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RESEARCH ARTICLE

Conservation agriculture and nutrient management strategies for enhancing crop performance, productivity and nutrient uptake under rice-wheat cropping system

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Abstract

Understanding the relationship between tillage and nutrient management strategies is crucial for maintaining the long-term sustainability of the rice-wheat cropping system (RWCS). Therefore, a field experiment was conducted from 2022 to 2024 at Dr. Rajendra Prasad Central Agricultural University in Pusa, Samastipur, Bihar to study the effect of nutrient management strategies under conservation agriculture (CA) for enhancing crop growth performance, protein content and productivity of RWCS. The experiment was conducted in a split-plot design replicated thrice with 3 different tillage and crop establishment methods [zero tillage direct seeded rice (ZTDSR)-zero tillage wheat (ZTW), puddled DSR (PDSR)-ZT with rice residue retention (ZT + RR) and puddled transplanted rice (PTR)-conventional tillage wheat (CTW)] in main plots and four nutrient management strategies [Farmer's Fertilizer Practices (FFP), Nutrient Expert recommended dose of fertilizer (NE-RDF), RDF + spray of nanourea (NU) and Customized fertilizer (CF)] in sub plots. In both years, crop growth attributes at harvest in rice were found maximum under PDSR while in wheat it was under ZT + RR. In wheat, ZT + RR recorded maximum grain yield which was 13 % and 14.5 % higher than CTW in 2022-23 and 2023-24 respectively. A decline in rice grain yield of 8.3 % and 8.9 % was recorded under FFP over NE-RDF in 2022 and 2023 respectively. Hence, PDSR followed by ZT+RR coupled with NE-RDF can increase agronomic performance and productivity under RWCS.

Keywords

growth; rice residue; sustainability; yield; zero tillage

Introduction

Rice-wheat cropping system (RWCS) is the most prevalent agricultural production system covering nearly 14 million ha in the Indo-Gangetic Plains (IGP) of South Asia (1, 2). In this system, farmers typically grow rice by manually transplanting 25 to 30 days old seedlings into puddled soil, which consumes a substantial amount of water, approximately 200-250 mm. Despite positive effects of puddling on weed control, nutrient availability and crop growth, this practice deteriorates soil properties and reduces overall productivity. Managing the loose and scattered rice residue after harvesting is challenging, as it impedes tillage operations for sowing wheat.

Farmers often resort to burning the leftover rice or wheat residue. Hence, the RWCS needs alternative options to maintain the productivity and sustainability. Adoption of zero tillage (ZT) method of sowing or incorporation of crop residue will not only counteract the greenhouse gas emission but can also improve soil health. In rice, puddled transplanting is common, whereas ZT is practiced for subsequent winter crops, indicating that conservation agriculture (CA) practices are partially adopted by the farmers. Additionally, improper nutrient management in RWCS leads to reduction in water and nutrient use efficiency, soil organic carbon (SOC) depletion, multiple nutrient deficiencies (3, 4).

Under field condition, N use efficiency of conventional fertilizers is around 30 %-35 % which leads to its excess application leading to severe environmental and ecological consequences (4). Considering these factors, the Indian Farmers Fertilizer Cooperative (IFFCO) has developed and patented nano urea (contains 4 % nitrogen), a nanofertilizer intended as an alternative to commercial urea. Furthermore, a newly developed decision support system called Nutrient Expert (NE) consolidates on-farm research data into a user-friendly delivery system to efficiently implement site-specific nutrient management (SSNM) in farmers' fields. Moreover, multi-nutrient deficiencies are emerging for Zn + Fe + B in highly calcareous soils of Bihar and Gujarat. These issues can be solved by the application of customized fertilizers (CF) which are defined as multi-nutrient carriers designed to contain macro-, secondary and/or micro- nutrients.

Adoption of best agronomic management practices such as DSR and ZT + RR along with efficient nutrient management technologies can be a way towards maintaining the productivity of RWCS (5, 6). There is scarcity of information on the effect of CA and different nutrient management options on productivity and soil health under RWCS in Eastern India. These inconsistencies in the literature highlight the need for more research on CA with efficient nutrient management. Based on the highlighted facts and research gap, this study was designed to assess the impacts of various crop establishment methods and nutrient management strategies on the growth, nutrient uptake and productivity of RWCS.

Materials and methods

Experimental treatments and design

The experiment was conducted in a split-plot design, consisting of 12 distinct treatment combinations replicated thrice. The main plots were assigned with 3 different tillage and crop establishment methods, viz. Zero tillage direct seeded rice (ZTDSR) - ZT Wheat (ZTW); Puddled DSR (PDSR) - ZTW + rice residue retention (RR); Puddled transplanted rice (PTR) - Conventional Tillage Wheat (CTW). On the other hand, the sub-plots comprised of 4 different nutrient management strategies viz. Farmer's Fertilizer Practices (FFP) at a rate of 120, 50 and 40 kg/ha of N, P_2O_5 and K_2O; NE recommended fertilizer (NE-RDF) which was 125, 35 and 58 kg/ha of N, P_2O_5 and K_2O for rice and 140, 50 and 59 kg ha^{-1} of N, P_2O_5, and K_2O for wheat; Recommended dose of fertilizer (RDF) (120 kg N, 60 kg P_2O_5 and 40 kg/ha K_2O) + spray of nanourea at the rate of 0.4 %; Customized Fertilizer (CF) at the rate of 200 kg/ha as basal followed by split application of N. The composition of the CF is N: P: K: S: Mg: Fe: Zn: Mn: B: 12: 11: 18: 8: 2.7: 0.2: 0.02: 0.02: 0.015 respectively. For ZTDSR and ZTW, there was no land preparation. Instead, rice (cv. Rajendra Bhagwati) and wheat (cv. HD 2967) seeds were directly sown into the soil with zero-tillage seed-cum-fertilizer planter and approximately 15 cm residue was retained from the previous crop. In puddled DSR, rice seeds are sown on puddled soil using a drum seeder in rows. In ZT + RR, wheat was sown in the soil in which about 30 cm rice residue was retained. In conventional tillage, the land was prepared using a tractor-drawn cultivator, which made two passes at a depth of approximately 0.15 ± 0.05 m, followed by planking. For rice cultivation, the puddling process was carried out manually and 25-days-old seedlings were transplanted at a row spacing of 20 cm and a hill spacing of 15 cm. On the other hand in DSR, a row spacing of 20 cm was maintained. In wheat, the seeds were sown after the land preparation with a row spacing of 23 cm.

Study site description

A field experiment was conducted during the rainy (*Kharif*) and winter (*Rabi*) seasons of 2022-24, at the research farm of Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar (25°59' N, 85°62' E at 52 m above mean sea level). The area receives an annual rainfall of 1210 mm. The average temperature varies from 19 °C to 30 °C with minimum temperature between 35.4 °C to 36.6 °C during April to June and 7.9 °C during January. The soil of experimental field was classified as sandy loam having low organic carbon content (0.39 %), pH (8.7), 230 kg/ha of available nitrogen, 12.5 kg/ha of available phosphorus and 140 kg/ha of available potassium.

Sampling measurement and analysis

During the crop growing season, growth characteristics such as plant height, number of tillers/m^2, leaf area index (LAI), dry matter accumulation and crop growth rate were monitored and recorded at harvest. Five randomly selected plants from each plot were tagged and their heights were measured from the ground surface level to the tip of the panicles. The average of these five plant height readings was reported in cm. Additionally, the number of tillers/m of row length was recorded from each plot and expressed as the average number of total tillers/m^2. The LAI was calculated with use of formula as described by Watson (7):

$$\text{LAI} = \frac{\text{Total leaf area (sq.cm)}}{\text{Total ground area (sq.cm)}}$$

For dry matter analysis, a row length of 25 cm was considered, and plants were uprooted by cutting them at ground level. The samples were then sun-dried initially and subsequently placed in a hot air oven at 65 ± 5 °C until a constant weight was achieved. The dry weight was then recorded and expressed in grams per square meter (g/m^2). Harvesting was conducted separately for each net plot and the crop was left in the plots for sun drying for 7 days.

The grain yield per plot was measured and converted into kg/ha. Straw yield was determined by subtracting the grain yield from the previously recorded biological yield. Grain and straw samples were collected for further chemical analysis. N, P and K content in grain and straw samples were estimated using the standard procedure (8). Nutrient uptake was calculated using the formula (9):

Grain nutrient uptake (kg/ha) =

Nutrient content (%) x grain or straw yield (kg/ha)

The protein content in rice and wheat grain was determined by multiplying the nitrogen content of the grain by a conversion factor of 6.25 and expressed in percentage (10).

The analysis of variance was used to perform the statistical analysis and the least significant differences (LSD) was used to compare the treatment means at 5 % confidence level. The box plots were drawn using the ggplot 2 package of R-software version 4.3.1.

Results

Plant height

Tillage and nutrient management strategies have significantly influenced growth of rice and wheat. PDSR recorded an increase of 12.9 % and 15.6 % in rice plant height as compared to ZTDSR in 2022 and 2023 respectively (Table 1). In wheat, CTW showed a decline of 16.6 % over ZT + RR in first year. Among nutrient management strategies, NE-RDF resulted in maximum rice plant height at harvest which was 15.9 % higher as compared to FFP in first year. On the other hand, in wheat NE recorded maximum plant height which was 14 % and 15 % as compared to FFP in 2022-23 and 2023-24 respectively (Table 2).

Number of tillers

During both the years of the experiment, the significantly highest number of tillers/m^2 in rice at harvest was observed under PDSR showing an increase of 10.8 % and 10.1 % as compared to ZTDSR in 2022 and 2023 respectively. Moreover, during the second year of the experiment in wheat, ZT + RR showed the maximum number of tillers/m^2. A decrease of 9.2 % and 9.6 % in number of tillers/m^2 in wheat was found with CTW over ZT + RR in 2022-23 and 2023-24 respectively (Table 2). Application of fertilizer by NE –RDF recorded significantly higher number of tillers/m^2 in rice i.e. 16 and 15.1 % more tillers in rice as compared to FFP in the first and second year respectively year. Moreover, in wheat application of FFP decreased the tillers/m^2 by 9.2 % and 10.5 % over NE-RDF in both the years respectively.

Dry matter accumulation

Among tillage and crop establishment methods, dry matter (DM) accumulation at harvest in rice was maximum under PDSR in both the years (Table 1). A decline in DM accumulation of 16.5 % and 17.3 % in rice was found in ZTDSR over PDSR in 2022. In wheat, ZT + RR showed 13.7 % and 14.8 % higher DM accumulation compared to CTW in both the years respectively. Nutrient management strategies also affected DM accumulation at harvest and was found maximum with NE–RDF application in both the years.

Leaf Area Index

LAI at 90 days after sowing (DAS) in rice during both the years, was observed maximum under PDSR and minimum under ZTDSR. In wheat, ZT + RR registered an increase of 18.3 % in the first year and 18.6 % in second year as compared CTW at 120 DAS (Table 2). In both rice and wheat, NE-RDF plots recorded maximum LAI while FFP recorded minimum LAI in both the years of the study.

Crop yield

In both the years of the study, highest grain yield of rice was observed with PDSR which was 9.8 % and 10.5 % more

Table 1. Effect of tillage and nutrient management strategies on rice crop growth attributes at harvest and LAI at 90 DAS.

Treatments	Plant height (cm)		Number of tillers/m^2		Dry matter accumulation (g/m^2)		LAI at 90 DAS	
	2022	2023	2022	2023	2022	2023	2022	2023
Tillage practices								
ZTDSR-ZTW	79.6	80.1	203	207	832	841	2.10	2.13
PDSR-ZT + RR	89.9	92.6	225	228	970	987	2.55	2.60
PTR-CTW	82.7	83.6	207	213	864	881	2.32	2.36
SEm (±)	2.0	2.1	4	3	15	16	0.05	0.04
LSD ($p \leqslant 0.05$)	7.9	8.3	15	13	60	61	0.21	0.17
Nutrient management								
FFP	78.9	80.8	199	204	822	836	2.02	2.04
NE recommended fertilizer dose	91.5	93.7	231	235	980	995	2.64	2.69
RDF + spray of NU at 0.4 %	83.9	84.5	212	215	884	899	2.36	2.38
CF at 200 kg/ha as basal *fb* split application of N	82.0	82.7	204	209	868	882	2.30	2.33
SEm (±)	3.4	2.8	5	5	19	19	0.09	0.08
LSD ($p \leqslant 0.05$)	10.1	8.5	16	15	55	56	0.26	0.23
LSD ($p \leqslant 0.05$) (T*N)	NS	NS	NS	NS	NS	NS	NS	NS

*SEm (±) : Standard error of mean; LSD: Least significant difference; (T*N): Interaction between tillage and nutrient management practice.

Table 2. Effect of tillage and nutrient management strategies on wheat crop growth attributes at harvest and LAI at 120 DAS.

Treatments	Plant height (cm)		Number of tillers/m²		Dry matter accumulation (g/m²)		LAI at 120 DAS	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Tillage practices								
ZTDSR-ZTW	94.8	95.2	303	308	742	757	2.14	2.17
PDSR-ZT + RR	99.1	99.7	323	331	794	818	2.32	2.36
PTR-CTW	82.6	83.1	293	299	698	712	1.96	1.99
SEm (±)	2.3	2.4	6	6	15	14	0.05	0.04
LSD ($p \leqslant 0.05$)	8.9	9.3	23	22	57	55	0.20	0.17
Nutrient management								
FFP	87.8	88.0	295	299	695	711	1.98	2.03
NE recommended fertilizer dose	100.1	100.8	325	334	828	847	2.37	2.40
RDF + spray of NU at 0.4 %	91.1	91.8	305	313	747	765	2.14	2.18
CF at 200 kg/ha as basal *fb* split application of N	89.7	90.1	301	305	710	726	2.07	2.09
SEm (±)	2.9	2.7	6	6	25	26	0.07	0.06
LSD ($p \leqslant 0.05$)	8.6	8.0	18	18	75	77	0.22	0.18
LSD ($p \leqslant 0.05$) (T*N)	NS	NS	NS	NS	NS	NS	NS	NS

*SEm (±) : Standard error of mean; LSD: Least significant difference; (T*N): Interaction between tillage and nutrient management practices.

as compared to ZTDSR respectively (Table 3). ZTDSR recorded lowest rice straw yield i.e. 11.9 % and 13.4 % lower in comparison to PDSR in 2022 and 2023 respectively. ZT + RR recorded maximum grain yield in wheat which was 13 % and 14.5 % more than CTW in 2022-23 and 2023-24 respectively (Fig. 1). A significant interaction for grain yield in wheat was found for tillage practices x nutrient management during both the years. However, no interaction effect for tillage practices × nutrient management was found for rice grain yield. In case of nutrient management strategies, application of fertilizer based on NE-RDF resulted in maximum grain yield and minimum was with FFP in both rice and wheat. In rice, a decline in grain yield of 8.3 % was recorded under FFP in the first year in comparison with NE. NE-RDF registered an increase in rice grain yield of 9.8 % under FFP in second year. In case of rice straw yield, NE recommended fertilizer recorded the highest straw yield and FFP showed a 16.8 % and 17.3 % decline in straw yield over NE-RDF in first and second respectively (Table 3). The maximum grain yield in wheat was found with NE-RDF which was 14.6 % and 15.8 % more as compared to FFP in the first and second year respectively. Wheat straw yield was observed minimum with FFP registering a decline of 21.1 % and 19.3 % in comparison to NE-RDF plots in 2022-23 and 2023-24 respectively.

Protein content

Protein content in rice and wheat did not varied significantly with different tillage and crop establishment methods. However, in rice PDSR recorded significantly higher protein content by 4.5 % and 5.9 % over ZTDSR in both years respectively (Fig. 2). During both the years of the experiment, in wheat, ZT + RR recorded maximum protein content. In case of nutrient management practices application of NE-RDF resulted in maximum protein content in both rice and wheat during both the years of the study (Fig. 2).

Table 3. Effect of tillage and nutrient management strategies on yield of rice-wheat cropping system.

Treatments	Grain Yield (kg/ha)				Straw Yield (kg/ha)			
	Rice		Wheat		Rice		Wheat	
	2022	2023	2022-23	2023-24	2022	2023	2022-23	2023-24
Tillage practices								
ZTDSR-ZTW	4116	4157	3683	3760	5229	5328	4298	4394
PDSR-ZT + RR	4523	4595	3945	4149	5938	6153	4695	4906
PTR-CTW	4142	4203	3490	3625	5311	5467	4012	4133
SEm (±)	86	72	86	89	132	118	102	116
LSD ($p \leqslant 0.05$)	338	284	336	349	519	463	402	455
Nutrient Management								
FFP	4137	4192	3554	3635	5019	5139	3905	4082
NE recommended fertilizer dose	4513	4601	4073	4210	6032	6216	4950	5057
RDF + spray of NU at 0.4 %	4199	4244	3678	3853	5505	5712	4434	4524
CF at 200 kg/ha as basal *fb* split application of N	4193	4236	3518	3680	5413	5531	4050	4248
SEm (±)	106	119	91	103	164	149	149	159
LSD ($p \leqslant 0.05$)	314	352	271	307	488	442	442	471
LSD ($p \leqslant 0.05$) (T*N)	NS	NS	503	526	NS	NS	NS	NS

*SEm (±) : Standard error of mean; LSD: Least significant difference; (T*N): Interaction between tillage and nutrient management practices.

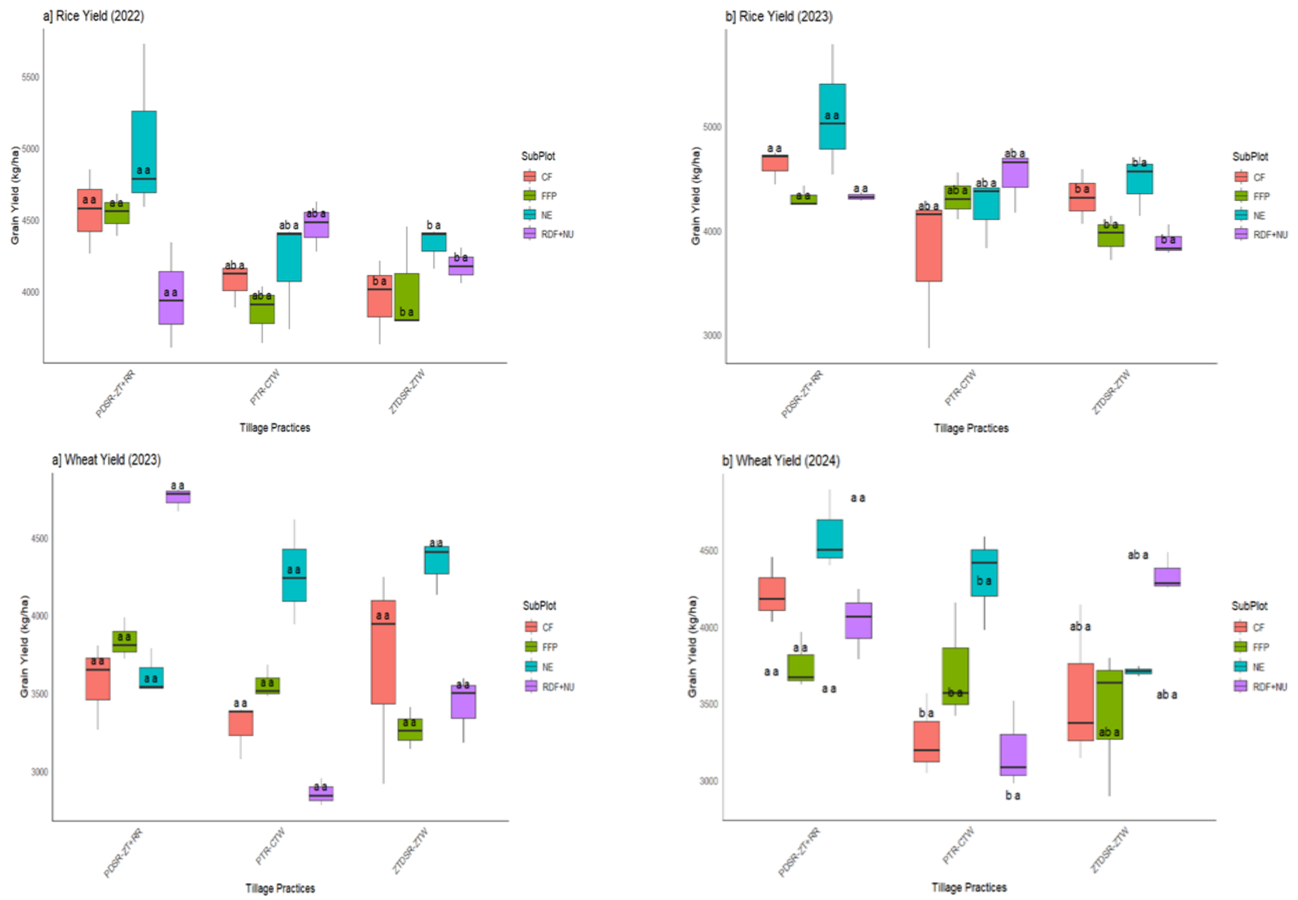

Fig. 1. Impact of tillage and nutrient management practices on the grain yield of rice and wheat in both the years of experimentation.

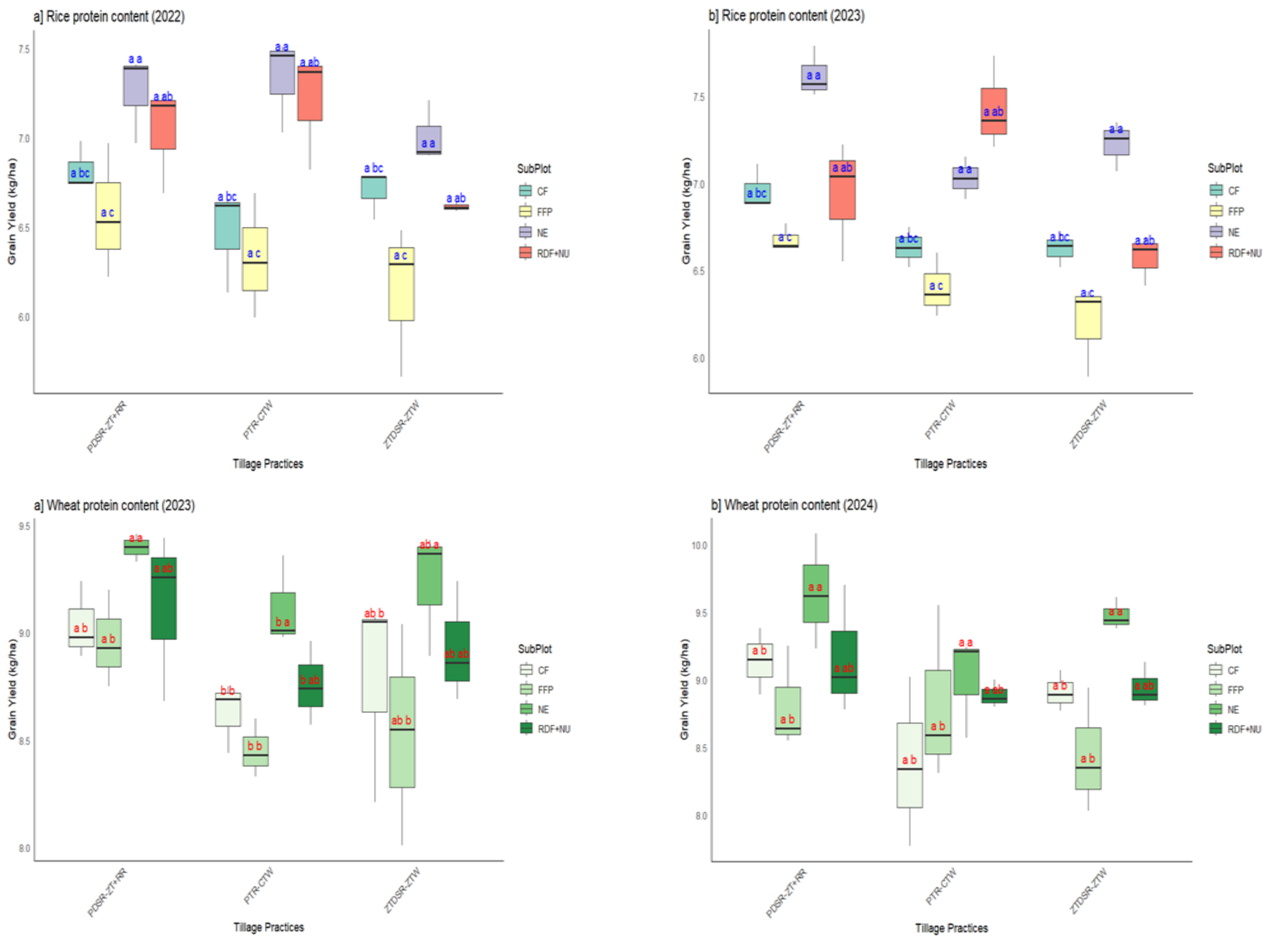

Fig. 2. Effect of tillage and nutrient management practices on the grain protein content of rice and wheat in both the years of experimentation.

Nutrient uptake

Nutrient uptake varied significantly with different tillage and nutrient management treatments. In the first year N, P and K uptake by rice grain was found significantly superior under PDSR which was 14.9 %, 12.6 % and 15.7 % more in comparison to ZTDSR (Table 4). Similar trend was followed in the consecutive year. Nutrient uptake by rice straw was found maximum under PDSR while minimum was found with ZTDSR during both the years. In wheat, ZT + RR resulted in maximum grain and straw nutrient uptake in both the years. ZT + RR recorded 17.7 %, 17.6 % and 17.3 % N, P and K grain uptake and 23.3 %, 21.1 % and 19.4 % higher N, P and K straw uptake than CTW during 2022-23. Furthermore, in the succeeding year CTW showed 16.6 %, 16.8 % and 17.1 % lower N, P and K wheat grain uptake and 21.8 %, 21.2 % and 19.6 % decrease in N, P and K straw uptake over ZT + RR. (Table 5).

In both rice and wheat maximum grain and straw nutrient uptake was observed with application of fertilizer based on NE-RDF and FFP showed minimum N, P and K in both the years. In rice, a decline of 19.2 %, 22.7 % and 13.9 % while19.8 %, 23.5 % and 15.1 % in N, P and K grain uptake was recorded under FFP over NE fertilizer application in 2022 and 2023 respectively (Table 4). An increase of 20.5 %, 18.8 % and 17.3 % in N, P and K rice straw uptake was found with PDSR over ZTDSR in 2022 and 21.6 %, 20 % and 18.7 % in 2023 respectively. Furthermore, in wheat NE-RDF showed 22.3 %, 33.3 % and 29 % while 24.8 %, 39.6 % and 29.4 % more N, P and K grain uptake over FFP in 2022-23 and 2023-24 respectively. N, P and K uptake by wheat straw uptake was recorded maximum under ZT + RR and lowest with CTW. In both the years of the study, straw uptake in wheat was also found minimum in FFP and maximum with NE-RDF (Table 5).

Discussion

During both the years of the study, maximum plant height in rice was found under PDSR while minimum was with ZTDSR. This could be due to the fact that puddling is reported to have beneficial effect on rice through better weed control, reduction in percolation loss of water and nutrients which might have contributed to better growth and establishment of seedlings leading to increased plant height (11, 12). On the other hand, ZT + RR in wheat resulted in highest plant height in both the years. The reason behind this can be increased organic matter content with addition of rice residue which might have influenced the vegetative growth of wheat (13). Furthermore, NE-RDF showed maximum plant height than all other nutrient management strategies. This was due to balanced fertilizer application as per crop requirements in NE-RDF plots which resulted in increase in plant height in both rice and wheat (14).

The maximum number of tillers per m^2 was in rice sown under PDSR while minimum was under ZTDSR. The possible reason for this might be better crop establishment under PDSR as compared to ZTDSR which might have led to proper growth and development of rice. Researchers have reported soil sickness, higher weed competition, biotic stresses, potential of mild water stress because of non-puddled condition in ZTDSR which might have reduced the growth (15). Moreover, wheat sown under ZT + RR condition recorded maximum tillers in first and second years respectively. This could be attributed to the decomposition of crop residues, which improves soil physical and chemical properties. This enhancement subsequently increased the availability of nutrients necessary for growth and development (16, 17). Application of fertilizer on the basis of recommendation provided by NE-RDF led to maximum tillers and minimum

Table 4. Effect of tillage and nutrient management strategies on nutrient uptake in rice.

Treatments	Grain						Straw					
	N uptake (kg/ha)		P uptake (kg/ha)		K uptake (kg/ha)		N uptake (kg/ha)		P uptake (kg/ha)		K uptake (kg/ha)	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
Tillage practices												
ZTDSR-ZTW	43.63	44.38	16.95	17.27	19.75	19.94	25.28	26.10	13.69	14.16	104.87	108.26
PDSR-ZT + RR	50.16	51.99	19.09	19.84	22.86	24.06	30.45	31.75	16.27	16.99	123.01	128.54
PTR-CTW	45.42	46.31	17.04	17.46	20.60	21.04	26.41	27.52	14.35	14.94	107.48	112.31
SEm (±)	0.73	1.21	0.39	0.50	0.44	0.71	0.57	0.68	0.28	0.49	2.15	2.94
LSD (p≤0.05)	2.86	4.76	1.52	1.98	1.71	2.77	2.25	2.68	1.11	1.92	8.43	11.55
Nutrient management												
FFP	42.06	43.15	15.86	16.33	19.95	20.67	22.18	23.01	12.06	12.52	97.87	101.71
NE recommended fertilizer dose	52.03	53.83	20.53	21.35	23.16	24.35	32.84	33.96	17.86	18.44	129.35	133.77
RDF + spray of NU at 0.4 %	46.76	47.51	17.70	18.03	20.94	20.90	28.14	29.74	15.06	15.97	112.82	119.46
CF at 200 kg/ha as basal *fb* split application of N	44.77	45.75	16.66	17.05	20.22	20.79	26.34	27.12	14.09	14.53	107.12	110.53
SEm (±)	1.36	1.29	0.54	0.63	0.43	0.73	0.88	0.87	0.51	0.60	3.65	4.28
LSD (p≤0.05)	4.05	3.82	1.61	1.88	1.27	2.16	2.60	2.57	1.50	1.79	10.85	12.71
LSD (p≤0.05) (T*N)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*SEm (±) : Standard error of mean; LSD: Least significant difference; (T*N): Interaction between tillage and nutrient management practices.

Table 5. Effect of tillage and nutrient management strategies on nutrient uptake in wheat.

Treatments	Grain						Straw					
	N uptake (kg/ha)		P uptake (kg/ha)		K uptake (kg/ha)		N uptake (kg/ha)		P uptake (kg/ha)		K uptake (kg/ha)	
	2022-23	2023-24	2022-23	2023-24	2033-23	2023-24	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Tillage practices												
ZTDSR-ZTW	52.38	53.88	11.67	12.04	12.33	12.72	23.21	24.20	8.97	9.33	59.98	62.36
PDSR-ZT + RR	57.59	61.10	12.63	13.61	13.28	14.03	25.93	27.67	9.96	10.66	66.05	70.34
PTR-CTW	48.92	50.93	10.74	11.32	11.32	11.63	21.03	21.62	8.22	8.40	55.30	56.53
SEm (±)	1.35	1.36	0.25	0.42	0.29	0.37	0.45	0.65	0.13	0.29	1.38	1.69
LSD (p≤0.05)	5.31	5.35	0.98	1.63	1.13	1.44	1.76	2.56	0.52	1.12	5.43	6.63
Nutrient management												
FFP	49.23	50.58	10.30	10.57	11.01	11.31	19.89	20.84	7.02	7.34	53.12	55.75
NE recommended fertilizer dose	60.23	63.13	13.73	14.76	14.21	14.64	28.06	29.75	11.21	11.83	70.80	74.05
RDF + spray of NU at 0.4 %	52.79	55.51	11.77	12.50	12.64	13.30	24.04	24.81	9.85	10.16	62.26	64.43
CF at 200 kg/ha as basal *fb* split application of N	49.59	52.01	10.91	11.46	11.38	11.92	21.56	22.58	8.11	8.52	55.61	58.07
SEm (±)	1.25	1.47	0.32	0.35	0.37	0.34	0.91	0.97	0.30	0.38	2.35	2.60
LSD (p≤0.05)	3.72	4.35	0.96	1.04	1.10	1.02	2.70	2.87	0.91	1.12	6.98	7.73
LSD (p≤0.05) (T*N)	6.44	7.54	1.66	1.81	1.90	1.77	NS	NS	NS	NS	NS	NS

*SEm (±) : Standard error of mean; LSD: Least significant difference; (T*N): Interaction between tillage and nutrient management practices.

was under FFP. The probable reason for this can be proper application of nutrients especially nitrogen to the crops which led to increased cell division causing an enhancement in number of effective tillers (18).

Highest accumulation of dry matter in rice was under PDSR and lowest was with ZTDSR. This may be due to increased water availability under puddled condition that maintained higher turgor potential, which led to longer stomatal openings and faster photosynthesis which lead to an increase in dry matter production (19). In wheat, ZT + RR resulted in more accumulation of dry matter as compared to CTW in both the years. The substantial dry matter accumulation observed in wheat under ZT with residue retention may be attributed to several factors, including moderate soil temperatures, favourable soil moisture levels and enhanced soil biota. This can be due to continuous nutrient supply through residue mineralization (20). The maximum and minimum dry matter was recorded under NE-RDF and FFP plots respectively. This could be due to more crop growth at a balanced level of nutrients leading to more dry matter accumulation through increased photosynthetic activities in both rice and wheat (21).

LAI was maximum in rice under PDSR and minimum in ZTDSR while in wheat it was maximum in ZT + RR. The minimum LAI in wheat was found with CTW. This can be attributed to the larger leaf area per stem and the greater number of tillers per plant in rice under PDSR condition (22). On the other hand, in wheat, the increase in nitrogen content in soil with crop residue retention effectively increased leaf area duration by increasing the LAI (23). NE-RDF plots showed maximum LAI due to more efficient nutrient supply aligned with crop demand, leading to an increased number of leaves per unit area and an overall enlargement of leaf area.

Higher rice yield was recorded in PDSR than ZTDSR in both years of the experimentation. The reason behind this could be more weed problems in ZTDSR and on the other hand, puddling is advantageous for rice as it controls weeds, reduces water and nutrient loss via percolation, enhances rice seedling establishment and boosts nutrient availability (24). ZTW and ZT + RR in wheat enhanced crop yield over CTW due to increased decomposition of crop residue which has likely enhanced nutrient availability, subsequently increasing wheat yield by promoting the soil microbial population and increasing soil organic matter content (25). The significant interaction found in wheat grain yield could be due to positive interaction between tillage and crop establishment strategies along with suitable nutrient application on wheat grain yield. NE-RDF showed more crop yield which might be attributed to the optimized distribution of nutrients in NE-RDF plots, which effectively met the nutrient requirements for growth from vegetative to reproductive stages in a balanced manner. Furthermore, unbalanced or excessive nutrient input may disrupt the physiological metabolism of crops and reduce the nutrient mobilization and grain-filling rate and eventually reduce yield (26).

Tillage practices did not showed a significant effect on the protein content of rice and wheat during both the years. This might be due to the reason that nutrient content in grain did not affect significantly due to tillage practices (27). Nutrient management using NE-RDF led to maximum protein content in grain due to maximum nutrient content of N, P and K in grain under these treatments owing to proper nutrient availability to crop under NE-RDF treatments as nutrient losses were reduced due to balanced and demand-based nutrient supply (28).

Nutrient uptake by rice grain and straw was higher under PDSR than ZTDSR. This could be due to the fact that both grain and straw yield was higher under PDSR which might have increased the nutrient uptake. Moreover, higher availability of nutrients under puddled conditions may be responsible for improving physiological and metabolic functions inside the plant leading to better nutrient uptake (29). On the other hand, adoption of ZT + RR in wheat showed maximum nutrient uptake. The reason behind this can be the improved soil physical properties due enrichment of soil with residue. This enhancement is pivotal in mobilizing nutrients, thus facilitating their availability and uptake for plants (30). Maximum nutrient uptake under NE-RDF indicated that balanced fertilizer application with nutrient-efficient strategies can maintain soil nutrient status, providing a prolonged nutrient supply to plants and reducing nutrient loss. This led to an increase in dry matter production and yield, resulting in higher nutrient uptake.

Pearson correlation analysis demonstrates a positive relationship among crop growth parameters, protein content and yield of both rice and wheat (Fig. 3 a, b). The grain yield of rice revealed significantly positive correlation with plant height (R^2 = 0.973) and number of tillers/m^2 (R^2 = 0.951). Similarly, straw yield showed a significant correlation with LAI at 120 DAS (R^2 = 0.977), dry matter accumulation at harvest (R^2 = 0.994) and protein content (R^2 = 0.986). These findings suggest that conservation tillage practices along with nutrient management strategies have a beneficial impact on the overall performance of RWCS.

Conclusion

This experiment provided an opportunity for the assessment of the impact of adopting CA-based tillage and crop establishment methods, combined with various nutrient management strategies, on the performance and productivity of RWCS. Adoption of PDSR in rice and ZT with rice residue retention in wheat have significantly enhanced the agronomic performance of both the crops. Among nutrient management practices, NE based fertilizer application has resulted in higher growth and yield of both the crops. However, further research should be focused towards increasing crop yield under ZTDSR for adaptation of basic elements of CA as it is critical for large scale adoption and long term impact of CA based systems. The interaction effect of crop establishment and nutrient management strategies was found in wheat grain yield. Therefore, other combinations of tillage and nutrient management practices should be adopted to found suitable method for achieving higher yield under RWCS.

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Authors' contributions

SR, DKR and BP contributed in the conceptualization, data curation and formal analysis and investigation of the study. SR prepared the original draft. SR, DKR, BP and SKS contributed in methodology. SR, DKR, BP, SKS and K provided the resources for the study. SR, DKR, BP, SKS, K and PKJ helped in investigation and writing - review and editing. All authors read and approved the final version of the manuscript.

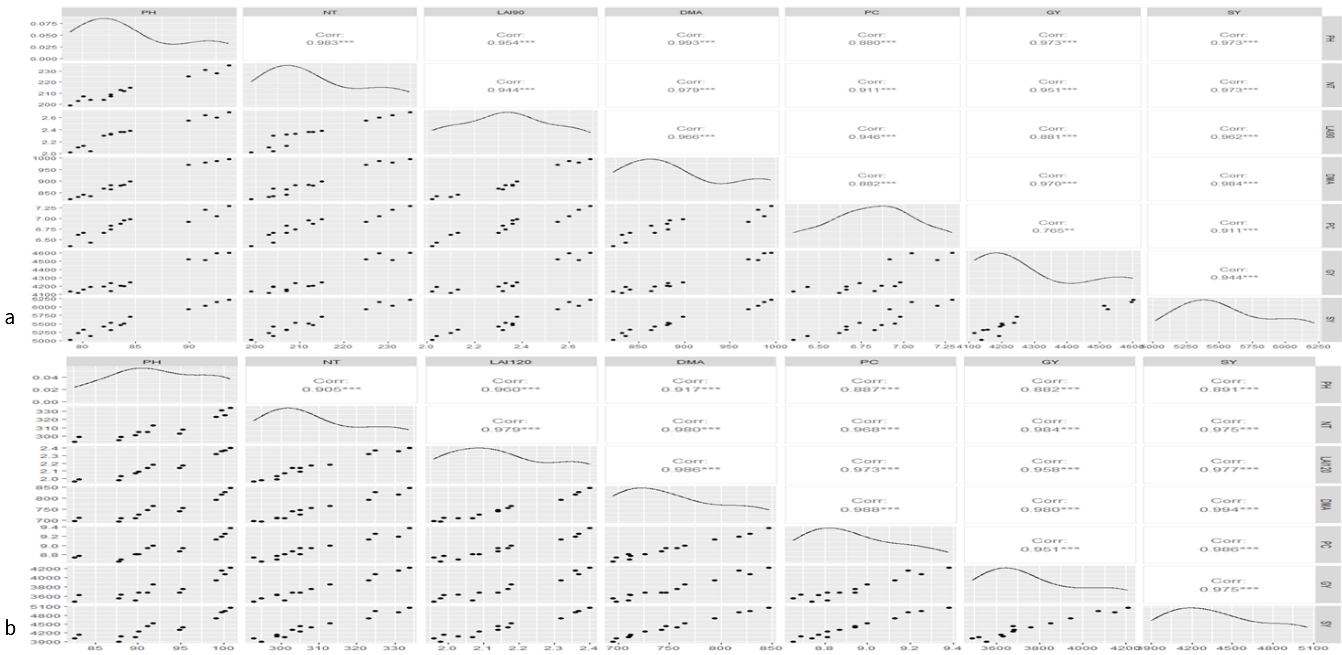

Fig. 3. Correlation panel graph of rice parameters (a) (PH: plant height at harvest, NT: number of tillers at harvest, LAI90: leaf area index at 90 DAS, DMA: dry matter accumulation at harvest, PC: protein content in grain, GY: grain yield, SY: straw yield) and of wheat parameters (b) (PH: plant height at harvest, NT: number of tillers at harvest, LAI120: leaf area index at 120 DAS, DMA: dry matter accumulation at harvest, PC: protein content in grain, GY: grain yield, SY: straw yield).

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

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