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Interactive effects of long-term management of crop residue and phosphorus fertilization on wheat productivity and soil health in the rice–wheat

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In the context of degradation of soil health, environmental pollution, and yield stagnation in the rice–wheat system in the Indo-Gangetic Plains of South Asia, an experiment was established in split plot design to assess the long-term effect of crop residue management on productivity and phosphorus requirement of wheat in rice–wheat system. The experiment comprised of six crop residue management practices as the main treatment factor with three levels (0, 30 and 60 kg P_2O_5 ha^{-1}) of phosphorus fertilizer as sub-treatments. Significant improvement in soil aggregation, bulk density, and infiltration rate was observed under residue management (retention/incorporation) treatments compared to residue removal or residue burning. Soil organic carbon (SOC), available nutrient content (N, P, and K), microbial count, and enzyme activities were also significantly higher in conservation tillage and residue-treated plots than without residue/burning treatments. The residue derived from both crops when was either retained/incorporated improved the soil organic carbon (0.80%) and resulted in a significant increase in SOC (73.9%) in the topsoil layer as compared to the conventional practice. The mean effect studies revealed that crop residue management practices and phosphorus levels significantly influenced wheat yield attributes and productivity. The higher grain yield of wheat was recorded in two treatments, i.e. the basal application of 60 kg P_2O_5 ha^{-1} without residue incorporation and the other with half the P-fertilizer (30 kg P_2O_5 ha^{-1}) with rice residue only. The grain yield of wheat where the rice and wheat residue were either retained/incorporated without phosphorus application was at par with 30 and 60 kg P_2O_5ha^{-1}. Phosphorus levels also significantly affected wheat productivity and available P content in the soil. Therefore, results suggested that crop residue retention following the conservation tillage approach improved the yield of wheat cultivated in the rice–wheat cropping system.

Rice–wheat cropping system is a predominant agricultural system followed in Asia, especially in South-eastern Asia covering an area of about 24 million hectares[1]. It occupies around 13.5 m ha spread over the Indo-Gangetic Plains of South Asia, of which India shares 10.5 m ha[2]. This cropping system is precarious for the livelihood, food security, employment, and income generation of millions of Asians, with a share of about 33 and 42% in total acreage under rice and wheat and a contribution of 25 and 33% in total rice and wheat production, respectively. The system is extensively practiced in southeastern countries, including the Indian peninsula. In India, it is the most prevalent cropping system in the northern states, with Punjab and Haryana contributing a principal

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share of 70% to the national food grain production. Straw generated from wheat cultivation is removed from the combine-harvested fields with the help of wheat straw combine for its utilization as animal feed. However, more than 80% of straw generated from rice fields is burnt because of the associated factors, viz., low economic value, labour scarcity, interference with the sowing of subsequent crops and short window period for managing rice straw before the sowing of wheat[3].

The heat generated from burning further kills the environment-friendly useful soil microbes[4,5] in addition to the release of greenhouse gases (GHGs) such as carbon dioxide (70%), carbon monoxide (7%), nitrous oxide (2.09%) and methane (0.66%)[6]. Unremitting the burning of these large amounts of crop residues causes a huge loss of nutrients and biodiversity, eventually raising the nutrient input cost and the depletion of long-term soil fertility and productivity[7]. Recent advancements in the field of crop residue management have developed numerous residue management options, viz. surface retention of rice straw and sowing of subsequent wheat with a happy seeder or zero tillage, mulching in other crops, in-situ incorporation; baling and bioenergy generation are available as possible alternatives to burning[8]. Crop residue management is important in determining the distribution and availability of phosphorus in cropped soils. The phytate organic P form accounts for ≥ 50% of the total soil P content. However, this form is unavailable to plants[9,10]. The bioavailability of organic P is greatly affected by the activities of soil enzymes, particularly phosphatase enzymes, and is balanced through residue decomposition and microbial immobilization processes. Although the information on the nutrient requirement in the rice–wheat system under conventional sowing is available but the same is lacking under long-term residue management conditions. Therefore, the present research work aimed to identify the effects of crop residue on rice–wheat system productivity and the interaction of crop residue management approaches with the applied P-fertilizer as crop productivity is often influenced by fertilizer application. As there is relatively little information available on the optimum dose of phosphorus fertilizer under long-term residue-treated soils and feasible savings, the outcome of this study can be useful to ascertain the most optimum fertilizer dosage. Therefore, keeping this in mind the present study was planned to study the interactive effect of long-term crop residue management and phosphorus levels on productivity and phosphorus requirement of wheat and soil health in rice–wheat systems.

Materials and methods
Experimental site description
A long-term field experiment was initiated on the rice–wheat system at a Research farm, Department of Agronomy, Punjab Agricultural University, Ludhiana (30°54' N, 75°48' E, 247 m average mean sea level), India, in 2008 to know the impact of crop residue management on productivity of rice–wheat cropping system. Considering the long-term crop residue management experiment the initial chemical properties and nutrient content of the soil samples has been presented as Supplementary Table 1. For the present study, the soil samples were randomly taken before the establishment of the P-level sub-plot experiment (0–15 cm) with a screw auger to study basic soil chemical and physical properties. The soil of the experimental site belonged to Typic Ustochrept, was sandy loam in texture with normal pH and electrical conductivity while exhibiting low soil organic carbon and medium available N, P, and K contents (Table 1).

Experimental set-up
In 2008, a field experiment was established consisting of six crop residue management practices/planting techniques to study the long-term effect of tillage and residue management on crop yields in rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.). The same experiment was modified after 11 years and continued for two more consecutive years (2019–20 and 2020–21), consisting of six crop residue management treatments as main plots. The subplots included three phosphorus levels viz., 0, 30 and 60 kg P_2O_5 ha^{-1} to study the interactive effect of long-term crop residue management and phosphorus levels on productivity and P-requirement of wheat and soil health in rice–wheat system. The experiment was conducted in a split-plot design with three replications. The plot size was 10.0 m^2 (2.5 m × 4.0 m). The details of various treatments carried out in the summer and winter seasons are given in Table 2. In zero tillage treatments without paddy straw, the sowing was done with a zero till drill machine after removing the straw. However, in zero tillage plots with paddy straw residue, the crop was sown with turbo happy seeder after uniformly spreading the rice residue. In conventional tillage treatments, sowing was done with a conventional seed cum fertilizer drill. In burning treatments, the loose straw was partially burnt, and sowing was done with zero till drill in standing rice stubbles.

Property	Values (units)
Soil texture	Sandy loam [Sand: 69.81%, silt: 18.12%, clay: 12.07%]
Soil pH (1:2.5)	7.16
Electrical conductivity	0.20 dS m^{-1}
Soil organic carbon	0.33%
Available N	127.29 mg kg^{-1}
Available P	8.84 mg kg^{-1}
Available K	111.61 mg kg^{-1}

Table 1. The physical and chemical properties of the experimental soil.

	Summer	Winter
Main plots: CRM practices[6]		
T1	Transplanted rice (after removing wheat straw)	Zero tillage sowing of wheat (after removing paddy straw)
T2	Transplanted rice (after removing wheat straw)	Conventional tillage sowing of wheat (after removing paddy straw)
T3	Transplanted rice (after removing wheat straw)	Conventional tillage sowing of wheat (with paddy straw)
T4	Transplanted rice (after removing wheat straw)	Zero tillage sowing of wheat (with paddy straw)
T5	Transplanted rice (with wheat straw)	Zero tillage sowing of wheat (with paddy straw)
T6	Transplanted rice after burning of wheat straw	Zero tillage wheat after partial burning of paddy straw
Subplots: phosphorus levels[3]		
P0	0 kg P_2O_5 ha^{-1}	
P1	30 kg P_2O_5 ha^{-1}	
P2	60 kg P_2O_5 ha^{-1}	

Table 2. Detail of treatments in summer and winter season.

Crop management

In the summer season, rice variety PR 127 was transplanted in the second fortnight of June with a spacing of 20 cm × 15 cm during both years of study. The nitrogen (125 kg ha^{-1}) to rice was applied through urea in three equal splits at 1, 3 and 6 weeks after transplanting. The crop was harvested in the first week of October for both years. In the winter season, sowing of high-yielding wheat variety *Unnat* PBW 343 was done in Ist week of November using seed (100 kg ha^{-1}) following row-to-row spacing of 22.5 cm during both years of study. Single super phosphate (16% P_2O_5) was used as a phosphorus fertiliser source, and a dose of phosphorus was applied per treatment. Fertilizer N (120 kg N ha^{-1}) was applied through urea (46% N) and potassium (30 kg K_2O ha^{-1}) through muriate of potash (60% K_2O) uniformly to all the treatment plots. Nitrogen to wheat was applied at sowing, crown root initiation (CRI) stage and maximum tillering in equal splits. The P and K-fertilizers were applied as basal soil doses by drilling the field soil at sowing. For root-damaging insect pests, particularly termite management, the seeds were treated with Chlorpyriphos 20 EC (4 ml per kg seed). For weed management, clodinafop (Topik 15 WP) at the rate of 400 g ha^{-1} and metsulfuron (Algrip 20 WP) (25 g ha^{-1}) were sprayed at 30–35 days after sowing by tank mixing in 375 L of water. Irrigations (75 mm depth each) were applied at four critical stages; CRI, late tillering, booting and milking stages. Two sprays of Tilt 25 EC (propiconazole) (500 ml ha^{-1}) at the booting and earing stage to protect the crop from yellow rust and one spray of Rogor 30 EC (dimethoate) (375 ml ha^{-1}) at the earing stage for control of aphid were given. The wheat crop harvesting was carried out manually during the month of April in both years of study.

Agrometeorological data

The climate of the study site is sub-tropical and semiarid with dry and hot summer (April–June), moist weather from July–September and cool and dry winter (November to January). The maximum temperature rises above 47 °C during summer, and the minimum temperature falls below 1 °C during winter in January due to frosty spells. The average annual rainfall during the two years under study was 705 mm. About 75% of annual rainfall is received during the south western monsoon from July to September, and the least rainfall is received in December-January or late spring. During cropping season (winter 2019–20), mean weekly maximum and minimum temperatures ranged from 10.3 to 35.5 °C and 4.9 to 18.4 °C, while respective values ranged from 14.0 to 36.1 °C and 3.5 to 17.9 °C during 2020–21 (Fig. S1).

Reagent used in the experiments

The analytical grade chemicals were used for the various soil chemical analysis studies and included potassium dichromate, sulphuric acid, ammonia, sodium hydroxide, potassium permanganate, sodium bicarbonate, ascorbic acid, ammonium molybdate, ammonium acetate, and acetic acid. The reagents were used for the microbial viable cell count studies included the prepared media as nutrient agar, actinobacteria agar, fungal agar were procured from HiMedia Laboratories Pvt. Ltd., Mumbai, Maharashtra, India. Analytical grade chemicals were used for the enumeration of the soil enzyme activities and included glucose, methanol, urea, 2,3,5-triphenyltetrazolium chloride,triphenylformazan, p-nitrophenyl phosphate, potassium chloride, and phenyl mercuric acetate.

Data collection and analysis

Soil physicochemical properties

Methods used. The soil was sampled in triplicate from 0 to 15 cm soil depth from each plot after harvesting of wheat crop in 2020–21 to know the impact of tillage and crop residue management and phosphorus levels on the soil properties. These samples were appropriately processed, including drying, grinding, and sieving before the analysis. Soil pH and EC (1:2 aqueous suspension)[11], organic carbon (%)[12], available N[13], P[14] and K[11] were determined. To determine bulk density, the undisturbed soil samples were taken from two sites in each plot from middle position of 0–15 cm soil depth after 2 year of the study, by using stainless steel cores (5 cm diameter and 5 cm height), soil was then transferred in moisture boxes and dried at 105 °C in an oven till the constant weight was

achieved[15]. A double-ring infiltrometer was used to measure the infiltration rate from two sites in each treatment after two years of study. The reading on the depth of water infiltrated into the soil with time was recorded from the inner ring until the water intake rate became constant. The infiltration rate was calculated and expressed in cm hour^{-1}[16]. Aggregate analysis to determine the size distribution of aggregates was carried out by using a wet sieving technique as per[17]. Large soil clods collected from 0 to 15 cm using a spade were dehydrated in the shade and crumbed into small aggregates along a natural cleavage using gentle strokes. The aggregates, which passed through an eighty mm sieve, were taken and passed through a 4 mm sieve. The aggregates collected on the 4 mm sieve were utilized to four sets of five sieves each (12.7 cm wide and 5 cm high). The sieve pores ranged in size from 2.0, 1.0, 0.5, 0.25, and 0.1 mm. Over the top sieve of the set, the soil peds were equally dispersed, and the capillary was moistened for approximately 10 min. After that, for 30 min, the sieve set was stirred. The sieves were then dried in an oven at 105 °C until the constant weight was achieved. The water stable aggregates (WSA) were evaluated by the formula below:

$$\text{WSA} > 0.25\,\text{mm}(\%) = \frac{\sum_{i=1}^{n} w_i}{\text{weight of soil peds}} \times 10, \tag{1}$$

where n is the Number of size fractions, d_i is the average diameter for each size range, and w_i is the weight of aggregates in a particular size range as a ratio of the total dry weight of the soil peds taken.

Soil biological properties

Methods used.   For analysing the soil biological properties, soil samples were taken from three spots in each plot after harvest of the crop. The total viable counts of soil bacteria, actinobacteria, and fungi were enumerated using standard serial dilution plate assay on different agar-based media. For serial dilution, 10 g soil samples were added to 90 mL of sterile water blank and shaken for 10 min at 120 rpm. From this 10^{-1} dilution, a series of dilutions were made up to 10^{-6}. For enumerating total viable count bacterial count, actinobacteria and fungi 10^{-6}, 10^{-5} and 10^{-3} dilutions were used, respectively. The Petri plates were incubated for 2 to 6 days at 28 ± 2 °C in a BOD incubator. The colonies were enumerated and expressed in dry soil per gram as colony-forming units (CFU).

The dehydrogenase enzyme activity was enumerated for the soil samples[18]. One gram of soil sample was incubated with 0.2 mL of TTC (2, 3, 5-triphenyl tetrazolium chloride, 3% w/v) and 0.5 mL of glucose solution (0.5 mL, 1% w/v). The samples were incubated at 28 ± 2 °C for 24 h and, after that, extracted with 10 mL methanol under mild shaking conditions and filtrated using Whatman No. 1. The extract was collected, and absorbance measurements ($\lambda = 485$ nm) against the methanol blank were obtained. The final values were calculated through TPF standard curve.

The soil alkaline phosphatase activity was determined[19] for the soil samples (1 g sample each). The yellow colour formed from the p-nitrophenyl phosphate solution was measured at 420 nm and expressed as µg p-nitrophenol released g^{-1} soil h^{-1}.

The urease activity was determined by Bremner and Douglas[20], in which 5 g of soil sample was taken in a volumetric flask and to this, 5 mL 2000 ppm urea solution was added. The moisture was maintained at 50% WHC and incubated at 37 for 7 h. To this, 2MKCl-PMA is added, and the solution is kept on a shaker for 60 min and filtered. Thereafter, extracting reagent (10 mL) and colouring agents (30 mL) are added, kept in the hot water bath for 30 min, cooled to room temperature and finally, the intensity of the red colour is measured at a wavelength of 527 nm. The enzyme activity is calculated from the standard curve, and the activity is expressed as µg urea/g dry soil/min.

Yield attributes and yield of wheat

Effective tillers data was taken from one-meter row length at two locations in each plot at harvest, averaged and then converted into number of effective tillers per m². Spike length was measured from five randomly selected spikes per plot, averaged and expressed in cm. Five randomly selected spikes from each plot was threshed manually, and their grains were counted and averaged for the number of grains per spike. A random sample of grains was drawn from the produce of each plot, and 1000 grains were counted, weighed, and expressed as a 1000-grain weight (g). The bundle weight of each net plot (4 m²) was taken before threshing and was expressed as biological yield (t ha^{-1}). After threshing, the grain weight of each net plot was measured and converted into grain yield per hectare. The straw yield for each treatment was calculated by subtracting grain weight from bundle weight and expressed as straw yield in t ha^{-1}.

Statistical analysis

The data was analyzed through Two-way ANOVA, and treatment means were separated by Duncan's multiple range test and compared by least significant difference (LSD)at $p \leq 0.05$ using SPSS version 16.0 (SPSS Inc., Chicago, USA) packages.

Ethics

All the authors abide by the IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Results

Soil chemical properties

Available soil nutrient (N, P, K) content
The data of available soil nutrients (N, P, K) presented in Fig. 1a–c revealed that different crop residue management practices significantly affected the availability of N, P and K in soil. Significant improvement in the availability of nutrients (N, P, K) was found with residue retention/incorporation as compared with residue removal or burning. The available nutrients in the topsoil layer fluctuate from 299.3 to 388 kg ha^{-1} available N, 22.1 to 33.5 kg ha^{-1} available P and 295.7 to 349.3 kg ha^{-1} available K. However, the highest values of available N, P and K of 389.1 kg ha^{-1}, 33.5 kg ha^{-1} and 349.3 kg ha^{-1}, respectively, were registered with T_5 treatment where the residue of both crops was retained, and it was significantly higher than conventional practice (T_2) or residue burning (T_6) treatments. The various doses of phosphorus did not significantly affect the availability of N and K. The availability of P increased with phosphorus application, and higher P availability was observed with 60 kg P_2O_5 ha^{-1}.

Soil organic carbon
Soil organic carbon content increased with crop residue retention/incorporation treatments irrespective of tillage (Fig. 1d). The soil organic carbon in zero tillage with residue retention treatment was 38.7 and 42.5% higher than in zero tillage without residue (T_1) and conventional tillage without residue treatment (T_2). The highest soil organic carbon content was observed under conservation tillage with residue retention treatments, and it was significantly higher than conventional sown wheat without residue or residue burnt treatments.

The perusal of data revealed that varied phosphorus levels had not significantly affected the soil's organic carbon content. However, a numerically higher value was found when a higher dose of phosphorus was applied. It might be due to the higher dry matter production and root mass produced by crops at higher phosphorus levels. The interactions between crop residue management practices and phosphorus levels were found to be non-significant.

Soil physical properties

Soil aggregation
Treatments T_4 and T_5, having conservation tillage along with residue retentions, had significantly higher macro-aggregates (8.0–4.75 mm and 4.0–2.0 mm size) as compared to traditional tillage treatments (T_2) with residue removal (Table 3). This confirms that conservation tillage favours improvement in soil structure by protecting them against destruction or binding the micro-aggregates.
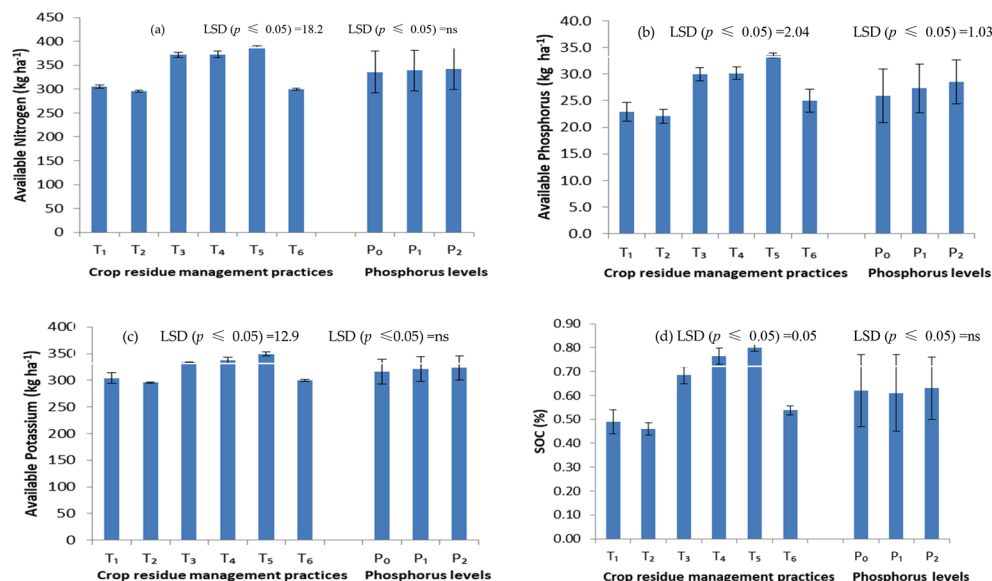

Figure 1. Effect of crop residue management practices and phosphorus levels on chemical properties of soil (**a**) available soil nitrogen, (**b**) available soil phosphorus, (**c**) available soil potassium and (**d**) soil organic carbon at harvest of wheat in the rice–wheat system (pooled data of 2 years). T1: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (After removing paddy straw) (winter season); T2: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (After removing paddy straw); T3: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (With paddy straw); T4: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T5: Transplanted rice (With wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T6: Transplanted rice after burning wheat straw (summer season) and zero tillage wheat after partial burning of paddy straw (winter season). P0: 0 kg P_2O_5 ha^{-1}; P1: 30 kg P_2O_5 ha^{-1}; P2: 60 kg P_2O_5 ha^{-1}.

Treatments	Soil bulk density (g cm⁻³)	Steady-state infiltration rate (cm hr⁻¹)	Aggregate size distribution		
CRM practices	0–15 cm		8.00−4.75 (mm)	4.00−2.00 (mm)	0.106−0.25 (mm)
T_1	1.40ᵃ	1.8ᵇ	10.1ᵇ	9.3ᶜ	19.8
T_2	1.42ᵃ	1.4ᶜ	9.5ᵇ	8.9ᵈᶜ	21.2
T_3	1.35ᶜ	1.5ᶜ	11.9ᵃᵇ	9.5ᶜ	18.2
T_4	1.36ᶜ	2.1ᵃ	14.1ᵃ	11.9ᵃ	16.4
T_5	1.34ᶜ	2.2ᵃ	15.5ᵃ	12.3ᵃ	15.8
T_6	1.39ᵃᵇ	1.8ᵇ	10.2ᵇ	10.1ᵇ	19.5
LSD ($p \leq 0.05$)	0.02	0.1	3.9	0.05	NS

Table 3. Effect of crop residue management practices on soil physical properties in the rice–wheat system (pooled data of 2 years). T1: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (After removing paddy straw) (winter season); T2: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (After removing paddy straw); T3: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (With paddy straw); T4: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T5: Transplanted rice (With wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T6: Transplanted rice after burning wheat straw (summer season) and zero tillage wheat after partial burning of paddy straw (winter season). P0: 0 kg P_2O_5 ha⁻¹; P1: 30 kg P_2O_5 ha⁻¹; P2: 60 kg P_2O_5 ha⁻¹. Different letters indicate significant differences between treatments at Duncan´s test at 5% significance.

Soil bulk density
Prolonged application of crop residue in intensive rice–wheat cropping systems had a significant effect on bulk density. Under both zero and conventional tillage, residue retention/incorporation for 11 years caused a significant reduction in bulk density compared to residue removal. At 0–15 cm soil depth, bulk density recorded in zero tillage treatments was lower than in tilled treatments. The lowest bulk density (1.34 g cm⁻³) was found in the T_5 treatment, where zero tillage was followed along with the retention of residue, and the highest bulk density (1.42 g cm⁻³) was found in T_2, where no crop residue was retained where conventional tillage was followed (Table 3).

Infiltration rate (IR)
The steady-state IR recorded at wheat harvest was significantly affected by different crop residue management practices (Table 3). It was consistently higher with an average of 2.2 cm hr⁻¹ in zero tillage wheat with residue retention treatments (T_5) compared with an average value of 1.4 cm hr⁻¹ in T_2 (conventional tillage treatment without residue). This might be due to less soil compaction and more porosity created by the retention of residue on the surface and the burrowing activity of some species. The improved infiltration rate in the Zero tillage + residue retention treatment might have improved the earthworm (surface-feeder group) activity.

Soil biological properties
Microbial count
Microbial activity is the driving force behind the decomposition processes in the soil. The total viable count indicates the overall viable microbial count in the soil. The highest total viable count (59.6 × 10⁶ CFU g⁻¹ of dry soil) was obtained in treatment having both wheat and rice residue retained, followed by Zero tillage + residue retention treatment (49.7 × 10⁶ CFU g⁻¹ of dry soil) and conventional till wheat with rice residue incorporation (49.5 × 10⁶ CFU g⁻¹ of dry soil). The zero tillage (37.9 × 10⁶ CFU g⁻¹ of dry soil) and conventional tillage (33.2 × 10⁶ CFU g⁻¹ of dry soil) without residues showed comparatively lower total viable count. A significantly lower total viable count (36.7 × 10⁶ CFU g⁻¹ of dry soil) was observed in the treatment involving the burning of the residues (Table 4).

The highest fungal activity (53.2 × 10³ CFU g⁻¹ of dry soil) was obtained in treatment having both wheat and rice residue retained, followed by Zero tillage + residue retention treatment (44.8 × 10³ CFU g⁻¹ of dry soil) and conventional till wheat with rice residue incorporation (36.7 × 10³ CFU g⁻¹ of dry soil). The zero tillage (25.9 × 10³ CFU g⁻¹ of dry soil) and conventional tillage (23.3 × 10³ CFU g⁻¹ of dry soil) without residues showed comparatively lower fungal count. The lowest fungal count (19.8 × 10³ CFU g⁻¹ of dry soil) was observed in the residue-burning treatment. The decline in fungal count could be attributed to the burning practice.

Actinobacteria play a very important role in the degradation of crop residues. The highest actinobacterial activity (64.0 × 10⁵ CFU g⁻¹ of dry soil) was obtained in treatment having both wheat and rice residue retained, which was statistically significant as compared to the actinobacterial count in burning practice (32.3 × 10⁵ CFU g⁻¹ of dry soil). Comparatively higher actinobacterial count (55.0 and 44.2 × 10⁵ CFU g⁻¹ of dry soil) was observed in treatments receiving crop residues (T_4 and T_3) however, less actinobacterial count (33.9 and 33.7 × 10⁵ CFU g⁻¹ of dry soil) was found in treatments without residue retention (T_2 and T_1).

Treatments	Microbial activity (0–15 cm)					
	Microbial count (CFU g^{-1} of dry soil)			Enzyme activity		
	Fungi ($\times 10^3$)	Actinobacteria ($\times 10^5$)	Total aerobic bacteria ($\times 10^6$)	Dehydrogenase (µg TPF g^{-1} soil day^{-1})	Alkaline phosphatase (µg pnp released g^{-1}soil h^{-1})	Urease (µg urea g^{-1} dry soil min^{-1})
CRM practices						
T$_1$	25.9^c	33.7^d	37.9^c	4.29^b	25.2^c	3.63
T$_2$	23.3^c	33.9^d	33.2^c	4.27^b	25.5^c	3.59
T$_3$	36.7^b	44.2^c	49.5^b	5.11^b	31.2^b	4.43
T$_4$	44.8^b	55.0^b	49.7^b	6.34^a	33.0^b	4.61
T$_5$	53.2^a	64.0^a	59.6^a	6.70^a	38.5^a	4.88
T$_6$	19.8^c	32.3^d	36.7^c	4.67^b	25.9^c	3.62
LSD ($p \leq 0.05$)	7.9	6.2	7.8	0.90	3.2	NS
Phosphorus levels						
P$_0$	33.5	43.8	42.2	4.69^c	24.5^b	4.01
P$_1$	32.7	43.6	45.0	5.10^b	32.1^a	4.27
P$_2$	35.5	44.1	46.0	5.89^a	33.1^a	4.09
LSD ($p \leq 0.05$)	NS	NS	NS	0.60	2.3	NS
Interaction	NS	NS	NS	NS	NS	NS

Table 4. Effect of crop residue management practices and phosphorus levels on soil biological properties in the rice–wheat system (pooled data of 2 years). T1: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (After removing paddy straw) (winter season); T2: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (After removing paddy straw); T3: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (With paddy straw); T4: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T5: Transplanted rice (With wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T6: Transplanted rice after burning wheat straw (summer season) and zero tillage wheat after partial burning of paddy straw (winter season). P0: 0 kg P$_2$O$_5$ ha^{-1}; P1: 30 kg P$_2$O$_5$ ha^{-1}; P2: 60 kg P$_2$O$_5$ ha^{-1}. *FUN* fungi, *ACT* actinobacteria, *TAB* total aerobic bacteria, *DHA* dehydrogenase, *PHOS* phosphatase and *URE* urease. Different letters indicate significative differences between treatments at Duncan´s test at 5% significance.

Microbial enzyme activities
Enzyme activity in soil is an indirect measure of different microbial processes going on in the soil. The highest dehydrogenase activity (6.7 µg TPF g^{-1} soil day^{-1}) was observed in zero till crop residue retention treatment (rice and wheat residue retention), followed by 6.34 µg TPF g^{-1} soil day^{-1} in zero till rice residue retention. Similarly, the highest phosphatase activity (38.5 µg p-nitrophenol released g^{-1} soil h^{-1}) was observed in zero till crop residue retention treatment (rice and wheat residue retention), followed by 33.0 µg p-nitrophenol released g^{-1} soil h^{-1} in zero till rice residue retention. Urease activity was highest for rice and wheat residue retention using zero till (4.88 µg urea/g dry soil/min) followed by zero (4.61 µg urea g^{-1} dry soil min^{-1}) and conventional till with rice residue retention (Table 4).

Yield attributes and yield of wheat

The crop residue management practices and graded phosphorus doses significantly affected the yield attributes and yield in wheat. The effective tillers of wheat under residue of rice alone or both rice and wheat were not significantly affected by phosphorus levels. However, the highest effective tillers had the highest phosphorus level (P$_2$). However, maximum effective tillers under treatment (T$_1$ and T$_2$) where wheat was sown without crop residue were obtained with P$_2$ (60 kg P$_2$O$_5$ ha^{-1}), significantly higher than P$_0$ and P$_1$. Maximum spike length (11.6 cm) was recorded in the T$_5$ treatment, which was at par with T$_3$ and T$_4$ but significantly higher than all other treatments. The improvement in spike length where both residues were retained was 11.5% compared to without residue treatment. The test weight (1000-grain weight) was not significantly differed among various treatments, but numerically higher test weight was reported where residue was retained or incorporated (Table 5).

Spike length and grains per spike were significantly affected by various phosphorus levels. The highest was registered with the highest phosphorus level (60 kg P$_2$O$_5$ ha^{-1}), significantly higher than the control treatment (0 kg P$_2$O$_5$).

Maximum grain yield (6.19 t ha^{-1}) was registered in T$_5,$ where wheat was sown with a happy seeder and residue of both wheat and rice crops was retained significantly higher than residue removal or burning treatments (Table 6). The improvement in grain yield in T$_5$ was 8.6 and 7.6% over T$_1$ and T$_2$ (without residue) while 5.7% over T$_6$ (partial burning). The interaction effect of crop residue management practices and phosphorus levels on grain yield was significant (Table 6). In T$_5$, where the residue of both the crops was retained, gave similar yields at 0, 30 and 60 kg P$_2$O$_5$ ha^{-1}. In the treatments where the residue of a single crop was retained/ incorporated (T$_3$ and T$_4$), grain yield obtained with P$_1$ and P$_2$ was statistically at par but significantly higher than P$_0$. However, without residue treatments (T$_1$ and T$_2$), the highest grain yield was obtained when 60 kg P$_2$O$_5$ ha^{-1} was applied,

Treatments	Effective tillers (No. m^{-2})	Spike length (cm)	Grains spike^{-1} (No.)	1000-grain weight (g)	Straw yield (t ha^{-1})	Biological yield (t ha^{-1})
CRM practices						
T$_1$	286.4^{c}*	10.2^{b}	43.6^{c}	39.6	7.02^{c}	12.23^{c}
T$_2$	290.3^{c}	10.4^{b}	43.7^{c}	39.4	7.18^{c}	12.49^{c}
T$_3$	309.9^{b}	11.2^{a}	49.2^{ab}	40.0	7.67^{b}	13.51^{b}
T$_4$	307.3^{b}	11.2^{a}	48.5^{b}	40.3	7.56^{b}	13.45^{b}
T$_5$	333.0^{a}	11.6^{a}	50.9^{a}	40.6	7.93^{a}	141.2^{a}
T$_6$	295.3^{c}	10.4^{b}	45.2^{c}	39.4	7.27^{c}	12.7.9^{c}
LSD (p ≤ 0.05)	11.3	0.5	2.6	NS	0.38	0.58
Phosphorus levels						
P$_0$	287.4^{c}	10.5^{b}	44.8^{c}	39.7	7.11^{c}	12.38^{c}
P$_1$	306.3^{b}	10.9^{a}	47.2^{b}	39.9	7.45^{b}	13.18^{b}
P$_2$	317.5^{a}	11.1^{a}	48.6^{a}	40.0	7.75^{a}	13.72^{a}
LSD (p ≤ 0.05)	6.3	0.2	1.1	NS	0.24	0.26
CRM x P	NS	NS	NS	NS	NS	NS

Table 5. Effect of crop residue management practices and phosphorus levels on yield attributes and yield of wheat in the rice–wheat system (pooled data of 2 years). T1: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (After removing paddy straw) (winter season); T2: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (After removing paddy straw); T3: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (With paddy straw); T4: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T5: Transplanted rice (With wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T6: Transplanted rice after burning wheat straw (summer season) and zero tillage wheat after partial burning of paddy straw (winter season). P0: 0 kg P_2O_5 ha^{-1}; P1: 30 kg P_2O_5 ha^{-1}; P2: 60 kg P_2O_5 ha^{-1}. *Different letters indicate significant differences between treatments at Duncan´s test at 5% significance. Means followed by the same letter or without letter in each column are not significantly different at P = 0.05.

Treatments	Grain yield (t ha^{-1})		
	Phosphorus levels (kg ha^{-1})		
CRM practices	P$_0$	P$_1$	P$_2$
T$_1$	4.62f.	5.25de	5.77bc
T$_2$	4.76f.	5.34d	5.84b
T$_3$	5.56c	5.95b	6.03ab
T$_4$	5.60c	6.01b	6.08ab
T$_5$	6.10ab	6.22ab	6.26a
T$_6$	5.04e	5.65c	5.87b
LSD (p ≤ 0.05) (CRM x P)	0.24		

Table 6. Interactive effect of crop residue management practices and phosphorus levels on grain yield of wheat (pooled data of 2 years). T1: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (After removing paddy straw) (winter season); T2: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (After removing paddy straw); T3: Transplanted rice (After removing wheat straw) (summer season) and conventional tillage sowing of wheat (With paddy straw); T4: Transplanted rice (After removing wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T5: Transplanted rice (With wheat straw) (summer season) and zero tillage sowing of wheat (With paddy straw) (winter season); T6: Transplanted rice after burning wheat straw (summer season) and zero tillage wheat after partial burning of paddy straw (winter season). P0: 0 kg P_2O_5 ha^{-1}; P1: 30 kg P_2O_5 ha^{-1}; P2: 60 kg P_2O_5 ha^{-1}. Different letters indicate significant differences between treatments as per the mean separation performed through Duncan´s test at 5% significance.

significantly higher than 30 kg P_2O_5 ha^{-1} and control (No P_2O_5) treatment. Maximum straw and biological yield were obtained in the T$_5$ treatment, which was significantly higher than other crop residue management treatments. The straw yield was 12.9 and 9.1% higher, where the residue of both rice and wheat crop was retained as compared to conventional tillage sown wheat with residue removal (T$_2$) and residue burning treatment (T$_6$). Phosphorus doses also significantly influenced the straw and biological yield. The highest straw yield (7.27 t ha^{-1})

was registered when 60 kg P_2O_5 ha^{-1} was applied, significantly higher than P_1 and P_0 treatments. The biological yield was 10.8 and 4.1% higher, with a higher dose of phosphorus (P_2) over the P_0 and P_1 levels.

Discussion

Soil health

Conservation tillage with residue retention has significantly improved the physicochemical, microbial counts and soil enzyme properties of soil. Conservation tillage increases soil aggregation by decreasing soil disturbance and also by increasing soil organic matter and possibly the growth of microflora, especially fungi, which help to bind soil particles and micro-aggregates together[21]. Significant improvement in mean weight diameter was recorded with residue retention under conservation tillage compared to conventional tillage without residue or residue burnt treatments. Singh et al.[22] also documented significant improvement in the mean weight diameter of aggregates and aggregate stability in sandy loam soil under rice–wheat cropping system with residue addition due to an increase in soil organic carbon since soil organic matter plays an important role in soil aggregation. Lower aggregation in conventional tillage might be due to heavy machinery and intensive tillage (twice disc, twice cultivators and one planking operation). Lower bulk density was observed in residue retained treatments, i.e. T_5 (1.34 g cm^{-3}) and T_4 (1.36 g cm^{-3}), and the highest was found in conventional tillage with residue removal T_2 (1.42 g cm^{-3}) at 0–15 cm soil depth (Table 1). The lower bulk density in zero-tilled treatments with residue retention might be associated with greater soil biological activities, especially earthworms[23] Also, the studies of Singh et al.[24], Alam et al.[25], Meena et al.[26] identify the similar results. Several studies have documented higher bulk density under ZT at the surface layer than in tilled soil[27–29]. However, the results of this field study do not comply with earlier reports regarding the lowering of bulk density in ZT + residue retention treatments as compared to the conventional tillage (CT) in the upper soil surface, especially in fine-textured soils, which is ascribed to the development of organic-rich mulch and therefore, a possibly enhanced microbial activity especially earthworms[23] and higher bulk density or no difference in bulk density in conventional tillage (CT) in the deeper soil layers[30]. The crop residues over the upper soil surface prevent aggregate breakdown by direct raindrop effect and rapid drying and wetting of soils. Various studies show little or no differences in bulk density between conventional tillage (CT) and zero tillage (ZT) in surface soil layers[31].

Conservation tillage + residue retention improved the infiltration rate over residue removal treatment[32]. The improved aggregate stability and moisture retention could explain the enhanced infiltration rates. Furthermore, the occurrence and sustenance of macrofauna components, particularly the earthworms, through burrowing activities can also be identified as the other possible aspect[33]. Significant improvement in the SOC in the upper soil layer (0–15 cm) in the crop residue management practices was recorded as compared to no residue or residue removal treatments (Fig. 1d). Gupta et al.[34], Mondal et al.[35], Fang et al.[36], Zhang et al.[37], Zhang et al.[38], Chen et al.[39], Liu et al.[40] and many other researchers reported significant improvement in soil organic carbon under zero tillage with residue retention as compared to conventional practice. Tillage and crop residue management practices improved soil structure associated with the protection of SOM and biological activities[41], ultimately improving soil aggregation, soil organic matter and nutrient cycling in the rice–wheat system. The increase in the availability of soil nutrients under conservation tillage with residue retention treatments might be due to improved soil health and SOC. Gupta et al.[34], Bhattachariya et al.[42], Zhang et al.[38] and Zhao et al.[43] also reported an increase in nutrient availability with residue incorporation/retention as compared to residue removal.

Soil microorganism is important in increasing soil quality, health, fertility and soil microbial community. Among all parameters, microbial activity is considered a sensitive indicator for evaluating soil quality. Adding crop residues stimulated the microbial activity of bacteria, fungi and actinomycetes[44]. The findings of these workers corroborate our findings where higher total viable count, fungal count and actinobacterial count were found in treatments receiving crop residues. In an experiment conducted by Pintari et al.[45], significantly higher soil respiration was observed when straw was incorporated into the top 10 cm compared to the control with no straw added. Higher total phospholipid-derived fatty acids (PLFAs), fungal PLFAs content and increased value of fungi/G$^+$ bacteria + G$^-$ bacteria under combined application of tillage with crop residue incorporation were observed by Tang et al.[46]. Likewise, another study identified the beneficial impact of residue returning on the soil microbial diversity[47].

Both microbial counts and enzyme activities were found to be lowest in treatment following a burning practice. This could be due to a reduction in microbial biomass, microbial activity, respiration, and decomposition process and sometimes also alters the composition of the microbial community. Kumar et al.[48], also reported a comparatively lower bacterial, fungal and actinobacterial count in treatments where paddy straw was burnt. The highest count was observed in the paddy straw retained plots.

The microbial decomposition process is a key component of nutrient geochemical cycles. The microbial diversity and physiological versatility are improved by incorporating or retaining the agri-residue in fields. The agri-residue comprised of complex carbohydrates, proteins and other useful minerals can be acted upon the soil microflora as an energy and nutrient source, favouring improved microbial growth and multiplication rates. Several microbial lytic enzymes released extracellularly by various genera can be measured and compared with no residue amendment treatments. In the present study higher enzyme activities were recorded in the plots amended with residues. Higher enzymatic activity of dehydrogenase and acid and alkaline phosphatase in residue-retained plots than those without residues have also been reported by Choudhary et al.[44] and Gupta et al.[21].

Yield attributes and yield of wheat

Significantly higher wheat grain yield under conservation tillage with residue retention could be due to more favourable conditions created by conservation agricultural practices, i.e. improvement in water conservation, lower bulk density, better soil aggregation and better nutrient recycling due to elevation in soil organic carbon

in T_5 and T_4 treatments where wheat was sown in standing stubbles of rice with both rice and wheat residue and single rice residue, respectively. Higher grain yield under residue retention/incorporation treatments might be due to increased growth parameters. Yield attributes (effective tillers, spike length, grains per spike, 1000-grain weight) resulted from the increase in soil organic matter content and availability of nutrients and moderation of the hydrothermal regime of the soil[49–51]. Straw incorporation/retention improves the soil properties (physical, chemical and biological), resulting in better root growth and more uptake of nutrients by the plants, ultimately leading to better plant growth and an increase in grain yield. Similar results were also documented by Gupta et al.[49], Chaudhary and Iqbal[52], Meena et al.[26] and Sharma et al.[53].

Conclusions

Phosphorus fertilizer dosages for wheat crop are required to be optimized for the crop residue management approaches. The residue retention/incorporation significantly influenced the soil's physical, chemical, and biological properties besides decreasing the phosphorus fertilizer requirements of the crop. The residue management practice exhibited a significant effect on the viable cell counts of all the test microbes and the urease enzyme activity except dehydrogenase and phosphatase activities. Furthermore, this study revealed that the phosphorus levels had a significant effect on grain yield traits of wheat and the P-levels exhibited significant interactions with the different crop residue management practices. The grain yield of wheat was equivalent to the recommended dose of the P-fertilizer (i.e. 60 kg P_2O_5 ha^{-1}) on retention/incorporation of rice residue alone with application of the half of the recommended dose of P-fertilizer (30 kg P_2O_5 ha^{-1}). While, incorporation/retention of both rice and wheat residues resulted no need for application of P-fertilizer. Therefore, the crop residue incorporation/retention can help facilitate the adequate P-content for the crop growth and productivity at relatively lower P_2O_5 fertilizer doses.

Data availability

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

References

1. Nawaz, A., Farooq, M., Nadeem, F., Siddique, K. H. M. & Lal, R. Rice- wheat cropping systems in South Asia: Issues, options and opportunities. *Crop Pasture Sci.* **70**, 395–427 (2019).
2. Padre, A. T. *et al.* Quantifying changes to the global warming potential of rice-wheat systems with the adoption of conservation agriculture in northwestern India. *Agric. Ecosyst. Environ.* **219**, 56–67 (2016).
3. Singh, Y. & Sidhu, H. S. Management of cereal crop residues for the sustainable rice-wheat production system in the Indo-Gangetic plains of India. *Proc. Indian Nat. Sci. Acad.* **80**, 95–114 (2014).
4. Abdurrahman, M. I., Chaki, S. & Saini, G. Stubble burning: Effects on health & environment, regulations and management practices. *Environ. Adv.* **2**, 100011. https://doi.org/10.1016/j.envadv.2020.100011 (2020).
5. Barros-Rodríguez, A., Rangseekaew, P., Lasudee, K., Pathom-aree, W. & Manzanera, M. Impacts of agriculture on the environment and soil microbial biodiversity. *Plants* **10**, 2325. https://doi.org/10.3390/plants10112325 (2021).
6. Bhuvaneshwari, S., Hettiarachchi, H. & Meegoda, J. Crop residue burning in India: Policy challenges and potential solutions. *Int. J. Environ. Res. Public Health* **16**, 832. https://doi.org/10.3390/ijerph16050832 (2019).
7. Venkatramanan, V., Shah, S., Rai, A. K. & Prasad, R. Nexus between crop residue burning, bioeconomy and sustainable development goals over North-Western India. *Front. Energy Res.* https://doi.org/10.3389/fenrg.2020.614212 (2021).
8. Dutta, A. *et al.* A state of the art review in crop residue burning in India: Previous knowledge, present circumstances and future strategies. *Environ. Chall.* **8**, 100581. https://doi.org/10.1016/j.envc.2022.100581 (2022).
9. Azeem, M. *et al.* Microbial phytase activity and their role in organic P mineralization. *Arch. Agron. Soil Sci.* **61**, 751–766. https://doi.org/10.1080/03650340.2014.963796 (2015).
10. Liu, X., Han, R., Cao, Y., Turner, B. L. & Ma, L. Q. Enhancing phytate availability in soils and phytate-P acquisition by plants: A review. *Environ. Sci. Technol.* **56**, 9196–9219. https://doi.org/10.1021/acs.est.2c00099 (2022).
11. Jackson, M. L. *Soil Chemical Analysis* 234–46 (Prentice Hall of India, Private Limited, 1967).
12. Walkley, A. & Black, C. A. An examination of the degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* **37**, 27–38 (1934).
13. Subbiah, B. V. & Asija, G. L. A rapid procedure for the estimation of available nitrogen in soils. *Curr. Sci.* **25**, 259–260 (1956).
14. Olsen, S. R., Cole, C. V., Watanabe, F. S. & Dean, L. A. Estimation of available phosphorus in soil by extraction with sodium bicarbonate. *USDA Circ.* **939**, 1–19 (1954).
15. Blake, G. R. Bulk density. In *Methods of Soil Analysis Part I. Physical and Mineralogical properties* (eds Black, C. A. *et al.*) (American Society of Agronomy Inc, 1965).
16. Black, C. A. *Soil Plant Relationship* (Wiley, 1965).
17. Kemper, W. D. & Rosenau, R. C. Aggregate stability and size distribution. In *Methods of Soil Analysis. Part I. Agronomy Monograph* Vol. 9 (ed. Klute, A.) 425–442 (Soil Science Society of America, American Society of Agronomy, 1986).
18. Casida, L. E., Klein, D. A. K. & Santoro, T. Soil dehydrogenase activity. *Soil Sci.* **98**, 371–376 (1964).
19. Tabatabai, M. A. & Bremner, J. M. Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. *Soil Biol. Biochem.* **1**, 301–307 (1969).
20. Bremner, J. M. & Douglas, L. A. Inhibition of urease activity in soils. *Soil Biol. Biochem.* **3**, 297–307 (1971).
21. Gupta, R. K. *et al.* Long-term impact of different straw management practices on carbon fractions and biological properties under rice-wheat system. *Agriculture* **12**, 1733. https://doi.org/10.3390/agriculture12101733 (2022).
22. Singh, G., Jalota, S. K. & Sidhu, B. S. Soil physical and hydraulic properties in a rice-wheat cropping system in India: Effects of rice-straw management. *Soil Use Manag.* **21**, 17–21 (2005).
23. Kahlon, M. S. & Khurana, K. Effect of land management practices on physical properties of soil and water productivity in wheat-maize system of northwest India. *Appl. Ecol. Environ. Res.* **15**, 1–13 (2017).
24. Singh, A., Kang, J. S. & Kaur, M. Planting of wheat with happy seeder and rotavator in rice stubbles. *Indo Am. J. Agric. Vet. Sci.* **1**, 32–41 (2013).

25. Alam, M. K., Islam, M. M., Salahin, N. & Hasanuzzaman, M. Effect of tillage practices on soil properties and crop productivity in wheat-mungbean-rice cropping system under subtropical climatic conditions. *Sci. World J.* https://doi.org/10.1155/2014/437283 (2014).

26. Meena, J. R., Behera, U. K., Chakraborty, D. & Sharma, A. R. Tillage and residue management effect on soil properties, crop performance and energy relations in green gram (*Vigna radiata* L.) under maize-based cropping systems. *Int. Soil Water Conserv. Res.* **3**, 261–72 (2015).

27. Jat, M. L. *et al.* 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 (2013).

28. Salinas-García, J. R., Hons, F. M. & Matocha, J. E. Long-term effects of tillage and fertilization on soil organic matter dynamics. *Soil Sci. Soc. Am. J.* **61**, 152–159 (1997).

29. Gathala, M. K. *et al.* Effect of tillage and crop establishment methods on physical properties of a medium textured soil under a seven-year rice–wheat rotation. *Soil Sci. Soc. Am. J.* **75**, 1851–1862 (2011).

30. Jabro, J. D., Stevens, W. B., Iversen, W. M., Sainju, U. M. & Allen, B. L. Soil cone index and bulk density of a sandy loam under no-till and conventional tillage in a corn-soybean rotation. *Soil Tillage Res.* **206**, 104842. https://doi.org/10.1016/j.still.2020.104842 (2016).

31. Huang, M. *et al.* Effect of tillage on soil and crop properties of wet-seeded flooded rice. *Field Crops Res.* **129**, 28–38 (2012).

32. Blanchy, G. *et al.* Soil and crop management practices and the water regulation functions of soils: A qualitative synthesis of meta-analyses relevant to European agriculture. *Soil* **9**, 1–20. https://doi.org/10.5194/soil-9-1-2023 (2023).

33. Cárceles Rodríguez, B. *et al.* Conservation agriculture as a sustainable system for soil health: A review. *Soil Syst.* **6**, 87. https://doi.org/10.3390/soilsystems6040087 (2022).

34. Gupta, R. K. *et al.* Tillage in combination with rice straw retention in rice-wheat system improves the productivity and quality of wheat grain through improving the soil physio-chemical properties. *Land* **11**, 1693. https://doi.org/10.3390/land.111101693 (2022).

35. Mondal, S. *et al.* Can yield, soil C and aggregation be improved under long-term conservation agriculture in the eastern Indo-Gangetic plain of India?. *Eur. J. Soil Sci.* **72**, 1742–1761 (2021).

36. Fang, H., Yi, L. I., Zhou, H., Yan, X. Y. & Peng, X. H. Effects of straw incorporation on paddy soil structure in rice-wheat rotation system. *Trans. Chin. Soc. Agric.* **49**, 297–302 (2018).

37. Zhang, Y. *et al.* Crop yield and soil properties of dryland winter wheat-spring maize rotation in response to 10-year fertilization and conservation tillage practices on the Loess Plateau. *Field Crops Res.* **225**, 170–179 (2018).

38. Zhang, J. *et al.* Long-term straw incorporation increases rice yield stability under high fertilization level conditions in the rice-wheat system. *Crop J.* https://doi.org/10.1016/j.cj.2020.11.007 (2021).

39. Chen, A. *et al.* Long-term partial replacement of mineral fertilizer with in situ crop residues ensures continued rice yields and soil fertility: A case study of a 27-year field experiment in subtropical China. *Sci. Total Environ.* **787**, 147523 (2021).

40. Liu, C., Lu, M., Cui, J., Li, B. & Fang, C. Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. *Glob. Change Biol.* **20**, 1366–1381 (2014).

41. Saikia, R., Sharma, S., Thind, H. S. & Singh, Y. Tillage and residue management practices affect soil biological indicators in a rice–wheat cropping system in north-western India. *Soil Use Manag.* **36**, 157–172 (2019).

42. Bhattachariya, S. *et al.* In situ decomposition of crop residues using lignocellulolytic microbial consortia: A viable alternative to residue burning. *Environ. Sci. Pollut. Res.* **28**, 32416–32433 (2021).

43. Zhao, X., Yuan, G. & Wang, H. Effects of full straw incorporation on soil fertility and crop yield in rice-wheat rotation for silty clay loamy cropland. *Agronomy* **9**, 133. https://doi.org/10.3390/agronomy9030133 (2019).

44. Choudhary, M. *et al.* Changes in soil biology under conservation agriculture-based sustainable intensification of cereal systems in Indo-Gangetic Plains. *Geoderma* **313**, 193–204 (2018).

45. Pintari, C. S., Suhadolc, M. & Eler, K. Straw management and slurry application affect the soil microbial community composition and its activity. *Agronomy* **12**, 2781 (2022).

46. Tang, H. *et al.* Impacts of short-term tillage and crop residue incorporation managements on soil microbial community in a double-cropping rice field. *Sci. Rep.* **12**(1), 2093 (2022).

47. Wang, E. *et al.* Effects of short-term rice straw return on the soil microbial community. *Agriculture* **11**, 561 (2021).

48. Kumar, A. *et al.* Effect of paddy straw burning on soil microbial dynamics in sandy loam soil of Indo-Gangetic plains. *Environ. Technol. Innov.* **16**, 100469 (2019).

49. Gupta, N. *et al.* Effects of tillage and mulch on the growth, yield and irrigation water productivity of a dry seeded rice-wheat cropping system in north-west India. *Field Crops Res.* **196**, 219–236 (2016).

50. Iqbal, M. F. *et al.* Happy seeder zero tillage equipment for sowing of wheat in standing rice stubbles. *Int. J. Adv. Res. Biol. Sci.* **4**, 101–105 (2017).

51. Ram, H., Kler, D. S. Y. & Kumar, K. Productivity of maize (*Zea mays*)-wheat (*Triticum aestivum*) system under different tillage and crop establishment practices. *Indian J. Agron.* **55**, 185–190 (2010).

52. Chaudhary, S. & Iqbal, J. Weed control and nutrient promotion in zero-tillage wheat through rice straw mulch. *Pak. J. Weed Sci. Res.* **19**, 465–474 (2013).

53. Sharma, S., Thind, H. S., Yadvinder-Singh, S. H. S., Jat, M. L. & Parihar, C. M. Effects of crop residue retention on soil carbon pools after 6 years of rice-wheat cropping system. *Environ. Earth Sci.* **78**, 296 (2019).

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Author contributions

Conceptualization, supervision, methodology, formal analysis, writing—original draft preparation, writing—review and editing, R.K.G., V.S., N.P., A.K., N.A.-A.; data curation, project administration, investigation, P.K.S., J.S.K., J.K., N.A.-A., A.A., A.Z.D., M.A.M. All authors have read and agreed to the published version of the manuscript.

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The authors declare no competing interests.

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