6% of the total K input in SP and 7.1–7.2% in CT was attributed to the water added. Similarly, total K loss from surface soil by leaching was estimated to be 26–30 kg K ha^{-1} yr^{-1} which accounted to 14–16% of total applied K. Singh et al. (2002) found that leaching losses of K in submerged sandy soil and loam soil profiles were 22 and 16% of the applied K, respectively. The leaching loss of K was marginally higher in CT than SP which may be related to the standing water remaining for longer than in SP.

Annual K removal by crops in this system ranged from 215 to 219 and 229 to 232 kg ha^{-1} yr^{-1} for crop establishment methods, 209–226 and 217–245 kg ha^{-1} yr^{-1} for residue levels and 198–236 and 209–251 kg ha^{-1} yr^{-1} for K doses in 2018 and 2020, respectively. The amount of K removed by rice–rice–wheat cropping systems from soil can be as high as 324 kg ha^{-1} in the IGP (Nambiar and Ghosh 1984). Timsina et al. (2013) reported that in Bangladesh, the apparent nutrient balances in the rice-maize system have been highly negative for K (−80 to −109 kg ha^{-1}). Panaullah et al. (2006) also reported negative K balance in three sites in Bangladesh (Ishwordi −46 to −212 kg ha^{-1}; Joydebpur −25 to −64 kg ha^{-1} and; Nashipur −67 to −135 kg ha^{-1}) of three crops per year in the rice–wheat system with maize or mungbean. Salam et al. (2014) also reported that wheat–rice and maize–rice system had negative K balances of −36 and −60 kg ha^{-1} in NPK treatment. Regmi et al. (2002a) also reported a negative K balance ranging from −63 to −85 kg^{-1} ha^{-1} yr^{-1} in the rice–wheat system. The K balance decreased from −76 kg^{-1} ha^{-1} yr^{-1} with no K added and straw removed) to −11 kg^{-1} ha^{-1} yr^{-1} with 66 kg of

K ha^{-1} and straw removed, whereas incorporation of rice straw converted the K balance to positive (Saha et al. 2009). Sinha et al. (2019) also reported the negative K balance of 90 kg ha^{-1} in rice-maize systems and 40 kg ha^{-1} in rice–wheat systems in both zero-tillage and conventional tillage.

Crop residues, especially rice straw, accumulate about 70–80% of the total crop's absorbed K and its recycling would substantially save K fertilizer and help maintain soil K (Saha et al. 2009). In Australia, Whitbread et al. (2000) reported a K balance + 8 kg ha^{-1} when wheat straw was retained, and − 102 kg ha^{-1} when straw was removed. Past reaserch where residues were not retained in soil reported more negative K balance in rice–wheat pattern e.g., 18 to 44 kg K ha^{-1} yr^{-1} net loss on a loamy sand soil at Parwanipur, Nepal (Gami et al. 2001), negative balance of 63–151 kg K ha^{-1} yr^{-1} in Indo-Gangetic Plains, Ludhiana, India (Yadvinder-Singh et al. 2005) and 12–62 K ha^{-1} yr^{-1} Bhairahwa, Nepal (Regmi et al. 2002b).

To reverse the balance of K in the present cropping system from negative to neutral or positive, a larger proportion of the crop residues should be retained in soils (see above) while split application of K fertilizer is another option (Correa et al. 2018; Surendran 2005, Sharma and Singh. 2021). However, it is challenging to retain more than 40% of residue because farmers use crop residues as animal feed, household fuel and raw materials for construction (Kaur et al. 2022). On farms, animal manure and fuel ash can recycle soil organic matter and K from residues that were fed to animals or burnt. Optimal allocation of residues to retention on soil, animal feed, fuel or for construction requires appropriate policy settings which optimse farmers' benefits as well as soil K status for sustainable and profitable agriculture. A change in current policy would benefit from understand the role of crop residues in agricultural fields where K deficiency is intensifying.

Effects of CA and K doses on system productivity of T lentil-T. Aus rice-T. Aman rice cropping pattern

While SP did not influence the rice yield it gave significantly higher lentil yield and System REY than in CT. In the triple-cropping systems of the EGP, SP generally has little effect on rice yields initially or for 3 years (Islam et al. 2014; Haque et al. 2016; Haque and Bell 2019), but positive effects may appear after 7 years of continuous SP practice (Kader et al. 2022). Hence over time, further changes in K balance of SP need to be assessed since higher yields would increase K removal in grain and crop residue, while also recycling more K to soil in retained residues.

In this study, crop REY in the conventional tillage approach was significantly ($p < 0.05$) higher when 50 cm of straw was incorporated into the soil compared to 20 cm of straw incorporation. Memon et al. (2017) and Zhang et al. (2014) showed that straw incorporation is a key management strategy to enhance crop production, along with improved soil fertility and water availability. Similar results obtained by Mandal et al. (2004) who found that rice straw incorporation at a rate of 5 Mg ha^{-1} yr^{-1} coupled with organic manure improved soil moisture, increased microbial activity, and grain yield in wheat relative to outcomes with residue removal or burning. Shah et al. (2003) reported that the shoot biomass of lentils increased with residue retention compared to residue removal. Islam et al. (2022a, b, c) reported that lentil yield at the present site increased by 22% in HR relative to LR in cropping season 2 and by 23% in SP relative to CT in cropping season 3. Mohammad et al. (2012) also found a higher yield of wheat in ZT with straw retention than in CT with straw removal.

In this study, SP together with high residue retention and 125% or 150% K of RD (SP-HR-HD) had 23–35% higher crop yield than that from the current crop establishment method and fertilizer rate (CT-LR-RD). The increased yield with a higher K dose than the current recommendation for crops in the agro-ecological zone where the experiment was conducted suggests that crops have higher yield potential if adequately supplied with K. Long-term CA practices improve soil fertility, nutrient availability and eventually the crop yield potential (Kader et al. 2022). The role of increased residue in conserving soil moisture coupled with enhanced nutrient supply through mineralization may also create a conducive soil environment for plant growth and development (Choudhary et al. 2019). Islam et al. (2022a, b, c) reported that in the legume-dominant cropping system, the cumulative REY of HR (40.3 Mg ha^{-1}) was higher than that of LR treatment (37.2 Mg ha^{-1}). A similar positive impact of CA practices on crop yield was also suggested by Bell et al. (2019) who reported higher rice and lentil grain yield by 12% and 28%, respectively.

The current K status of the soil is declining due to negative K balance caused by inadequate fertilization (Salam et al. 2014; Islam et al. 2022a), loss through leaching (Rosolem et al. 2010) and the increased K uptake by crops of high yielding varieties (Miah et al. 2008; Bijay Singh et al. 2004) which together increased the fertilizer K requirement of crops. It is therefore likely that the fertilizer K rate for this cropping system under CA practices may need to increase by 25–50% from the current recommended dose (RD) to achieve the potential yield. Saleque et al. (1998) also observed a significant K response in wetland rice grown in silt loam soil and suggested that increasing the K rate from 30 to 90–120 kg ha^{-1} increased rice yield from 3.5 to 4–4.1 Mg ha^{-1}. Islam et al. (2016) conducted an experiment for eight years with several doses of K where the highest K rate (80 kg K ha^{-1}) had the maximum grain yield of 5.17 Mg ha^{-1} in the dry season and 4.37 Mg ha^{-1} in the wet season.

Conclusions

To counter soil K mining which is common in many rice-based cropping systems, the combination of strip planting and increased crop residue retention were effective measures in retaining and recycling soil K. However, while strip planting and high residue retention significantly reduced the negative K balance compared to the conventional tillage with low residue retention, a 50% or more increase of the recommended dose of K, using current K application methods, is needed to achieve neutral K balance. Increased recycling of K from crop residues and decreases in K leaching are other strategies to reverse negative K balances. Strip planting, high residue retention and increasing K dose above the current recommendation all increased the yield of lentil and rice. The positive effects of increased residue retention on recycling K to the soil also benefit the conventional tillage system.

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Author contributions RWB, MJ and MJ, EH and MBH: Research conceptualization, experimental designing, supervision, and article editingJI, MC, UK, MM and SSN: Field and lab work, data processing and analysisJI: Preparation of article draft, data analysis and interpretation

Declarations

Conflict of interest The authors declare no conflict of interests.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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