



Assessing and Ranking Influence of Rates of Rice (*Oryza sativa* L.) Straw Incorporation and N Fertilizer on Soil Physicochemical Properties and Wheat (*Triticum aestivum* L.) Yield in Rice-Wheat System

P. R. Ramteke¹ · B. B. Vashisht¹ · Sandeep Sharma¹ · S. K. Jalota¹

Received: 26 May 2021 / Accepted: 19 October 2021 / Published online: 1 November 2021
© The Author(s) under exclusive licence to Sociedad Chilena de la Ciencia del Suelo 2021

Abstract

The purpose of this study is to assess the individual and interactive effects of different rates of rice straw incorporation, Rsti, (0, 5, 7.5, and 10 t ha⁻¹) and nitrogen fertilizer, N, (0, 90, 120, and 150 kg ha⁻¹) on changes in physicochemical properties, available nutrients of surface soil, and wheat yield in a long-term rice-wheat system field experiment. Following rice in wheat crop, four rates of Rsti in the main plots and four rates of N in the sub plots were applied in a split-plot design with three replications. After wheat harvest of the 10th rice-wheat cropping cycle, triplicate soil samples were collected from 0 to 15 cm soil layer. Rice straw incorporation improved the soil organic carbon, soil aggregation, porosity, retention, and availability of water, as well as macro and micronutrients availability, and reduced resistance to root penetration, but increased soil bulk density. Wheat yield increased up to 7.5 t ha⁻¹ Rsti and N up to 120 kg N ha⁻¹. Among the assessed soil properties and available nutrients influenced by Rsti and N, supplementary soil organic carbon and available potassium were the top-ranked soil properties responsible for increased wheat yield. Wheat yield increased with rice straw incorporation was mainly due to increased soil organic carbon and available potassium.

Keywords Rice straw incorporation · Nitrogen fertilizer · Soil physicochemical properties · Nutrient availability · Wheat yield · Principal components analysis

1 Introduction

Rice-wheat is a dominant cropping system of Asia. In Indo-Gangetic plains (IGP), the seed yield of rice and wheat ranges from 5.5 to 6.5 and 4.0 to 5.5 t ha⁻¹, respectively, which results in 10–12 t ha⁻¹ of rice and 8–10 t ha⁻¹ of wheat straw production. The management of wheat straw is not a serious concern, but managing the rice straw is a great challenge for farmers. Most (>70%) of the rice straw is burnt in the fields to ensure timely planting of the wheat crop after rice. In Punjab, almost 80% of the rice crop is harvested using combine harvesters, nearly 19.7 million metric tons of paddy straw is left on the soil surface, and 15.4 million metric tons are burnt in fields (Gupta 2019).

This leads to deterioration of soil health by reducing soil organic matter, damaging soil properties, killing soil flora and fauna, and multi-nutrient deficiencies. It also contributes to environmental pollution creating health hazards. Other options are its removal from the field, retention as mulch on the soil surface, and incorporation into soil. Several studies have indicated the incorporation of crop residue into surface soil is beneficial for crop production and soil conservation as it improves the biological activity, soil physical and chemical fertility, and availability of nutrients (Jat et al. 2013; Neugschwandtner et al. 2014; Zhang et al. 2014; Hati et al. 2015; Gathala et al. 2017; Jayaraman et al. 2020; Li et al. 2021). With rice straw incorporation (Rsti), the expected improved soil properties realized after a long period are soil organic carbon, aggregation, intake, retention and availability of water, and availability of nutrients as well as decreased soil penetration resistance. It is hypothesized that the improved edaphic environment with Rsti due to addition of organic carbon (OC) and potassium (K) inherited by rice

✉ B. B. Vashisht
bharatpau@pau.edu

¹ Dept. of Soil Science, Punjab Agricultural University, Ludhiana, Punjab, India

straw is liable for increased wheat yield in rice-wheat system. Though the effect of crop residue incorporation on soil physicochemical properties has been studied extensively, but little is known about the order of dominance of modified soil properties affecting subsequent wheat yield. Thus, a study was under taken to assess (i) the individual and interactive effects of different rates of rice straw incorporation (Rsti) and fertilizer nitrogen (N) on physicochemical properties and available nutrients in the surface soil (0–15 cm), (ii) impact of different rates of Rsti and N on wheat yield, and (iii) dominant soil properties related to wheat yield.

2 Materials and Methods

2.1 Site Description

A long-term field experiment on rice-wheat cropping system was started in 2008–2009 on a sandy clay loam (typic ustochrept) soils at the Department of Soil Science research farm (30° 58' N, 75° 50' E), Punjab Agricultural University, Ludhiana (247 m above sea level). The type of climate for the area is sub-tropical and semi-arid. The weather is characterized by a very hot summer with monsoon season and dry spells, and a bracing winter. The southwest monsoon sets in from the last week of June and withdraws at the end of September. The maximum summer temperature is around 38°C and sometimes touches 45°C. Winter experiences frequent frosty spells, especially in December and January, and the minimum temperature dips to 0.5°C.

2.2 Experimental Design and Treatments

A field experiment on rice-wheat cropping system was started in 2008–2009. Every year, all the plots after wheat harvest (mid-April) were kept fallow until pre-sowing irrigation for rice (first week of June). For rice, the preparatory tillage included two diskings followed by two passes of tyne cultivator in standing water to puddle the soil followed by planking. On the puddle soil, 30 days old rice seedlings (variety PR 118) were transplanted manually at 15 cm × 20 cm spacing in the second week of the June each year. At transplanting, a uniform dose of 13 kg P ha⁻¹ as diammonium phosphate (DAP), 25 kg K ha⁻¹ as muriate of potash (MOP), and 10 kg of Zn ha⁻¹ as zinc sulfate was applied to all the treatments. Different doses of nitrogen (120, 150, and 200 kg ha⁻¹) as urea were applied in 3 equal split doses at transplanting and at 3rd and 6th week after transplanting. Rice crop was harvested manually at physiological maturity in the 3rd week of October and grains from the biomass were removed by using a plot-thresher. In the ongoing field experiment, every year, after rice crop, the straw was removed from the plots and chopped with a chopper. In

split-plot design with three replications, four rates of rice straw (0, 5, 7.5, 10 t ha⁻¹) were incorporated (Rsti) in the main plots with a rotavator. It was followed by pre-sowing irrigation of 80 mm, and sowing wheat in rows 20 cm apart with zero till drill at proper soil moisture conditions. Four N rates (0, 90, 120, 150 kg ha⁻¹) were applied in the subplots. The wheat crop was irrigated (80 mm each) at four critical growth stages (crown root initiation, maximum tillering, panicle initiation, and dough). The 60 kg P₂O₅ ha⁻¹ and 30 kg K₂O ha⁻¹ were applied as per recommendation by Punjab Agricultural University's package of practices (https://www.pau.edu/content/pf/pp_rabi). The wheat crop was harvested at physiological maturity in the third week of April. Grain yield was calculated at 10% moisture content.

2.3 Soil Sampling and Analysis

After wheat harvest of the 10th rice-wheat cropping cycle, triplicate soil samples were collected from 0 to 15 cm soil layer of all plots. The physicochemical properties and available nutrients in soil samples were determined following the standard procedures (Pansu and Gautheyrou 2016): to be exact, the bulk density by core sampler method, soil texture by international pipette method, aggregate stability by wet sieving method, hydraulic conductivity by constant head method, sorptivity cumulative infiltration and steady state infiltration rate in situ by ring infiltrometer method, pH by Beckman's glass electrode pH meter (1:2 soil-water suspension), electrical conductivity at 25 °C by Solu bridge conductivity meter (1:2 soil-water supernatant), soil organic carbon by rapid titration method, available nitrogen by alkaline KMNO₄ method, ammonium and nitrate N by Kjeldahl distillation method, available phosphorus by 0.5 M NaHCO₃ (pH 8.5) extraction method, available potassium by neutral normal ammonium acetate method, available micronutrients cations by DTPA extract method using atomic absorption spectrophotometer (AAS).

2.4 Statistical Analysis

The effects of Rsti and N rates on wheat grain yield, soil physicochemical properties, and available nutrients in soils were analyzed using analysis of variance (ANOVA). Least significant difference (LSD) at $p=0.05$ was used for multiple comparisons of treatment means. The Pearson correlation matrix between soil variables was calculated using "IBM SPSS v.20" statistics. To identify and rank the dominant soil properties responsible for wheat yield improvement, the dimensionality reduction technique "principal component analysis" (PCA) and relative variable importance in terms of mean increase error were performed on the data set using "XLSTAT" software. The variables with high Eigen and factor loading values were selected for each PC,

and the correlation matrix was run separately. The highly correlated variables under different PCs were selected for the final minimum data set, MDS (Andrews et al. 2002a). After determining the MDS indicators, every observation of each MDS indicator was transformed using a linear scoring method (Andrews et al. 2002b).

3 Results

The ANOVA showed that the effect of main (Rsti amounts) and sub (N rates) treatments and their interaction (Rsti×N) on soil physicochemical properties and available nutrients (macro and micro) were mostly significant ($p=0.05$). Therefore, treatments and their interactive effects are presented and discussed.

3.1 Effect of Rice Straw Incorporation and Nitrogen Fertilizer Rates on Soil Physical Properties

The bulk density (BD) of surface soil (0–15cm) increased significantly with rates of Rsti and N over the Rsti0 and N0

checks (Table 1). The significant increase in BD was up to Rsti7.5 (6.6%). The significant increase in BD was up to 120 kg N ha⁻¹ (3.8%), but thereafter decreased at N150. The total porosity (POR) of the soil, inversely related to BD, was significantly decreased by rates of Rsti as well as N (Table 1). Compared to Rsti0, the POR decreased by 7.2% in Rsti5, 11.6% in Rsti7.5, and 11.0% in Rsti10 (Table 1). The PORs in Rsti7.5 and Rsti10 were statistically at par. The N120 treatment reduced POR significantly (8.8%), while for the N0, N90, and N120 rates, it was statistically at par with each other. The Rsti×N interaction was significant, and the same POR of 0.38 m³ m⁻³ was observed in treatment combinations of Rsti5+N90 and Rsti7.5+N120.

Soil moisture characteristics curves (SMCC), depicting the relationship between volumetric moisture content and matric suction, showed that the rates of Rsti and N influenced the moisture content at various suctions (Fig. 1a, b). The moisture content at all suctions increased with Rsti and N rates. At field capacity (FC), soil moisture content was increased by Rsti incorporation over the Rsti0 (0.220 m³ m⁻³), by 21.4, 25.4, and 33.9% in Rsti5, Rsti7.5, and Rsti10 treatments, respectively (Table 1). The FC values in

Table 1 Effect of rice residue incorporation and nitrogen levels on physical properties of 0 to 15 cm soil layer

Treatments	N ₀	N ₉₀	N ₁₂₀	N ₁₅₀	Mean	N ₀	N ₉₀	N ₁₂₀	N ₁₅₀	Mean
Bulk density (Mg m ⁻³)						Total porosity, m ³ m ⁻³				
Rsti0	1.52efg	1.49g	1.57cdef	1.54defg	1.53c	0.41ab	0.43a	0.40bc	0.40bc	0.41a
Rsti5	1.52fg	1.60cd	1.61bc	1.57cdef	1.58b	0.41ab	0.38cde	0.38efg	0.39bc	0.38b
Rsti7.5	1.63abc	1.59cde	1.67ab	1.58cdef	1.62a	0.36def	0.40bc	0.32g	0.38cde	0.36c
Rsti10	1.59cde	1.61bc	1.68a	1.64abc	1.63a	0.37cde	0.38bcd	0.33fg	0.38cde	0.37c
Mean	1.57b	1.57b	1.63a	1.58b		0.39a	0.40a	0.35b	0.39a	
LSD ($p=0.05$)	Rsti:0.03, N:0.03, Rsti×N:0.06					LSD ($p=0.05$) Rsti:1.300.013, N:1.30, Rsti×N:2.600.026				
SED	Rsti:0.014, N:0.014, Rsti×N:0.029					SED Rsti:0.64, N:0.64, Rsti×N:1.28				
Field capacity, m ³ m ⁻³						Permanent wilting point, m ³ m ⁻³				
Rsti0	0.22d	0.24cd	0.22d	0.21d	0.22c	0.088fg	0.101def	0.092fg	0.079g	0.089d
Rsti5	0.24cd	0.27bc	0.29ab	0.29ab	0.27b	0.095efg	0.107cdef	0.115bcde	0.131ab	0.112c
Rsti7.5	0.28ab	0.28ab	0.29ab	0.27bc	0.28b	0.126abc	0.116bcd	0.131ab	0.131ab	0.126b
Rsti10	0.30ab	0.31a	0.29ab	0.28ab	0.30a	0.142a	0.140a	0.140a	0.142a	0.141a
Mean	0.26a	0.27a	0.27a	0.26a		0.113a	0.116a	0.119a	0.121a	
LSD ($p=0.05$)	Rsti:0.019, N:0.019, Rsti×N:0.038					LSD ($p=0.05$) Rsti:0.010, N:0.010, Rsti×N:0.019				
SED	Rsti:0.009, N:0.009, Rsti×N:0.019					SED Rsti:0.005, N:0.005, Rsti×N:0.009				
Available water, m ³ m ⁻³						Soil penetration resistance, MPa				
Rsti0	0.133c	0.136c	0.132c	0.137c	0.134a	2.42ab	2.42abc	2.43a	1.89abcd	2.26a
Rsti5	0.143bc	0.162abc	0.178a	0.157abc	0.160a	1.89abc	1.81abcd	1.67abcd	1.60abcd	1.96b
Rsti7.5	0.155abc	0.165abc	0.160abc	0.138c	0.155a	2.00abcd	1.84abcd	1.85abcd	1.86cd	1.89b
Rsti10	0.163abc	0.176ab	0.156abc	0.141c	0.159a	2.08abcd	2.03bcd	1.83bcd	1.17d	1.78b
Mean	0.148ab	0.160a	0.156ab	0.143b	Mean	2.29a	2.02ab	1.95ab	1.65b	Mean
LSD ($p=0.05$)	Rsti:0.014, N:0.014, Rst N:0.029					LSD ($p=0.05$) Rsti:0.083, N:0.083, Rst N:0.166				
SED	Rsti:0.005, N:0.005, Rst N:0.009					SED Rsti:0.040, N:0.040, Rst N:0.082				

Rsti0, Rsti5, Rsti7.5, and Rsti10 represent rice straw incorporation at 0, 5, 7.5, and 10 t ha⁻¹, respectively

N0, N90, N120, and N150 represent nitrogen fertilizer at 0, 90, 120, and 150 kg N ha⁻¹, respectively

Means followed by the same letter in a column do not differ significantly at 5% probability

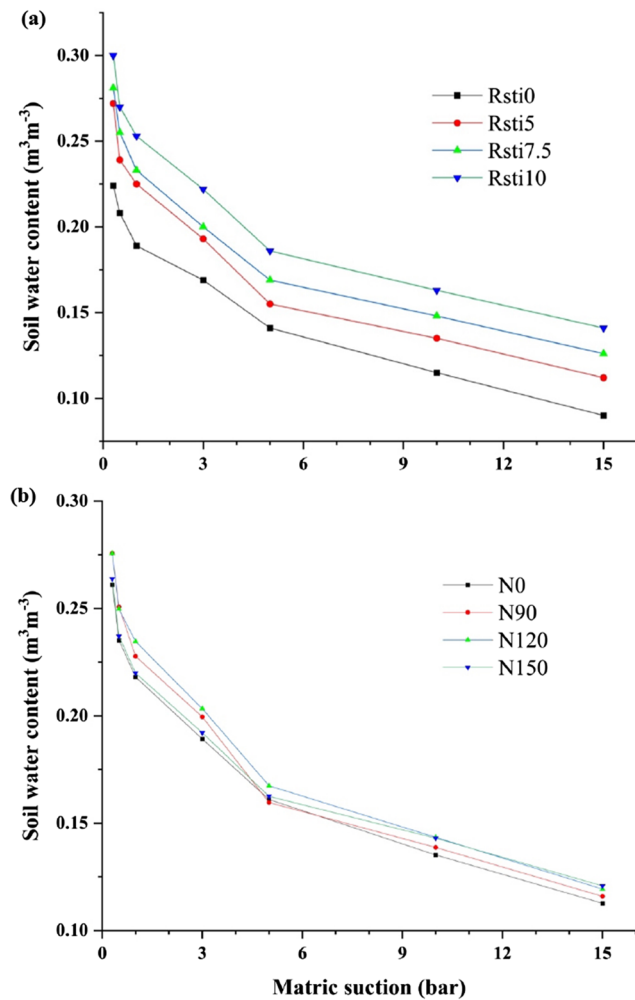


Fig. 1 Soil moisture and matric suction relation as influenced by **a** rice straw incorporation and **b** nitrogen levels. Rsti0, Rsti5, Rsti7.5, and Rsti10 represent rice straw incorporation at 0, 5, 7.5, and 10 t ha⁻¹, respectively. N0, N90, N120, and N150 represent nitrogen fertilizer at 0, 90, 120, and 150 kg N ha⁻¹, respectively. Standard errors for field capacity (0.3 bar) and permanent wilting point (15 bar) are given in Table 1

Rsti5 and Rsti7.5 treatments were statistically at par. Similar trend was observed in soil moisture content at permanent wilting point (PWP). As a consequence of increased moisture at FC and PWP with Rsti incorporation rate, the available water content was also 21.6% higher at Rsti7.5 than Rsti0.

Soil penetration resistance decreased significantly with the rate of Rsti (Table 1). The decrease below Rsti0 was 13.3% in Rsti5, 16.4% in Rsti7.5, and 21.2% in Rsti10. The SPR of 2.29 MPa in N0 decreased by 11.8% in N90, 14.8% in N120, and 27.9% in N150. Total water stable aggregates (TWSA) increased significantly with Rsti. The increase was 15.1% in Rsti7.5 and 15.5% in Rsti10 compared to Rsti0 (54.2%).

The TWSA contained 24.0–34.4% macroaggregates (>0.25 mm) and 28.2–30.2% microaggregates (0.25–0.10 mm) (Table 2). Apart from total of TWSA, the percentage of water stable aggregates within an aggregate size was also changed with Rsti and N addition (Table 3). With the increase in rate from Rsti0 to 10 t ha⁻¹, the percentage of aggregates >0.25 mm increased, mainly for size range 0.25–5.0 mm (by 24.2%). Though the percentage of these aggregates has increased with the Rsti rate increase, the corresponding percentage of aggregate from 0.25 to 0.10 mm has decreased by 6.6%. The TWSA in N0 and N90 and N120 and N150 were significantly at par. The percent TWSA within aggregates of 0.25–0.10 mm and >2.0 mm were increased significantly with increased N from 0 to 150 kg ha⁻¹. The MWD and GMD increased significantly with the Rsti rate. In Rsti10, the MWD increased by 26.8% over the Rsti0 (0.41 mm) and the GMD increased by 42.9% over the Rsti0 (0.28 mm) (Table 2). Likewise, the aggregate ratio (AR), which indicates the proportion of macroaggregates (MaA) over microaggregate (MiA), showed the following order-Rsti10 > Rsti7.5 > Rsti5 > Rsti0 (Table 3). The MWD, GMD, and AR decreased significantly with the N rate compared to N0. In N150, the decrease was 7.8% MWD, 9.8% GMD, and 18.6% AR.

The cumulative infiltration (CI) increased with Rsti and N rates. After 450 min, the CI increase over the Rsti0 (102.8 cm) was by 22.6% in Rsti5, 24.8% in Rsti7.5, and 37.0% in Rsti10 (Fig. 2a). The CI was increased over the N0, respectively, by 21.3, 21.5, and 24.6% in N90, N120, and N150 kg ha⁻¹ (Fig. 2b). Saturated hydraulic conductivity (SHC) of 9.0 mm h⁻¹ for Rsti0 decreased, by 40.0% in Rsti5, 44.4% in Rsti7.5, and 47.8% in Rsti10 (Fig. 3). Saturated hydraulic conductivity also decreased with the N rate. For instance, SHC of 6.0 mm h⁻¹ for N0 treatment was decreased by 8.3% in N90, 11.9% in N120, and 13.3% in N150 kg ha⁻¹.

3.2 Effect of Rice Straw Incorporation and Nitrogen Rates on Soil Chemical Properties

The soil organic carbon (SOC) significantly increased with Rsti rates. Compared to the Rsti0 (4.8 g kg⁻¹), it was higher by 20.8, 25.0, and 33.3% in the Rsti5, Rsti7.5, and Rsti10 treatments, respectively (Table 4). The N rate also significantly increased the SOC. With N90, N120, and N150, the SOC was increased by 7.4, 9.3, and 9.3%, respectively, than the N0 (5.4 g kg⁻¹). The effects of Rsti and N rates and their interactions were significant on electrical conductivity and pH (Table 4). The EC in different treatment combinations varied from 0.14 to 0.18 dS m⁻¹. Significant interaction revealed that pH was highest (7.54) in treatment Rsti0+N0 and lowest (7.03) in Rsti10+N150.

Table 2 Effect of rice residue incorporation and nitrogen levels on physical properties of 0 to 15 cm soil layer

Treatments	N_0	N_{90}	N_{120}	N_{150}	Mean	N_0	N_{90}	N_{120}	N_{150}	Mean
Water stable macroaggregate, %					Water stable microaggregates, %					
Rsti0	24.1h	25.0fgh	21.9gh	25.1fgh	24.0c	24.9ab	30.9ab	31.0ab	34.2ab	30.2a
Rsti5	26.8bcd	22.6h	26.4efgh	33.61efgh	27.4b	18.9a	34.3ab	33.0b	33.7ab	30.0a
Rsti7.5	30.1a	32.6bcd	28.6defg	39.0cdef	32.6a	26.1a	30.2ab	31.1ab	32.0ab	29.9a
Rsti10	30.4cde	36.3ab	33.8ab	37.0bc	34.4a	24.0ab	27.4ab	30.4ab	30.9ab	28.2a
Mean	27.8a	29.1a	27.7a	33.7a	Mean	23.5a	30.7a	31.0a	32.7a	
LSD ($p=0.05$) Rsti:2.28, N:2.28, Rsti N:4.57					LSD ($p=0.05$) Rsti:4.94, N:4.94, Rsti N:9.88					
SED Rsti:1.12, N:1.12, Rsti N:2.24					SED Rsti:2.42, N:2.42, Rsti N:4.85					
Mean weight diameter, mm					Geometric mean weight diameter, mm					
Rsti0	0.47fgh	0.35efg	0.39bcde	0.4h	0.41c	0.36efg	0.20de	0.25bcd	0.31g	0.28c
Rsti5	0.51bc	0.37gh	0.39bc	0.51fgh	0.44b	0.43bc	0.22fg	0.25ab	0.40efg	0.32bb
Rsti7.5	0.47bcde	0.46cde	0.44def	0.46bcde	0.46b	0.36bcd	0.34bcd	0.31cde	0.35bcd	0.34ab
Rsti10	0.58a	0.49b	0.43bcd	0.52defg	0.51a	0.49b	0.38	0.30bcd	0.43def	0.40a
Mean	0.51a	0.42b	0.41a	0.47c	Mean	0.41a	0.28b	0.28a	0.37c	
LSD ($p=0.05$) Rsti:0.026, N:0.026, Rsti N:0.052					LSD ($p=0.05$) Rsti:0.037, N:0.037, Rsti N:0.075					
SED Rsti:0.012, N:0.012, Rsti N:0.025					SED Rsti:0.018, N:0.018, Rsti N:0.036					

Rsti0, Rsti5, Rsti7.5, and Rsti10 represent rice straw incorporation at 0, 5, 7.5, and 10 t ha⁻¹, respectively

N_0 , N_{90} , N_{120} , and N_{150} represent nitrogen fertilizer at 0, 90, 120, and 150 kg N ha⁻¹, respectively

Means followed by the same letter in a column do not differ significantly at 5% probability

Table 3 Percent water stable aggregates within aggregate fractions (mm)

Treatment	Per cent aggregates of different sizes					TWSA (%)	Aggregate ratio
	>2 mm	2–1mm	1.0–0.5mm	0.5–0.25mm	0.25–0.10mm		
Rsti0	1.67c	2.07b	2.95b	17.32b	30.21a	54.22c	0.86c
Rsti5	3.11b	3.14a	4.29a	16.85a	29.98a	57.35ac	1.02bc
Rsti7.5	3.46b	3.43a	4.44a	21.28a	29.85a	62.45ab	1.10ab
Rsti10	4.68a	3.39a	4.79a	21.52a	28.19a	62.57a	1.25a
LSD ($p=0.05$)	0.59	0.45	0.667	1.85	3.80	5.02	0.169
SED	0.29	0.220	0.32	0.91	1.867	2.46	0.083
N_0	3.64a	2.58ab	3.82a	17.8a	23.45a	51.30a	1.29b
N_{90}	2.74bc	2.95a	4.26a	19.19a	30.69a	59.82a	0.99b
N_{120}	2.63b	2.75a	3.66a	18.65a	31.41b	59.09b	0.89a
N_{150}	3.92c	3.70b	4.73a	21.33a	32.69a	66.38ab	1.05b
LSD ($p=0.05$)	0.59	0.45	0.667	1.85	3.80	5.02	0.169
SED	0.29	0.220	0.32	0.91	1.867	2.46	0.083

Rsti0, Rsti5, Rsti7.5, and Rsti10 represent rice straw incorporation at 0, 5, 7.5, and 10 t ha⁻¹, respectively

N_0 , N_{90} , N_{120} , and N_{150} represent nitrogen fertilizer at 0, 90, 120, and 150 kg N ha⁻¹, respectively

TWSA represents total water stable aggregates

Means followed by the same letter in a column do not differ significantly at 5% probability

3.2.1 Effect of Rice Straw Incorporation and Nitrogen Rates on Nutrients Availability in Soil

The macronutrients were significantly affected by Rsti and N (Table 4). The Rsti significantly increased the available N (Avail N) content in the soil. Avail P was highest (35.7 kg ha⁻¹) in Rsti10+N0 and lowest (9.4 kg ha⁻¹) in Rsti0+N0.

Available potassium (Avail K) was differently affected by Rsti and N rates (Table 4). The Rsti rate increased Avail K significantly over the Rsti0 (100.6 kg ha⁻¹), by 20.9, 37.2, and 47.5% in Rsti5, Rsti7.5, and Rsti10, respectively. In contrast, the Avail K was significantly reduced by 9.5, 14.1, and 12.6% at N_{90} , N_{120} , and N_{150} , respectively. The interactive effect of rates of Rsti and N was also significant, with the

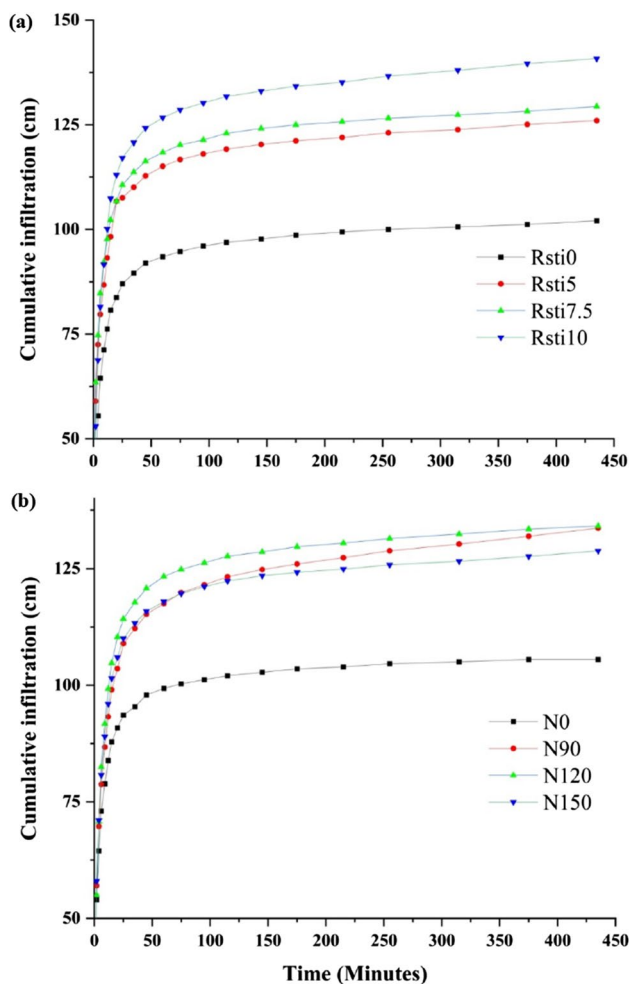


Fig. 2 Cumulative infiltration as influenced by **a** rice straw incorporation and **b** nitrogen levels. Rsti0, Rsti5, Rsti7.5, and Rsti10 represent rice straw incorporation at 0, 5, 7.5, and 10 t ha⁻¹, respectively. N0, N90, N120, and N150 represent nitrogen fertilizer at 0, 90, 120, and 150 kg N ha⁻¹, respectively

highest Avail K (164.2 kg ha⁻¹) in Rsti7.5+ N0 and lowest Avail K (94.9 kg ha⁻¹) in Rsti0+N90.

Rsti increased the available Fe, Mn, Zn, and Cu content significantly (Table 5). In general, available Fe, Mn, and Zn contents were statistically at par in Rsti5, Rsti7.5, and Rsti10, and significantly higher than Rsti0. The Rsti5, Rsti7.5, and Rsti10, respectively, increased the Avail Fe by 4.6, 8.5, and 5.6%; Avail Mn by 21.8, 33.9, and 41.3%; Avail Zn by 9.5, 11.5, and 13.6%; and Avail Cu by 0, 0, and 3.7%. The N addition also significantly affected the available Fe, Mn, Zn, and Cu contents. The N90, N120, and N150, respectively, decreased Avail Fe by 3.9%, increased by 13.4%, and increased 13.8%. The Avail Mn was increased by 6.1, 11.9, and 23.3% at the N90, N120, and N150, respectively. The Avail Zn content decreased by 1.5% at N90, while it increased by 2.3% and 3.8% at N120 and N150, respectively. Unlike Rsti, N addition significantly decreased the available

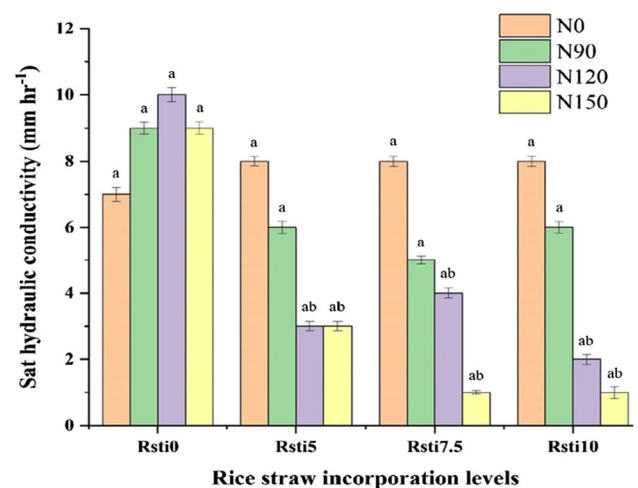


Fig. 3 Saturated hydraulic conductivity as influenced by rice straw incorporation and nitrogen levels. Rsti0, Rsti5, Rsti7.5, and Rsti10 represent rice straw incorporation at 0, 5, 7.5, and 10 t ha⁻¹, respectively. N0, N90, N120, and N150 represent nitrogen fertilizer at 0, 90, 120, and 150 kg N ha⁻¹, respectively. Error bars indicate standard error of means. Histograms with the same letters do not differ significantly at 5% probability

Cu content in soil. Avail Cu content with the N90, N120, and N150 was decreased by 17.2, 1.7, and 0.9%, respectively.

3.3 Effect of Rates of Rice Straw Incorporation and Nitrogen on Wheat Yield

Both the Rsti and N additions affected the grain yield of wheat significantly (Table 6). The mean yield was significantly higher in Rsti7.5 than other rates of Rsti, and in Rsti5 and Rsti10, was statistically at par and significantly higher than Rsti0. Mean yield was higher by 5.4% in Rsti5, 11.10% in Rsti7.5, and 6.95% in Rsti10 than the Rsti0 (4688 kg ha⁻¹). Wheat yield increased significantly from N addition, with the yield from N120 (6321 kg ha⁻¹) and N150 (6092 kg ha⁻¹) being statistically at par (Table 6). The 7.5t ha⁻¹ Rsti+120 kg ha⁻¹ N fertilizer gave the highest yield of 6504 kg ha⁻¹. The treatment combination of Rsti7.5+N90 gave yield (5749 kg ha⁻¹) that was statistically at par with the recommended practice of Rsti0+N120 (5980 kg ha⁻¹), suggesting saving of 30 kg N ha⁻¹ from Rsti7.5.

3.4 Principal Component Analysis

Principal component analysis, performed to describe the soil's most variable parameter(s) explaining wheat yield based on factor loadings from each principal component (PC), showed that maximum variability in the data was explained by the factor loading up to 3 principal components, which is evident from the cumulative variability up to 89.0% and eigen values of 17.8 (Table 7). The PC1 explained

Table 4 Effect crop residue incorporation and nitrogen levels on chemical properties of 0- to 15-cm soil layer

Treatments	N_0	N_{90}	N_{120}	N_{150}	Mean	N_0	N_{90}	N_{120}	N_{150}	Mean
Soil organic carbon (g kg ⁻¹)					Electrical conductivity of soil (dS m ⁻¹)					
Rsti0	4.7g	5.0fg	5.2efg	4.4g	4.8c	0.10c	0.15c	0.16bc	0.16c	0.15b
Rsti5	5.5def	5.8cdef	6.0bcde	6.1bcd	5.8b	0.17ab	0.17ab	0.16bc	0.14c	0.16a
Rsti7.5	5.7cdef	5.7cdef	6.0bcd	6.7ab	6.0b	0.14c	0.18a	0.17ab	0.16ab	0.16a
Rsti10	5.9cde	7.0a	6.3abcd	6.5abc	6.4a	0.10a	0.17ab	0.14c	0.17ab	0.16a
Mean	5.4b	5.8a	5.9a	5.9a		0.16b	0.17a	0.16b	0.16b	
LSD ($p=0.05$) Rsti:0.36, N:0.36, Rsti×N:0.72					LSD ($p=0.05$) Rsti:0.010 N:0.010, Rsti×N:0.020					
SED Rsti:0.177, N:0.177, Rsti×N:0.35					SED Rsti:0.005 N:0.005, Rsti×N:0.010					
Soil pH					Soil available nitrogen (kg ha ⁻¹)					
Rsti0	7.54bc	7.30ef	7.30a	7.52ef	7.41a	119.17a	109.76abcd	90.94g	81.54h	100.35a
Rsti5	7.45ef	7.41f	7.52bc	7.17bc	7.39b	109.76abcd	109.76abcd	116.03def	97.22fg	108.19ab
Rsti7.5	7.48ef	7.54de	7.28b	7.26ef	7.39b	109.76abcd	112.90abcde	97.22dfg	106.62bcdef	106.62a
Rsti10	7.20f	7.42cd	7.50ef	7.03cd	7.29b	100.35defg	84.67cdef	116.03ab	112.90abc	103.49a
Mean	7.42b	7.41b	7.40a	7.24b		109.76a	104.27a	105.06a	99.57b	
LSD ($p=0.05$) Rsti:0.054, N:0.054, Rsti×N:0.109					LSD ($p=0.05$) Rsti:4.51 N:4.51, Rsti×N:9.03					
SED Rsti:0.027, N:0.027, Rsti×N:0.053					SED Rsti:2.21 N:2.21, Rsti×N:4.43					
Soil available phosphorus (kg ha ⁻¹)					Soil available potassium (kg ha ⁻¹)					
Rsti0	9.4f	25.4cd	22.8de	25.3cd	20.7d	105.8efg	94.9g	98.3fg	103.3efg	100.6d
Rsti5	22.3de	24.8cd	26.3c	27.9c	25.3c	130.5cd	117.9de	131.3cd	107.0efg	121.7c
Rsti7.5	26.2c	31.7b	31.2b	21.5e	27.6b	164.2a	141.4bc	111.5ef	138.6bc	138.9b
Rsti10	35.7a	31.1b	31.2b	32.4b	32.6a	159.7a	152.9ab	140.3bc	140.6bc	148.4a
Mean	23.4b	28.2a	27.9a	26.8a		140.1a	126.8b	120.3b	122.4b	
LSD ($p=0.05$) Rsti:1.46, N:1.46, Rsti×N:2.92					LSD ($p=0.05$) Rsti:7.16, N:7.16, Rsti×N:14.32					
SED Rsti:0.71, N:0.71, Rsti×N:1.43					SED Rsti:3.52, N:3.52, Rsti×N:7.03					

Rsti0, Rsti5, Rsti7.5, and Rsti10 represent rice straw incorporation at 0, 5, 7.5, and 10 t ha⁻¹, respectively

N_0 , N_{90} , N_{120} , and N_{150} represent nitrogen fertilizer at 0, 90, 120, and 150 kg N ha⁻¹, respectively

Means followed by the same letter in a column do not differ significantly at 5% probability

Table 5 Effect crop residue incorporation and nitrogen levels on chemical properties of 0- to 15-cm soil layer

Treatments	N_0	N_{90}	N_{120}	N_{150}	Mean	N_0	N_{90}	N_{120}	N_{150}	Mean
Fe, mg kg ⁻¹					Mn, mg kg ⁻¹					
Rsti0	32.95cde	28.06efg	32.92cde	28.60efg	30.64a	6.09f	5.93f	5.80f	6.58ef	6.10d
Rsti5	28.25efg	27.35g	31.32cdefg	41.14a	32.02ab	6.48ef	7.23de	8.20c	7.82cd	7.43c
Rsti7.5	33.11cde	29.32defg	35.54bc	34.92bc	33.22a	6.61ef	8.30c	8.45c	9.31b	8.17b
Rsti10	27.72fg	32.55cdef	38.67ab	34.27bcd	33.30a	8.28c	7.72cd	8.30c	10.18a	8.62a
Mean	30.51b	29.32b	34.61a	34.73a		6.87d	7.29c	7.69b	8.47a	
LSD ($p=0.05$) Rsti:2.20, N:2.20, Rsti×N:4.40					LSD ($p=0.05$) Rsti:0.37, N:0.37, Rsti×N:0.74					
SED Rsti:1.08, N:1.08, Rsti×N:2.16					SED Rsti:0.182, N:0.182, Rsti×N:0.364					
Zn, mg kg ⁻¹					Cu, mg kg ⁻¹					
Rsti0	2.47defg	2.20g	2.40efg	2.66bcdef	2.43b	1.18a	0.90cd	1.20a	1.08abcd	1.09a
Rsti5	2.77abcd	2.56cdef	2.66bcdef	2.64bcdef	2.66a	1.19a	0.88d	1.04abcd	1.26a	1.09a
Rsti7.5	2.64bcdef	2.87abc	2.32fg	3.01a	2.71a	1.14ab	0.93bcd	1.19a	1.15ab	1.10a
Rsti10	2.68abcde	2.76abcd	2.95ab	2.65bcdef	2.76a	1.15ab	1.13ab	1.12abc	1.12abc	1.13a
Mean	2.64a	2.60a	2.58a	2.74a		1.16a	0.96b	1.14a	1.15a	
LSD ($p=0.05$) Rsti:0.15, N:0.15, Rsti×N:0.30					LSD ($p=0.05$) Rsti:0.10, N:0.10, Rsti×N:0.20					
SED ($p=0.05$) Rsti:0.073, N:0.073, Rsti×N:0.15					SED Rsti:0.05, N:0.05, Rsti×N:0.098					

Rsti0, Rsti5, Rsti7.5, and Rsti10 represent rice straw incorporation at 0, 5, 7.5, and 10 t ha⁻¹, respectively

N_0 , N_{90} , N_{120} , and N_{150} represent nitrogen fertilizer at 0, 90, 120, and 150 kg N ha⁻¹, respectively

Means followed by the same letter in a column do not differ significantly at 5% probability

Table 6 Effect of rice straw incorporation and nitrogen levels on grain yield (kg ha⁻¹) of wheat (pooled data of 3 years)

Treatments	N ₀	N ₉₀	N ₁₂₀	N ₁₅₀	Mean
Rsti0	1797.50f	5181.53e	5980.32abcd	5790.93abcde	4687.57b
Rsti5	1943.04f	5343.90de	6425.94ab	6057.13abc	4942.50ab
Rsti7.5	2222.77f	5749.58bcde	6503.77a	6349.10ab	5206.31a
Rsti10	2025.95f	5481.72cde	6373.74ab	6171.23abc	5013.16ab
Mean	1997.32c	5439.18b	6320.94a	6092.10a	
LSD (<i>p</i> =0.05)	Rsti:314.4, N: 314.4, Rsti×N: 628.8				
SED	Rsti:154.3, N: 154.3, Rsti×N: 308.7				

Rsti0, Rsti5, Rsti7.5, and Rsti10 represent rice straw incorporation at 0, 5, 7.5, and 10 t ha⁻¹, respectively
 N0, N90, N120, and N150 represent nitrogen fertilizer at 0, 90, 120, and 150 kg N ha⁻¹, respectively
 Means followed by the same letter in a column do not differ significantly at 5% probability

Table 7 Loading values and percent contribution of assayed physicochemical variables on axis identified by the principal component analysis

Soil variables	PC1		PC2		PC3	
	Loading values	Contribution of variables (%)	Loading values	Contribution of variables (%)	Loading values	Contribution of variables (%)
Gy wheat	0.527	2.449	-0.804	17.956	0.042	0.062
pH	0.327	0.941	0.636	11.219	-0.544	10.326
SOC	0.980	8.482	0.092	0.234	-0.143	0.713
BD	0.872	6.709	-0.052	0.075	0.249	2.157
Porosity	-0.766	5.172	-0.024	0.016	-0.414	5.964
PR	-0.966	8.229	0.235	1.533	-0.049	0.083
FC	0.916	7.406	0.222	1.366	-0.184	1.178
PWP	0.954	8.024	0.243	1.644	-0.037	0.047
AW	0.656	3.803	0.137	0.524	-0.370	4.770
TWSA	0.791	5.524	-0.420	4.905	-0.099	0.341
MWD	0.376	1.248	0.817	18.518	0.155	0.836
SSIR	0.323	0.922	-0.319	2.829	-0.856	25.567
Ks	-0.919	7.447	0.207	1.193	-0.195	1.322
Avail P	0.925	7.553	-0.006	0.001	-0.219	1.668
Avail K	0.674	4.009	0.697	13.480	-0.111	0.433
Fe	0.663	3.877	-0.311	2.690	0.659	15.158
Mn	0.973	8.356	-0.015	0.007	0.062	0.133
Zn	0.871	6.689	0.359	3.571	-0.003	0.000
Cu	0.156	0.215	0.317	2.796	0.905	28.580
Eigen value		11.331		3.601		2.869
Variability (%)		56.657		18.005		14.343
Cumulative variance (%)		56.657		74.662		89.004

SOC soil organic carbon, BD bulk density, PR soil penetration resistance, FC field capacity, PWP permanent wilting point, TWSA total water stable aggregates, MWD mean weight diameter, SSIR steady state infiltration rate, ks saturated hydraulic conductivity, Avail K available potassium, Avail P available phosphorus, AW available water, GY wheat grain yield of wheat

about 56.7% of the variability with the eigen vector value of 11.3; and the variable with highest positive loading values (0.980) and percent contribution (8.4%) was SOC. The PC2 explained 18.0% of the variability with eigen vector value of 3.6; and the variable with highest positive loading value (0.817) and percent contribution (18.51%) was MWD. Furthermore, the PC3 explained about 14.34% variability with

eigen vector values of 2.87; and the variables with highest positive loading (0.905) and percent contribution (28.5%) values were available Cu. Also, all the assessed variables showed positive correlation except SPR, SHC, and POR in PC1; BD, POR, TWSA, SSIR, Avail P, Avail Fe, and Avail MN in PC2; and pH, SOC, POR, SPR, FC, PWP, AW, TWSA, SSIR, Avail P, Avail K, and Zn in PC3. The bi-plots

of PC1 and PC2 showed that SPR, SHC, and POR were negatively correlated to all other variables (Fig. 4). Segregation of treatments and variables in the factorial space in the figure indicates that the assayed variables are closely ordinate with the data points representing the high correlation among the various soil properties in the orthogonal space, which depicts that variables were more influenced by Rsti7.5 and Rsti10 treatments compared to Rsti5 and Rsti0 as well as all N treatments. The closeness in the distribution lines for FC, PWP, available water, SOC, Rsti7.5, and Rsti10 indicates the positive correlation among these and the significance of high rates of rice straw incorporation (Rsti7.5 and Rsti10) in improving soil physical health. Moreover, Rsti had a positive correlation with pH and available nutrients like K, Cu, Zn, and Mn. Both the Rsti and N variables enhance wheat yield by improving soil physical health and nutrients availability. The random forest algorithm in the present study forecasts that SOC and Avail K are the most important variables to predict wheat yield (Fig. 5).

4 Discussion

Increased BD and decreased POR with Rsti are consistent with the results of Osunbitan et al. (2005). Keller et al. (2019) ascribed it to resettling of the soil particles, resulting from broken down of aggregates during incorporation operation, and compression caused by wheeling action of machinery used for incorporation. Both these mechanisms get accentuated when the incorporated straw is chopped. The

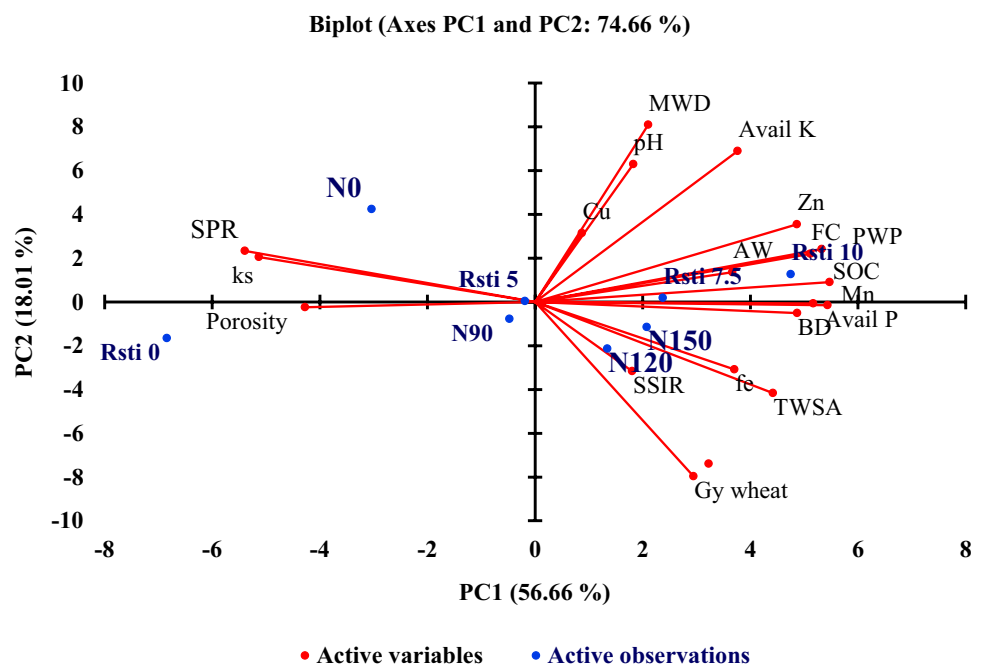
space freed on decomposition gets occupied with finer soil particles and as a consequence, BD is increased.

The decrease in SPR with Rsti is due to significantly higher moisture content retention in the 0 to 15 cm soil layer as a result of improved soil structure owing to the higher amount of SOM and proportion of micro-pores (Table 1). Such decrease in SPR with crop residue incorporation compared to burning or removal has been reported by Zhang et al. (2014); Verhulst et al. (2010); Salahin et al. (2014); Lal (2000); and Gathala et al. (2017).

The significant improvement of total water stable aggregates (TWSA) and percent of water stable aggregates with Rsti are supported by the findings of Walia and Dick (2018) and Karami et al. (2012). The increased percentage of macroaggregates and decreased percentage of 0.2 to 1.0 mm aggregates are in line with the observations of Singh et al. (2018) in Indian Punjab and Wang et al. (2015) and Wei et al. (2006) in China, who observed increased macro- and decreased microaggregates with rice straw application. The significant increase of mean weight diameter (MWD) and geometric mean diameter (GMD) with Rsti is because of the increased proportion of macroaggregates (>0.25 mm). The increased SOC and TWSA results are in line with those of Verhulst et al. (2010) and Ozpinar and Cay (2006).

The cumulative infiltration (CI) increase with Rsti substantiates the observations of Gathala et al. (2017), Govaerts et al. (2009), and Jat et al. (2013) and is probably because of the presence of a greater proportion of macro- and mesopores. The decreased saturated hydraulic conductivity (SHC) with Rsti is attributed to increased bulk density (Table 1). These results corroborate the findings of Turmel et al. (2015)

Fig. 4 Principal component analysis of soil physicochemical properties. SOC, soil organic carbon; BD, bulk density; SPR, soil penetration resistance; FC, field capacity; PWP, permanent wilting point; AW, available water; TWSA, total water stable aggregates; MWD, mean weight diameter; SSIR, steady state infiltration rate; ks, saturated hydraulic conductivity; Avail K, available potassium; Avail P, available phosphorus; GY wheat, grain yield of wheat



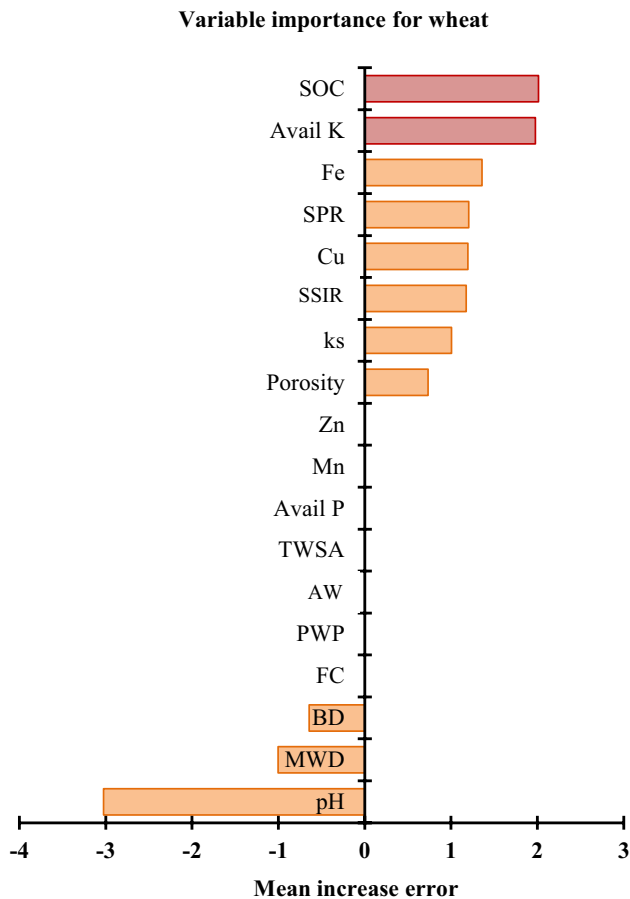


Fig. 5 Relative importance of soil variables for predicting yield. SOC, soil organic carbon; Avail K, available potassium; SPR, soil penetration resistance; SSIR, steady state infiltration rate; ks, saturated hydraulic conductivity; Avail P, available phosphorus; TWSA, total water stable aggregates; AW, available water; PWP, permanent wilting point; FC, field capacity; BD, bulk density; MWD, mean weight diameter

who reported a decrease in hydraulic conductivity of a sandy soil with crop residue. All these studies on hydraulic conductivity clarify that it may decrease with Rsti if soil bulk density and tortuosity of the pores are increased especially when the straw is chopped. The N fertilizer increases BD, decreases POR and saturated hydraulic conductivity (SHC), while it increases cumulative infiltration (CI) due to more root proliferation (Tripathi et al. 2007) which compresses the soil particles by its pressure (Lucas et al. 2019). The improved water retention characteristics of soil could be attributed to higher amount of SOM and conversion of macro-pores into more stable water transmitting micro-pores, as evident from the aggregation ratio in the present study and that of Singh et al. (2011).

Regarding the change in soil chemical properties and nutrient availability, the increase in SOC content may be ascribed to more decay and release of carbonaceous material

after incorporation of crop residue (Choudhury et al. 2014; Lehtinen et al. 2014). Increased SOC with N may be due to more root and shoot growth as well as increased amount of leaf fall as crop progresses towards its maturity (Sivakumar and Ahlawat 2008; Hati et al. 2015; Virk et al. 2017). Both Rsti and N significantly increased available N, P, and K contents in soil. Increased available N in soil with Rsti is similar to the results of Shafi et al. (2007) and Kushwaha et al. (2000). Increased available N in soil with Rsti is similar to the results of Shafi et al. (2007) and Urra et al. (2018) who attributed it to the increased values of soil microbial activity and biomass. The increased Avail P with Rsti is attributed to reduced direct contact between Avail P and soil particles and increased phosphatase enzyme activity (Lemanowicz 2011). Higher Avail K at higher Rsti is ascribed to the fact that about 80–85% of total plant K remains in vegetative part at crop maturity, which may contribute to the soil Avail K after microbial decomposition. The results of the present study are analogous with the findings of Gathala et al. (2017) and Surekha et al. (2003). The increased available micronutrient contents with Rsti could be attributed to the fact that about 50–80% of micronutrient cations (Zn, Fe, Cu, and Mn) taken up by rice crop remains in the vegetative part after maturity and can be recycled through incorporated residue (Singh et al. 2009).

Increase in wheat yield with crop residue incorporation has been reported either due to improved soil physicochemical properties (Zhao et al. 2019; Chen et al. 2020) or availability of micronutrients (Sharma and Dhaliwal 2020), but no study is available that obviously shows the dominant variable responsible for yield increase.

The principal component analysis in the present study adds that among the measured soil properties and available nutrients, the top-ranked responsible for increased wheat yield from Rsti were soil organic carbon and available potassium. These results are consistent with those of Sarkar and Kar (2011) who also reported significant improvement of grain rice and wheat yield with addition of rice straw and wheat straw either separately or in combination. The supplemented soil organic carbon improves the soil aggregation, water intake, retention, and availability, as well as nutrients availability, while it decreases resistance to root penetration. Combined effect of these helps in boosting the grain yield.

Beneficial effect of Rsti into surface soil for crop production and soil conservation has also been reported as it rebuilds the biological activity and plays a vital role in improvement and maintenance of edaphic environment (Gathala et al. 2017; Jat et al. 2013; Zhang et al. 2014). Significant increase in grain yield with Rsti and N in the present study is in line with the results of Yuana et al. (2014). Yield may decrease in the first and second cropping cycle due to immobilization of nitrogen and phosphorus (Karlen et al. 2014; Varvel et al. 2008). Nitrogen fertilizer improves

the yield by proliferating root system and canopy size. The wheat yield response to rice straw incorporation may vary with the longevity of the practice, soil (textural and structural properties, which governs the distribution of soil separates and pore spaces), type of the rice straw (as such or chopped), and the machinery used for incorporating it.

5 Conclusions

In India and Indo-Gangetic plains, rice straw disposal is a problem in the rice-wheat cropping system. In general, rice straw is burnt in situ which causes deterioration of soil health by reducing soil organic matter, damaging soil properties, killing soil flora and fauna, and multi-nutrient deficiencies. Moreover, it contributes to environmental pollution creating health hazard. Incorporating an appropriate fraction of total rice straw into surface soil is a viable option of safe disposal as it not only increases wheat yield, but improves soil organic carbon, ensuing soil physicochemical properties and nutrient availability.

Declarations

Conflict of Interest The authors declare no competing interests.

References

- Andrews SS, Mitchell JP, Mancinelli R, Karlen DL, Hartz TK, Horwath WR, Pettygrove GS, Scow KM, Munk DS (2002a) On-farm assessment of soil quality in California's Central Valley. *Agron J* 94:12–23. <https://doi.org/10.2134/agronj2002.1200>
- Andrews SS, Karlen DL, Mitchell JP (2002b) A comparison of soil quality indexing methods for vegetable production systems in northern California. *Agric Ecosyst Environ* 90:25–45. [https://doi.org/10.1016/S0167-8809\(01\)00174-8](https://doi.org/10.1016/S0167-8809(01)00174-8)
- Chen Y, Fan P, Li L, Tian H, Ashraf U, Mo Z, Pan S (2020) Straw incorporation coupled with deep placement of nitrogen fertilizer improved grain yield and nitrogen use efficiency in direct-seeded rice. *J Soil Sci Pl Nutr* 20:2338–2347. <https://doi.org/10.1007/s42729-020-00301-2>
- Choudhury SG, Srivastava S, Singh R, Chaudhary SK, Sharma DK, Singh SK, Sarkar D (2014) Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice-wheat cropping system under reclaimed sodic soil. *Soil Till Res* 136:76–83. <https://doi.org/10.1016/j.still.2013.10.001>
- Gathala MK, Jat ML, Saharawat YS, Sharma SK, Singh Y (2017) Physical and chemical properties of a sandy loam soil under irrigated rice-wheat sequence in the Indo-Gangetic Plains of South Asia. *J Ecosyst Ecography* 7:246–258. <https://doi.org/10.4172/2157-7625.S7-002>
- Govaerts B, Sayre KD, Goudeseune B, De Corte P, Lichter K (2009) Conservation agriculture as a sustainable option for the central Mexican highlands. *Soil Till Res* 103:222–230. <https://doi.org/10.1016/j.still.2008.05.018>
- Gupta N (2019) Paddy residue burning in Punjab: understanding farmers' perspectives and rural air pollution. Council on Energy, Environment and Water, New Delhi
- Hati KM, Chaudhary RS, Mandal KG, Bandyopadhyay KK, Singh RK, Sinha NK, Mohanty M, Somasundaram J, Saha R (2015) Effects of tillage, residue and fertilizer nitrogen on crop yields, and soil physical properties under soybean-wheat rotation in vertisols of Central India. *Agric Res* 4:48–56. <https://doi.org/10.1007/s40003-014-0141-7>
- Jat ML, Gathala MK, Saharawat YS, Tatarwal JP, Gupta R (2013) Double no-till and permanent raised beds in maize-wheat rotation of north-western Indo-Gangetic plains of India: effects on crop yields, water productivity, profitability and soil physical properties. *Field Crops Res* 149:291–299. <https://doi.org/10.1016/j.fcr.2013.04.024>
- Jayaraman S, Sinha NK, Mohanty M, Hati KM, Chaudhary RS, Shukla AK, Shirale AO, Neenu S, Naorem AK, Rashmi BAK, Patra AK, Rao C, Srinivasa, Dalal Ram C (2020) Conservation tillage, residue management, and crop rotation effects on soil major and micro-nutrients in semi-arid vertisols of India. *J Soil Sci Pl Nutr* 21:523–535. <https://doi.org/10.1007/s42729-020-00380-1>
- Karami A, Homae M, Afzalnia S, Ruhipour H, Basirat S (2012) Organic resource management impacts on soil aggregate stability and other soil physicochemical properties. *Agric Ecosyst Environ* 148:22–28. <https://doi.org/10.1016/j.agee.2011.10.021>
- Karlen DL, Birrel SJ, Johnson JMF, Osborne SL, Schumacher TE, Varvel GE, Ferguson RB, Novak JM, Fredrick JR, Baker JM, Lamb JA, Adler PR, Roth GW, Nafziger ED (2014) Multilocation corn stover harvest effects on crop yields and nutrient removal. *Bioenerg Res*. 7:528–539. <https://doi.org/10.1007/s12155-014-9419-7>
- Keller T, Sandin M, Colombi T, Horn R, Or D (2019) Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil Till Res* 194:104293. <https://doi.org/10.1016/j.cub.2017.05.064>
- Kushwaha CP, Tripathi SK, Singh KP (2000) Variations in soil microbial biomass and N availability due to residue and tillage management in a dryland rice agro-ecosystem. *Soil Till Res* 56:153–166. [https://doi.org/10.1016/S0167-1987\(00\)00135-5](https://doi.org/10.1016/S0167-1987(00)00135-5)
- Lal R (2000) Mulching effects on soil physical quality of an Alfisol in Western Nigeria. *Land Degrad Develop* 11:383–392. [https://doi.org/10.1002/1099-145X\(200007/08\)11:4<383::AID-LDR393>3.0.CO;2-6](https://doi.org/10.1002/1099-145X(200007/08)11:4<383::AID-LDR393>3.0.CO;2-6)
- Lehtinen T, Sclatter N, Baumgarten A, Bechini L, Uger JKR, Grignani R, Zavattaro L, Costamagna C, Spiegel H (2014) Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils. *Soil Use Manage* 30:524–538. <https://doi.org/10.1111/sum.12151>
- Lemanowicz J (2011) Phosphatase activity and plant available phosphorus in soil under winter wheat (*Triticum aestivum* L.) fertilized minerally. *Policy J Agron* 4:12–15 <http://iung.pl/PJA/wydane/PJA4.pdf#page=12>
- Li J, Ye X, Zhang Y, Chen J, Ya N, Zou H (2021) Maize Straw Deep-Burying Promotes Soil Bacteria Community Abundance and Improves Soil Fertility. *J Soil Sci Plant Nutr* 21:1397–1407. <https://doi.org/10.1007/s42729-021-00448-6>
- Lucas M, Schlüter S, Vogel H, Doris V (2019) Roots compact the surrounding soil depending on the structures they encounter. *Scientific Report* 9:16236. <https://doi.org/10.1038/s41598-019-52665-w>
- Neugschwandtner RW, Liebhard P, Kaul HP, Wagentristl H (2014) Soil chemical properties as affected by tillage and crop rotation in a long-term field experiment. *Pl Soil Environ* 60:57–62. <https://doi.org/10.17221/879/2013-PSE>
- Osunbitan JA, Oyedele DJ, Adekalu KO (2005) Tillage effects on bulk density, hydraulic conductivity and strength of a loamy sand soil in Southwestern Nigeria. *Soil Till Res* 82:57–64. <https://doi.org/10.1016/j.still.2004.05.007>

- Ozpinar S, Cay A (2006) Effect of different tillage systems on the quality and crop productivity of a clay–loam soil in semiarid north–western Turkey. *Soil Till Res* 88:95–106. <https://doi.org/10.1016/j.still.2005.04.009>
- Package of Practices for Crops of Punjab, Rabi (n.d.) Punjab Agricultural University, Ludhiana, Punjab, India. https://www.pau.edu/content/pf/pp_rabi. Accessed 10 Apr 2021
- Pansu M, Gautheyrou J (2016) Handbook of soil analysis: mineralogical, organic and inorganic methods. Springer, Berlin Heidelberg
- Salahin N, Jahiruddin M, Islam MR, Bell RW, Haque ME, Alam MK (2014) Effects of minimum tillage practices and crop residue retention on soil properties and crop yields under a rice–based cropping system. In: Proceedings of the Conference on Conservation Agriculture for Smallholders in Asia and Africa. December 2014, Mymensingh, Bangladesh. (Eds. Vance, W, H, Bell, R., W., & Haque, M.E.). pp 133–134
- Sarkar R, Kar S (2011) Temporal changes in fertility and physical properties of soil under contrasting tillage–crop residue management for sustainable rice–wheat system on sandy loam soil. *J Crop Improvement* 25:262–290. <https://doi.org/10.1080/15427528.2011.559145>
- Shafi M, Bakht J, Jan MT, Shah Z (2007) Soil C and N dynamics and maize (*Zea mays* L.) yield as affected by cropping systems and residue management in North–western Pakistan. *Soil Till Res* 94:520–529. <https://doi.org/10.1016/j.still.2006.10.002>
- Sharma S, Dhaliwal SS (2020) Rice residue incorporation and nitrogen application: effects on yield and micronutrient transformations under rice–wheat cropping system. *J Plant Nutr* 43:2697–2711. <https://doi.org/10.1080/01904167.2020.1783295>
- Singh Y, Humphreys E, Kukal SS, Singh B, Kaur A, Thaman S, Prashar A, Yadav S, Timsina J, Dhillion SS, Kaur N, Smith DJ, Gajri PA (2009) Crop performance in permanent raised bed rice–wheat cropping system in Punjab, India. *Field Crops Res* 110:1–20. <https://doi.org/10.1016/j.fcr.2008.06.009>
- Singh B, Humphreys F, Eberbach PL, Katupitiya A, Singh Y (2011) Growth, yield and water productivity of zero till wheat as affected by rice straw mulch and irrigation schedule. *Field Crops Res* 121:209–225. <https://doi.org/10.1016/j.fcr.2010.12.005>
- Singh G, Bhattacharyya R, Das TK, Sharma AR, Ghosh A, Das S, Jha P (2018) Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo–Gangetic Plains. *Soil Till Res* 184:291–300. <https://doi.org/10.1016/j.still.2018.08.006>
- Sivakumar BG, Ahlawat AH (2008) Integrated nutrient management in soybean (*Glycine max*)–wheat (*Triticum aestivum*) cropping system. *Ind J Agron* 53:273–278 DOI not assigned
- Surekha K, Kumari AP, Reddy NM, Satyanarayana K, Cruz PC (2003) Crop residue management to sustain soil fertility and irrigated rice yields. *Nutr Cycl Agroecosys* 67:145–154. <https://doi.org/10.1023/A:1025543810663>
- Tripathi R, Sharma P, Singh S (2007) Influence of tillage and crop residue on soil physical properties and yields of rice and wheat under shallow water table conditions. *Soil Till Res* 92:221–226. <https://doi.org/10.1016/j.still.2006.03.008>
- Turmel MS, Speratti A, Baudron F, Verhulst N, Govaerts B (2015) Crop residue management and soil health: a systems analysis. *Agric Syst* 134:6–16. <https://doi.org/10.1016/j.agsy.2014.05.009>
- Urta J, Mijangos I, Lanzén A, Lloveras J, Garbisu C (2018) Effects of corn stover management on soil quality. *Eur J Soil Biol* 88:57–64. <https://doi.org/10.1016/j.ejsobi.2018.06.005>
- Varvel GE, Vogel KP, Mitchell RB, Follett R, Kimble J (2008) Comparison of corn and switchgrass on marginal soils for bioenergy. *Biomass Bioener* 32:18–21. <https://doi.org/10.1016/j.biombio.2007.07.003>
- Verhulst N, Govaerts B, Verachtert E, Castellanos-Navarrete A, Mezzalama M (2010) Conservation agriculture, improving soil quality for sustainable production systems. In: Lal R, Stewart BA (eds) *Advances in soil science: food security and soil quality*. CRC Press, Boca Raton, FL, USA, pp 137–208
- Virk HK, Singh G, Sharma P (2017) Effect of tillage, crop residues of preceding wheat crop and nitrogen levels on biological and chemical properties of soil in soybean–wheat cropping system. *Com in Soil Sci Pl Anal* 48:1764–1771. <https://doi.org/10.1080/00103624.2017.1395446>
- Walia MK, Dick WA (2018) Selected soil physical properties and aggregate-associated carbon and nitrogen as influenced by gypsum, crop residue, and glucose. *Geoderma* 320:67–73. <https://doi.org/10.1016/j.geoderma.2018.01.022>
- Wang X, Jiaa Z, Liang L, Yang B, Dingac R, Nie J, Wang J (2015) Maize straw effects on soil aggregation and other properties in arid land. *Soil Till Res* 153:131–136. <https://doi.org/10.1016/j.still.2015.05.001>
- Wei CF, Gao M, Shao JG, Xie DT, Pan GX (2006) Soil aggregate and its response to land management practices. *China Particology* 4:211–219. <https://doi.org/10.1142/S1672251506000418>
- Yuana L, Zhang Z, Cao X, Zhu S, Zhang X, Wu L (2014) Responses of rice production, milled rice quality and soil properties to various nitrogen inputs and rice straw incorporation under continuous plastic film mulching cultivation. *Field Crops Res* 155:164–171. <https://doi.org/10.1016/j.fcr.2013.09.009>
- Zhang P, Wei T, Jia Z, Han Q, Ren X (2014) Effects of straw incorporation on soil organic matter and soil water–stable aggregates content in semiarid regions of Northwest China. *PLOS ONE* 9:928–939. <https://doi.org/10.1371/journal.pone.0092839>
- Zhao X, Yuan G, Wang H, Lu D, Chen X, Zhou J (2019) Effects of full straw incorporation on soil fertility and crop yield in rice–wheat rotation for silty clay loamy cropland. *Agron-Basel* 9:133. <https://doi.org/10.3390/agronomy9030133>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.