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Trade-offs and synergies of conservation agriculture: Soil properties and crop performance after five years of minimum tillage and residue retention

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Abstract

Conservation agriculture (CA) practices have shown promise in various cropping systems globally, yet their effects on soil properties and yields in paddy-dominated intensive systems remain understudied. A five-year field experiment was conducted in the High Ganges River Floodplain (AEZ-11) of Rajshahi Division, western Bangladesh (approximately 24.4°N, 88.6°E) to evaluate crop establishment and residue management effects on soil properties and crop yields in a wheat–mungbean–rice rotation. The experiment followed a split-plot design with four replications. Main plots comprised two establishment methods: conventional tillage for upland crops and conventional wet tillage with puddling for rice (CT) versus minimum tillage using strip planting for upland crops with non-puddled rice transplanting (MT). Subplots compared residue retention (R+; 30 cm stubble height for wheat and rice plus full mungbean stover retention) against complete residue removal (R−).

Wheat grain yields were significantly higher under MT with R+ (3.91–4.45 t ha^{-1}) compared to CT with R− across all five years, with yield advantages increasing over time. These yield gains coincide with improved soil moisture availability during critical growth stages and enhanced nutrient supply. Rice yields showed no significant difference between establishment methods ($p > 0.05$). After five years, MT with R+ significantly improved soil biological, physical and chemical properties compared to CT with R−: soil organic carbon increased from 0.67% to 0.92%, total nitrogen from 0.042% to 0.09%, and exchangeable potassium increased approximately threefold. Microbial populations were highest under MT with R+, including fungal spores (99 ± 8.8 per 100 g soil), Rhizobium (3.2 × 104 CFU g-1), phosphate-solubilising bacteria (3.8 × 105 CFU g-1), and Azotobacter (5.0 × 105 CFU g-1). These findings suggest that combining minimum tillage with residue retention progressively improves soil fertility, which may explain the increasing yield advantages observed in later cropping years.

1. Introduction

Ensuring agricultural productivity while preserving soil health is a critical global priority, particularly in intensively cultivated regions facing pressure from population growth and resource degradation. Conventional tillage (CT) and residue burning, still prevalent in many farming systems, disrupt soil structure, deplete organic matter and increase erosion risk (Orr et al. 2015). In South Asian rice-based systems, puddling, a wet tillage operation used to prepare fields for rice transplanting under flooded condition, compounds these problems. Although puddling reduces water percolation and suppresses weeds during rice cultivation (Arora et al. 2006), it causes subsoil compaction and plough pan formation that impair the establishment and yield of subsequent upland crops such as wheat and mungbean (Gathala et al. 2011). Besides, the soil benefits accrued by the conservation cropping get destroyed by puddling soils for rice transplantation (Alam et al. 2018). However, the adoption of conservation agriculture (CA) often involves agronomic trade-offs, particularly in rice-based systems, where gains in soil health and upland crop performance may coincide with constraints in rice establishment, weed pressure or short-term productivity.

Conservation Agriculture, defined by minimal soil disturbance, permanent soil cover through residue retention and diversified crop rotations, offers a pathway to reverse such degradation. CA practices improve soil physical, chemical and biological properties (Hobbs et al. 2008; Salahin et al. 2021), enhance crop yields (Swanepoel et al. 2018) and reduce production costs (Bell et al. 2019). However, integrating CA into rice-dominated systems is inherently challenging because traditional puddled rice establishment conflicts fundamentally with CA principles of minimal disturbance. Recent innovations in non-puddled transplanting and strip planting for upland crops now enable rice cultivation compatible with CA frameworks (Salahin et al. 2021; Alam et al. 2020; Bell et al. 2019), though long-term cropping system-level evidence remains limited.

Residue management is pivotal to CA's effectiveness. Retaining crop residues builds soil organic matter (SOM), improves aggregation and water retention, while supports microbial communities essential for nutrient cycling (Blanco-Canqui and Lal 2009). In rice–wheat systems, residue retention also maintains potassium (K) balance, since up to 80% of plant K uptake remains in straw; without residue return, soil K can decline by over 20% within a decade (Singh et al. 2018; Darilek et al. 2009). Studies from South Asia confirm that minimum tillage with residue retention increases SOM and sustains yields over multiple seasons (Alam et al. 2016; Chaki et al. 2021). However, the optimum retention level is context-dependent, varying with soil type, climate and management duration (Blanco-Canqui et al. 2014).

Despite growing evidence for CA benefits, critical knowledge gaps persist for intensive rice-based rotations in South Asia. Most studies have examined short-term or single-crop responses; few have evaluated multi-year, system-level outcomes combining strip-planted upland crops with puddled/non-puddled rice and varying residue management (Alam et al. 2020; Bell et al. 2019). In the Gangetic Plains, where rice dominates cropping systems and puddling remains standard practice, such integrated assessments are particularly needed to inform practical adoption strategies.

Thus, understanding how CA simultaneously generates synergies (improved soil fertility, microbial activity and upland crop yields) and trade-offs (weed pressure and rice yield constraints) at the system level is critical for its sustainable adoption in rice-dominated rotations. This study addresses these gaps through a five-year field experiment conducted in the High Ganges River Floodplain (Agro-Ecological Zone 11) of western Bangladesh, a region characterised by calcareous alluvial soils and intensive rice–wheat–mungbean rotations. The wheat–mungbean–rice sequence is regionally important: wheat provides winter grain production, mungbean contributes biological nitrogen (N) fixation and short-season income and monsoon rice remains the dietary staple. We hypothesised that combining minimum tillage (strip planting for upland crops and non-puddled rice transplanting in strip) with partial residue retention would progressively improve soil fertility and crop yields compared to conventional puddled systems with residue removal under rice dominant rotation.

The specific objectives were to:

- Quantify the effects of tillage method (conventional puddled vs. minimum tillage non-puddled) and residue management (retention vs. removal) on soil physical, chemical and biological properties over five years.
- Compare crop yields and identify yield trajectories under different tillage–residue combinations across the rotation.
- Evaluate overall system productivity and assess the agronomic sustainability of CA-compatible practices in this rice-dominated cropping system.

2. Materials and Methods

2.1 Crops used in the study

The experiment included wheat (*Triticum aestivum* L., cv. BARI Gom-33), mungbean (*Vigna radiata* L. Wilczek, cv. BARI Mung-6), and transplanted rice (*Oryza sativa* L., cv. BRRI dhan57, T. aman ecotype).

2.2 Description of experimental site

The experiment was conducted at the Regional Agricultural Research Station (RARS) in Jashore (approx. 24.4° N, 89.1896° E), carried out from the Rabi season of 2018–2019 to the Kharif-II season of 2022–2023. The field experiment represents the western Gangetic floodplain agro-ecosystem. The study site was situated in the agro-ecological zone 11 known as “High Ganges River Floodplain”. Initial assessments of soil properties and microbial populations were conducted in the experimental field. Data regarding soil texture, bulk density, pH, SOM, total N, exchangeable K, available phosphorus (P), sulphur (S), zinc (Zn) and boron (B) content in the top 0–15 cm of soil are provided in Tables 1, 2 and 3.

Table 1
Particle size distribution, textural class and bulk density of initial soil of the experimental field, RARS, Jashore

Soil depth (cm)	Particle size distribution			Textural class	Bulk density
	Sand%	Silt%	Clay%		(g cm^{-3})
0–15	53.0	24.3	22.7	Sandy clay loam	1.42

Table 2
Initial soil pH, soil organic matter, total nitrogen, available phosphorus, potassium, sulphur, zinc (Zn) and boron (B) contents of the experimental field, RARS, Jashore

Soil depth	Soil pH	SOM	Total N	Available other nutrients				
(cm)		(%)		K	P	S	Zn	B
meq 100 g soil^{-1}	mg kg^{-1}							
0–15	7.6	1.27	0.065	0.18	13.0	14	0.56	0.16
Composite	Slightly alkaline	Low	Very Low	Low	Low	Low	Low	Low

Table 3
Initial soil microbial population at RARS, Jashore during 2018–2019

Treatment	Fungus spore (per 100 g soil)	Rhizobium	PSB	Azotobacter
		cfu/g soil		
CT × R^{+}	85 ± 6.5	$6.0 \cdot 10^3$	$5.3 \cdot 10^4$	$2.7 \cdot 10^5$
CT × R^{-}	77 ± 8.9	$2.5 \cdot 10^3$	$2.5 \cdot 10^4$	$4.8 \cdot 10^4$
MT × R^{+}	96 ± 6.8	$2.8 \cdot 10^4$	$2.7 \cdot 10^5$	$4.0 \cdot 10^5$
MT × R^{-}	84 ± 15.4	$5.3 \cdot 10^3$	$1.5 \cdot 10^5$	$5.2 \cdot 10^4$

2.2 Climate

The study area has a subtropical monsoon climate with a clear wet season (June–September) and

a dry season (November–March). Between 2018 and 2023, the site received about 1500 mm of rain each year, around 70% of which fell during the monsoon. The temperature regime showed clear seasonal variation. Rabi season (season stretching from mid-October to mid-March) was characterised by cooler conditions, with minimum temperatures of approximately 10–15°C and maximum temperatures of approx. 23–27°C. Kharif-I (season stretching from mid-March to mid-end of June) experienced rising temperatures, with maxima reaching around 32–36°C, while Kharif-II (early July to mid-October) remained consistently warm, with maximum temperatures of approx. 30–35°C and minimum temperatures approx. 25–27°C (Fig. 1). These seasonal differences create distinct growing conditions for rabi (wheat), kharif-I (mungbean), and kharif-II (rice) crops.

2.3 Treatments and experimental design

The experiment was conducted using a split-plot design with four replications. Each experimental plot measured 7.2 m × 5.0 m. Two crop establishment methods were assigned to the main plots: conventional tillage (CT) and minimum tillage (MT). The CT involved chiselling to a depth of approximately 200 mm, followed by three passes of a rotavator for upland crops, while rice fields were prepared through wet tillage using a high-speed rotary tiller followed by laddering and levelling (puddling). Minimum tillage was implemented through strip tillage and seeding using a power tillage operated seeder (PTOS) for upland crops and transplanting of rice seedlings into wet strips without puddling.

Each main plot was divided into two subplots representing residue management treatments. Residue retention (R^{+}) involved retaining approximately 30 cm of standing rice and wheat residue along with the full amount of mungbean biomass, while residue removal (R^{-}) involved complete removal of crop residues, following common farmer practice. This resulted in four treatment combinations: CT × R^{-}, CT × R^{+}, MT × R^{-}, and MT × R^{+}.

2.4 Land preparation, fertiliser application, sowing/transplanting and intercultural operations

2.4.1 Tillage and Crop Establishment

Under the MT treatment, a power tillage operated seeder (PTOS) was used to simultaneously till narrow strips and place seed in a single pass for upland crops. Row spacing was maintained at 20 cm for wheat and rice and 40 cm for mungbean. For rice, seedlings were transplanted into wet strips without puddling, following a single shallow rotavator pass to facilitate strip preparation.

Under CT, upland crop establishment involved chisel ploughing to approximately 20 cm depth, followed by two to three passes with a rotavator to achieve a fine seedbed. Rice fields were prepared using conventional puddling practices, consisting of three passes with a high-speed rotary tiller under flooded conditions, followed by two to three levelling operations (laddering) prior to transplanting.

2.4.2 Residue Management

In R^+ subplots, wheat and rice were harvested at 30 cm stubble height, leaving standing residues in the field. Mungbean plants were cut at ground level and the entire aboveground biomass was retained and incorporated during subsequent CT practice or left on the surface for MT practice. In R− subplots, all crop residues were removed from the field immediately after harvest.

2.4.3 Crop Management

Varieties and seeding rates: The wheat, mungbean and rice varieties used were BARI Gom-33, BARI Mung-6 and BRRI dhan57, respectively. Seeding rates were 130 kg ha^{-1} for wheat, 35 kg ha^{-1} for mungbean and 2 seedlings $hill^{-1}$ for rice.

Planting schedule: Wheat was sown in the third week of November (first sowing: 20 November 2018), mungbean in the last week of March, and transplanted Aman rice (monsoon season rice, locally termed T. Aman) in the last week of July. Rice seedlings were 20 days old at transplanting. Sowing, harvesting and turnaround dates for all seasons are presented in Fig. 2.

Fertilisers and fertiliser application: Nutrient application rates followed national recommendations (BARC 2018). Fertiliser inputs were applied following locally recommended rates for each crop in the rotation. Wheat received 131 kg N ha^{-1}, 16 kg P ha^{-1}, 60 kg K ha^{-1}, 11 kg S ha^{-1}, 2 kg Zn ha^{-1} and 1 kg B ha^{-1}. Mungbean was supplied with 20 kg N ha^{-1}, 14 kg P ha^{-1}, 24 kg K ha^{-1}, 13 kg S ha^{-1}, 1 kg Zn ha^{-1} and 0.5 kg B ha^{-1}. For T. Aman rice, fertiliser application rates were 66 kg N ha^{-1}, 7 kg P ha^{-1}, 33 kg K ha^{-1}, 8 kg S ha^{-1}, 1 kg Zn ha^{-1}.

For wheat and rice, all fertilizers except urea were applied basally at sowing or transplanting. Urea was applied in three equal splits: at around 24 and 47 days after sowing (DAS) for wheat, and at around 7, 28, and 44 days after transplanting (DAT) for rice. For mungbean, all fertilizers including urea were applied basally.

2.4.4 Pest management

In MT plots, weed control relied primarily on manual weeding with minimal soil disturbance, whereas in CT plots early weed flushes were suppressed through initial tillage operations. In wheat, manual weeding at 20 DAS was conducted in both tillage treatments, with minimal soil disturbance under MT and soil disturbance under CT, following local farmer practices. In mungbean and T. Aman rice, weed control followed the same principle, with manual control under MT before seeding or transplanting and tillage- or puddling-based control under CT, supplemented by hand weeding where required.

In wheat, insect pests and diseases were managed using need-based, farmers' recommended practices. Pest pressure in mungbean was minimal and managed through routine monitoring. For T. Aman rice, pests were managed manually and in accordance with integrated pest management (IPM) recommendations.

2.4.5 Irrigation

Besides, initial irrigation immediately after wheat sowing, in every year, three irrigations were applied to wheat at crown root initiation, early tillering and late tillering (keeping some in line with weeding and fertiliser application). For mungbean,

supplemental irrigations were applied upon monitoring and when required. The T. Aman rice was rainfed but supplemental irrigations were applied when the dry spells were prolonged.

2.5 Crop harvesting and data collection

Wheat was harvested in the first week of March, mungbean was harvested twice during the second and third weeks of June, and T. Aman rice was harvested in the third week of October each year. For yield assessment, two 1 m^2 quadrats per plot (total harvest area of 2.0 m^2) were selected. From each quadrat, ten plants were sampled to record yield-contributing characters. Grain samples from each plot were used to determine thousand-grain weight. From each quadrat, two independent subsamples of 1000 grains were taken and thousand-grain weight was calculated as the mean of the subsamples at the plot level.

In wheat, the entire plant was cut at ground level in residue-removed (R^-) plots, whereas approximately 30 cm of standing wheat straw was retained in residue-retained (R^+) plots. Grain and straw from the 2.0 m^2 harvest area were separated, sun-dried, and weighed. The amount of retained residue in R^+ plots was measured from one 1 m^2 quadrat. Final grain and straw yields were expressed on an area basis (t ha^{-1}).

2.6 Total residue retained in the plots under different tillage and residue retention treatment

Table 4 summarises the amounts of crop residues retained or removed under the various tillage and residue management practices across five years. Residue retention (R^+) consistently resulted in substantially higher residue amounts, while residue removal (R^-) left no residues on the field. Among tillage treatments, conventional and minimum tillage had similar overall residue retention patterns, mainly influenced by the residue management strategy.

Table 4
Retention of residues by the component crops in the cropping system over the years

Treatments	Crops' name	Amount of residues retained (t ha^{-1})					
		2018–2019	2019–2020	2020–2021	2021–2022	2022–2023	Yearly average
Tillage practices							
Conventional tillage	T. Aman	1.15	1.51	1.22	1.70	1.46	8.80
	Wheat	1.49	1.44	1.36	1.45	1.19	
	Mungbean biomass	6.73	5.13	6.45	6.45	5.25	
	Total	9.37	8.08	9.03	9.60	7.90	
Minimum tillage	T. Aman	1.19	1.49	1.18	1.49	1.40	8.55
	Wheat	1.49	1.60	1.41	1.48	1.36	
	Mungbean biomass	6.38	5.48	6.10	6.00	4.70	
	Total	9.06	8.57	8.69	8.97	7.46	
Residue retention levels							
Residue retention	T. Aman	2.34	3.00	2.41	3.19	2.86	17.34
	Wheat	2.98	3.04	2.78	2.92	2.55	
	Mungbean biomass	13.1	10.6	12.6	12.40	9.95	
	Total	18.42	16.64	17.79	18.51	15.36	
Residue removal	0	0	0	0	0	0	0

2.7 Soil Analysis

Soil samples were collected from 0–15 cm depth after the 15th crop harvest (T. Aman rice, 22 October 2023). Three samples per plot were composited for analysis. After harvesting of the 15th crop (T. Aman rice), soil bulk density (BD) was measured by core sampler method (Celik and Altikat, 2010). Soil water content (SWC) was measured during rabi season in the wheat field by using an MPM–160 Moisture Probe Meter (ICT International Pty Ltd.). Soil pH was measured by a glass electrode pH meter (JENWAY 3510 pH Meter) in a soil-water ratio of 1: 2.5 (w: v) as described by Ghosh (1983). Soil organic carbon (SOC) was measured by the wet oxidation method (Jackson 1973) and SOM was calculated by multiplying percent SOC with the van Bemmelen factor, 1.73 (Piper, 1942). Total N was measured by micro-Kjeldahl method (Bremner and Mulvaney, 1982), available P by the 0.5 M $NaHCO_3$ (Olsen et al. 1954), exchangeable K by NH_4OAc extraction (Black, 1965), available S by $CaCl_2$ extraction (Fox et al. 1964) and available Zn by DTPA extraction (Lindsay and Norvell 1978) and Available B content of soil was determined by the mono-calcium biphosphate [$Ca(H_2PO_4)_2$] extraction method. Microbial populations were quantified using the serial dilution technique, where the number of colonies was multiplied by the dilution factor (Ben-David and Davidson 2014). Mycorrhizal (fungal) spores were counted using the wet sieving and sucrose centrifugation method (Gerdemann and Nicolson 1963). *Rhizobium* was cultured on YEMA medium (Vincent 1970), PSB on Pikovskaya's agar (Pikovskaya 1948) and *Azotobacter* on Ashby's medium (Subba Rao 1999), following the serial dilution and plate count technique.

2.8 Calculation of Rice Equivalent Yield

Rice Equivalent Yield (REY) of component crops (rice and wheat) in the cropping pattern was computed according to Anjeneyul et al. (1982) by using the following formula:

$$REY = \text{Rice yield} + \frac{\text{Component crop yields} \times \text{Market price of component crop}}{\text{Market price of rice}}$$

2.9 Statistical analysis

All data related to crop and soil properties were statistically analysed using a split-plot design. The effects of different treatments on the measured variables were assessed using analysis of variance (ANOVA) and comparisons between treatment means were made using the least significant difference (LSD) multiple range test at a 5% level of significance ($P \leq 0.05$). Statistical analyses were performed with the software program Statistix 10.0 (Analytical Software, Tallahassee, FL, USA).

2.10 Principal Component Analysis and Pearson correlation

Principal component analysis (PCA) was conducted to examine treatment-level clustering and to identify the key variables driving changes in soil quality. The analysis used standardised, plot-level post-harvest data for soil chemical properties (organic matter, total N, P, K, S, Zn and B in their available forms), microbial populations (Rhizobium, phosphate-solubilising bacteria, Azotobacter and mycorrhiza) and bulk density. A biplot of the first two principal components (PC1 and PC2) was generated using Python (v3.10) in Google Colaboratory (Google, 2025) to visualise relationships among treatments and soil indicators. In addition, Pearson correlation analysis was performed to assess associations between soil nutrients and crop yields (wheat yield and rice equivalent yield). The resulting correlation matrix was visualised as a heatmap to interpret the strength and direction of relationships among variables.

2.11 Language Editing Compliance

For language clarity and improvement of grammar, we used ChatGPT (OpenAI GPT-5.2, December 2025 version) to assist in rephrasing sections of the manuscript text. This tool was employed solely to enhance readability and did not contribute to the scientific content, analysis or interpretation of results.

3. Results

3.1 Effect of tillage practices and residue retention on weed biomass in wheat field

Tillage practices and crop residue retention significantly influenced weed infestation in the wheat fields over the years. As shown in Table 5, MT consistently exhibited higher weed biomass compared to CT across all years. For example, in 2022–2023, MT recorded 32 g m^{-2} while CT had 24 g m^{-2}. However, the weed pressure reduced from 50% (in the 2018–2019) higher to 33% higher in 2022–2023 than CT practice.

Table 5

Effects of tillage practices and residue retention on weed biomass (g m^{-2}) in wheat field over the years of study (from 2018–2019 to 2022–2023)

Treatments	2018–2019	2019–2020	2020–2021	2021–2022	2022–2023
Tillage practices					
Conventional tillage (CT)	24 b	23 b	23 b	26 b	24 b
Minimum tillage (MT)	36 a	32 a	31 a	35 a	32 a
LSD0.05 value	6**	6*	9*	11*	10*
CV (%)	13.03	12.58	9.82	11.35	14.44
Residue retention levels					
Residue retention	-	25 b	24 b	22 b	24 b
Residue removal	-	30 a	29 a	30 a	29 a
LSD0.05 value	-	3**	3**	4**	2**
CV (%)	-	7.31	8.18	7.96	6.22
Different letters within columns indicate significant differences at P < 0.05. * P < 0.05; ** P < 0.01; ns = not significant					

Residue effects on weed biomass emerged from the second year onwards, as no residues were present during the initiated crop of the experiment (2018–2019). From 2019–2020 onwards, residue retention (R^+) consistently reduced weed biomass compared to residue removal (R-). By 2022–2023, weed biomass was 24 g m^{-2} under R+ compared to 29 g m^{-2} under R-.

3.2 Effect of tillage practices and residue retention on grain and straw yield of wheat

Wheat grain yields varied among tillage practices across the 2018–2019 to 2022–2023 cropping years (Fig. 3). Minimum tillage consistently outperformed CT in these years, achieving yields of 3.91, 4.41, 4.37 and 4.45 t ha^{-1} compared to CT yields of 3.66, 3.53, 4.10 and 3.97 t ha^{-1}.

Residue retention effects on grain yield became significant in the later years. In 2021–2022 and 2022–2023, R^+ plots yielded 4.38 and 4.29 t ha^{-1} respectively, compared to 4.09 and 4.13 t ha^{-1} under R^-. These effects were not significant in earlier years (Fig. 3). Straw yields showed no consistent treatment effects.

3.3 Effect of tillage practices and residue retention on seed and biomass yields of mungbean

Neither tillage practices nor residue retention significantly affected mungbean seed or biomass yields over the five-year period (Table 6). Seed yields averaged 1.35 t ha^{-1} under both CT and MT, while biomass yields were similarly unaffected. Seed yields under residue retention (R^+) varied between 1.20 to 1.48 t ha^{-1}, while those under residue removal (R^-) ranged from 1.11 to 1.52 t ha^{-1} over the study period. Biomass yields similarly overlapped, with R^+ ranging from 10.43 to 13.4 t ha^{-1} and R^- from 9.95 to 13.9 t ha^{-1} (Table 6).

Table 6

Effects of tillage practices and residue retention on the yields of seed and biomass of mungbean (t ha^{-1})

Treatments	2019		2020		2021		2022		2023	
	Seed yield	Biomass yield	Seed yield	Biomass yield	Seed yield	Biomass yield	Seed yield	Biomass yield	Seed yield	Biomass yield
Tillage practices										
Conventional tillage	1.34	14.2	1.12	10.4	1.44	13.6	1.50	13.3	1.36	10.69
Minimum tillage	1.46	12.9	1.19	11.7	1.51	12.2	1.45	12.1	1.20	9.70
LSD0.05 value	0.26^{ns}	4.0^{ns}	0.35^{ns}	4.0^{ns}	0.8^{ns}	2.1^{ns}	0.59^{ns}	3.3^{ns}	0.22^{ns}	2.15^{ns}
CV (%)	11.58	13.01	9.20	12.74	10.04	9.32	15.18	6.45	10.78	13.25
Residue retention levels										
Residue retention	1.38	13.1	1.20	11.4	1.43	13.4	1.48	12.9	1.30	10.43
Residue removal	1.42	13.9	1.11	10.6	1.52	12.6	1.47	12.4	1.26	9.95
LSD0.05 value	0.24^{ns}	1.17^{ns}	0.14^{ns}	1.1^{ns}	0.42^{ns}	3.0^{ns}	0.35^{ns}	0.6^{ns}	0.19^{ns}	1.25^{ns}
CV (%)	13.96	6.87	10.09	8.43	7.90	7.16	9.54	4.55	12.33	10.06

3.4 Effect of tillage practices and residue retention on grain and straw yields of T. Aman rice

In the final two years (2022 and 2023), tillage practices began to show notable effects on T. Aman yields (Fig. 4). Conventional tillage resulted in significantly higher grain and straw yields than minimum tillage (Fig. 4). For example, grain yields under CT were 5.75 and 5.84 t ha^{-1} in 2022 and 2023, compared to 4.82 and 4.97 t ha^{-1} under MT. This likely reflects the continued benefit of puddling in rice establishment within this system. Residue retention had no significant impact on either grain or straw yields of T. Aman across the five years (Fig. 4).

3.5 Effects of tillage practices and residue retention on cropping system productivity

Although MT often resulted in numerically higher system yields compared to CT, for example, achieving 13.4 t ha^{-1} $year^{-1}$ in 2020–2021 versus 12.3 t ha^{-1} $year^{-1}$ under CT, the differences were not statistically significant ($p > 0.05$) (Fig. 5).

Similarly, residue retention levels did not significantly affect REY over the study period; however, the residue-retained treatment (R^+) consistently produced higher REY than residue removal (R^-) across all study years. Mean REYs under R^+ and R^- were closely aligned with minor annual variations. For instance, in 2021–2022, REY was 13.8 t ha^{-1} $year^{-1}$ under R^+ compared to 13.2 t ha^{-1} $year^{-1}$ under R^- (Fig. 5).

3.6 Effect of tillage practices and residue retention levels on post-harvest soil

Soil microbial, physical and chemical properties as influenced by tillage practices and residue retention are reported below in Tables 7–9 and Fig. 6–7).

Table 7
Effect of tillage practices and residue retention on soil microbial population after 5-crop cycle of the wheat-mungbean-rice cropping

Treatment	Mycorrhizal spore (per 100 g soil)	Rhizobium cfu/g soil	PSB	Azotobacter
CT × R+	87 ± 7.5	$7.3 \cdot 10^3 \pm 228$	$6.6 \cdot 10^4 \pm 293$	$3.7 \cdot 10^5 \pm 1492$
CT × R-	70 ± 9.9	$2.8 \cdot 10^3 \pm 110$	$3.7 \cdot 10^4 \pm 225$	$5.8 \cdot 10^4 \pm 423$
MT × R+	99 ± 8.8	$3.2 \cdot 10^4 \pm 1455$	$3.8 \cdot 10^5 \pm 1385$	$5.0 \cdot 10^5 \pm 1905$
MT × R-	88 ± 16.4	$6.5 \cdot 10^3 \pm 202$	$2.6 \cdot 10^5 \pm 1543$	$6.2 \cdot 10^4 \pm 672$

Here, CT denotes conventional tillage/crop establishment, MT denotes minimal tillage crop establishment, R^+ indicates residue retention and R^- indicates residue removal; cfu-colony forming unit; PSB-phosphate solubilising bacteria

Table 8
Effects of tillage and residue retention on soil bulk density after 5- cycles of the wheat-mungbean-rice cropping

Treatments	Soil bulk density (g cm^{-3})
Tillage practices	
Conventional tillage	1.40
Minimum tillage	1.38
$LSD_{0.05}$ value	0.08^{ns}
CV (%)	3.51
Residue retention levels	
Residue retention	1.38
Residue removal	1.40
$LSD_{0.05}$ value	0.02^{ns}
CV (%)	1.90

Table 9
Effects of tillage and residue retention on soil water content (%) in wheat field in 2022–2023

Treatment	At 20 DAS (12 Dec. 2022)	At 50 DAS (11 Jan. 2023)	At 80 DAS (10 Feb. 2023)	At harvest (8 March 2023)
Tillage practices				
Conventional tillage (CT)	22.0 b	17.4 b	16.0 b	15.0
Minimum tillage (MT)	23.9 a	20.6 a	19.4 a	16.5
LSD0.05 value	1.5**	2.6*	2.4*	1.3ns
CV (%)	5.98	6.32	7.07	4.89
Residue retention levels				
Residue retention	23.7 a	19.7 a	18.3 a	16.3
Residue removal	22.2 b	18.3 b	17.1 b	15.2
LSD0.05 value	0.5*	0.8**	0.9**	0.7ns
CV (%)	6.63	4.87	8.25	4.64
Initial soil water	CT = 24.2% & MT = 24.5% and R^+ = 24.5% & R^- = 24.1%			

3.6.1 Effect of tillage practices and residue retention on soil microbial population

Soil microbial populations after five cropping cycles varied with tillage practices and residue management (Table 7). The highest microbial counts were consistently recorded under MT combined with R^+, while the lowest populations were found under CT with R.

Specifically, MT × R^+ plots recorded the greatest abundance across all groups, including 99 ± 8.8 mycorrhizal spores per 100 g soil, 3.2 × 10^4 Rhizobium, 3.8 × 10^5 phosphate-solubilizing bacteria (PSB) and 5.0 × 10^5 Azotobacter cfu per g soil. In contrast, CT × R^- plots showed markedly lower populations, for example only 70 ± 9.9 mycorrhizal spores, 2.8 × 10^3 Rhizobium, 3.7 × 10^4 PSB and 5.8 × 10^4 cfu Azotobacter (Table 7).

3.6.2 Effects of tillage practices and residue retention levels on soil bulk density

After five cropping cycles, neither tillage practices nor residue retention levels produced significant effects on soil bulk density (BD) at the 0–15 cm depth (Table 8). Mean BD values were 1.40 g cm^{-3} under CT and 1.38 g cm^{-3} under MT, with LSD of 0.08 g cm^{-3} indicating no statistical difference. Similarly, soils under residue retention (R^+) exhibited a BD of 1.38 g cm^{-3}, while residue removal (R^-) resulted in a slightly higher BD of 1.40 g cm^{-3}, but this difference was also not significant

3.6.3 Effects of tillage practices and residue retention on soil water content during the wheat growing season of 2022–2023

Soil water content (SWC) was measured at wheat planting and at 20, 50, 80 DAS, as well as at harvest, to assess how tillage and residue management influenced soil moisture dynamics during the 2022–2023 season. At the start of the season, SWC levels were relatively uniform across treatments, with values of 24.2% under CT and 24.5% under MT. Similarly, initial SWC in plots with residue retention (R^+) was 24.5%, compared to 24.1% in residue removal (R^-) plots.

As the season progressed, clear differences emerged. The MT consistently maintained higher soil moisture levels at all critical crop stages compared to CT. For example, at 20, 50 and 80 DAS, SWC under MT averaged 23.9%, 20.6% and 19.4%, respectively, whereas CT plots showed significantly lower moisture at 22.0%, 17.4% and 16.0%. Similarly, residue retention effectively conserved soil moisture, with R^+ plots maintaining 23.7%, 19.7% and 18.3% SWC across these periods, compared to 22.2%, 18.3% and 17.1% under R^-.

3.6.4 SOC and total N

Both tillage and residue management significantly affected SOC and total N (Fig. 6a-b). MT increased SOC by 17% (0.835% vs 0.713%) and total N by 34% (0.078% vs 0.058%) compared to CT. Residue retention increased SOC by 21% and total N by 49% compared to residue removal. The combined effect of MT × R^+ maximized both parameters, achieving 36% higher SOC and 114% higher total N than CT × R^-.

3.6.5 Available K

Available soil K was significantly affected by both tillage and residue practices. MT plots recorded 0.32 meq 100 g^{-1}, compared to 0.15 under CT. Similarly, residue retention led to a substantial increase, with 0.31 meq 100 g^{-1} K under R^+, nearly double the 0.16 recorded in R^-. The MT × R^+ treatment showed the highest K level at 0.43, while CT × R^- had the lowest at 0.11 meq 100 g^{-1}. This represents a 290% increase in K level with the MT × R^+ treatment over CT × R^- (Fig. 6c and Fig. 7).

3.6.6 Available P

Available P also increased under minimum tillage and residue retention. MT plots had 16.0 µg ml^{-1} P versus 12.7 µg ml^{-1} under CT. Residue retention resulted in 16.0 µg ml^{-1} P compared to 14.0 µg ml^{-1} in R^-. The MT × R^+ combination achieved the highest P at 18.5 µg ml^{-1}, whereas CT × R^- was the lowest at 11.5 µg ml^{-1} (Fig. 7), reflecting a 60% increase in P level under MT × R^+ compared to CT × R^- (Fig. 6d and Fig. 7).

3.6.7 Other nutrients

Similar trends were observed for S, Zn and B, all showing significant increases under MT with R^+ (Fig. 6e-g and Fig. 7).

4. Discussion

This five-year study conducted in the Gangetic plains of Bangladesh provides compelling evidence on how integrating minimum tillage with moderate crop residue retention progressively enhances soil quality and sustains or improves productivity in intensive rice-based cropping systems. Overall, the results highlight clear synergies of MT × R^+ for soil health and wheat performance, but also trade-offs in terms of higher weed pressure and constrained rice yields under non-puddled establishment. These results are especially meaningful for smallholder agriculture in South Asia, where adapting CA to rice-dominated rotations presents unique agronomic and cultural challenges (Gupta and Seth 2007; Haque et al. 2016).

4.1 Soil physical properties and moisture conservation

Our findings revealed that soil BD remained statistically unchanged across tillage and residue treatments after five cropping cycles. This agrees with similar observations in rice–upland systems by Zhang et al. (2009) and Salahin (2017), who reported that moderate durations under reduced tillage rarely show strong BD shifts, as structural reconfiguration typically requires longer-term biological activity and aggregate stabilization (Blanco-Canqui and Lal 2007; Sapkota et al. 2017).

The contrasting response of SWC despite unchanged BD reflects different controlling mechanisms. While BD changes require fundamental alterations in soil structure and pore architecture that develop over 7–10 years (Six et al. 2002), SWC responds immediately to surface management practices. The residue mulch reduces evaporation by 20–30% through surface shading and wind speed reduction, while MT maintains surface pore continuity that enhances infiltration, even without measurable changes in overall soil density (Verhulst et al. 2010; Balwinder-Singh et al. 2011). Additionally, improved soil organic matter

under MT × R^+ increased water holding capacity by approximately 1.5% per unit increase in SOM without necessarily affecting bulk density (Hudson 1994; Minasny and McBratney 2018).

These SWC improvements under MT and residue retention were particularly evident at critical wheat growth stages, mirroring studies in Bangladesh and beyond (Alam et al. 2016; Salahin et al. 2017). The 3–4% higher SWC under MT × R + at 50 and 80 DAS provides an important buffer during wheat's moisture-sensitive flowering and grain-filling stages, potentially explaining part of the yield advantage observed under these treatments.

4.2 SOC, total N and available K dynamics

One of the key outcomes of the study was the strong improvement in soil organic carbon (SOC) and total N under minimum tillage with residue retention. After five years, SOC increased by 36%, and total N more than doubled (114% increase) under MT × R+ compared with CT × R-. These changes are consistent with results from the Eastern Gangetic Plains, where conservation agriculture practices have been shown to raise SOC by 20–40% through slower carbon loss and steady residue inputs (Alam et al. 2018; Sapkota et al. 2017; Nandan et al. 2019). The much larger increase in N than in C suggests that, in addition to residue inputs, biological nitrogen fixation also played an important role, supported by the 10-fold higher populations of Rhizobium and Azotobacter under MT × R+.

Potassium showed the most remarkable response. Available K increased by 291% under MT × R^+ compared to CT × R^- (0.43 vs 0.11 meq 100 g^{-1}) (Fig. 6c). Residue retention alone nearly doubled K availability, but when combined with minimum tillage, the effect became clearly synergistic. With 8–9 t ha^{-1} yr^{-1} of retained residues (Table 4) containing 1.5–2.0% K, an estimated 120–180 kg K ha^{-1} was returned annually, far more than the 60 kg K ha^{-1} supplied through fertilizer. This agrees with studies showing that 75–80% of plant K remains in crop residues (Singh et al. 2018; Islam et al. 2022). The higher K availability under MT likely reflects reduced K fixation in clay minerals due to better soil structure, along with greater microbial activity releasing K from primary minerals (Saikia et al. 2019; Das et al. 2021).

These improvements in C, N, and K are associated with one another. Higher SOC increased the soil's ability to hold cations such as K, and better K nutrition supported higher biomass production, which in turn added more residues to the soil. The strong correlation between K availability and wheat yield (r = 0.84) and K availability and REY (r = 0.74) shows how improved soil K status directly contributed to productivity. This is especially important in South Asia, where long-term negative K balances have led to widespread K deficiency (Das et al. 2022; Majumdar et al. 2021).

4.3 Soil P, S, Zn and B improvement

Beyond the gains in SOC, total N and available K, minimum tillage with residue retention also improved available P and micronutrient availability. Available P increased by 61% under MT × R^+ compared with CT × R^-. This response aligns with the 10-fold higher population of phosphate-solubilizing bacteria (3.8×10^5 vs 3.7×10^4 CFU g^{-1}). These bacteria release organic acids and phosphatase enzymes that release up P bound to calcium phosphates in the alkaline soil of the study site (pH 7.6) (Richardson and Simpson 2011; Alori et al. 2017). The organic matter at the soil surface under MT also creates biologically active zones where organic P mineralisation is high (Damon et al. 2014; Hallama et al. 2019).

Micronutrient responses varied depending on their cycling pathways. Sulphur availability improved due to greater mineralisation of organic S, which makes up more than 95% of total soil S (Scherer 2009). The 36% increase in SOC under MT × R^+ provided more organic substrates for sulphatase-producing microbes. Increases in Zn and B likely came from a combination of factors: nutrient return through residues (especially important for B), chelation by organic matter that reduces fixation and surface pH conditions that favor micronutrient availability (Alloway 2008; Rengel 2015).

These changes created a clear "nutrient stratification" effect, where P, Zn, B, and other nutrients became concentrated in the top 0–5 cm. This has practical benefits in rice–wheat systems. Wheat seedlings grow in cool conditions and initially develop shallow roots, so the enriched surface layer aligns with the highest early root density. This likely contributed to the higher wheat yields observed, even when deeper soil layers remained unchanged (Franzluebbers 2002; Martínez et al. 2016). The

effect is less relevant for transplanted rice, which has a different rooting pattern, helping explain the crop-specific yield differences.

4.4 Enhanced microbial populations and biological health

The sharp rise in beneficial microorganisms under MT × R^+, a 10-fold increase in Rhizobium and PSB, and an 8.6-fold increase in Azotobacter, suggests a major shift in soil biological functioning. These populations likely reached the critical thresholds needed to deliver key ecosystem services such as N_2 fixation, phosphate solubilisation, and overall nutrient cycling, benefits that chemical fertilisers alone cannot provide (Kumar et al. 2020; Bargaz et al. 2021). The coordinated increase across several microbial groups shows that CA improves the entire soil food web rather than favouring only specific microbes (Choudhary et al. 2018a).

These microbial gains arise from well-known CA mechanisms. Continuous residue inputs supply steady C sources for heterotrophic microbes, while reduced soil disturbance preserves fungal hyphae and bacterial colonies normally disrupted by conventional tillage (Helgason et al. 2010; Säle et al. 2015). Better soil moisture under MT × R^+ also extends the active microbial window, especially important in South Asia, where biological activity typically drops sharply between monsoon seasons (Saikia et al. 2019).

Overall, the results support the growing recognition that restoring soil health depends on rebuilding biological communities, not simply increasing chemical inputs. The strong correlations between microbial populations and nutrient availability indicate that, as CA systems mature, nutrient cycling becomes increasingly biologically driven. This shift from a fertiliser-dependent system to one powered by soil biology represents a meaningful transformation for intensive agriculture, offering economic benefits through reduced input needs and environmental gains through improved ecosystem services (Kibblewhite et al. 2008; Lehmann et al. 2020).

4.5 Crop yields and system productivity

Crop yield responses to conservation practices differed sharply among species, reflecting their contrasting ecological needs and management histories. Wheat adapted quickly to MT: yields matched CT in the first year and became significantly higher from year two onward, reaching a 12% advantage by year five. This steady gain aligns with the cumulative improvements in soil moisture, nutrient supply, and biological activity under MT × R^+, and is consistent with regional findings that wheat responds well to residue mulch and improved surface soil conditions (Jat et al. 2018; Choudhary et al. 2018).

The effects of tillage and residue retention on rice yield differed from those observed in wheat. Yields under both CT and MT showed an increasing trend; however, non-puddled MT exhibited lower yields in years 4–5 ($p > 0.05$), reinforcing the well-documented challenge of sustaining rice productivity without puddling in heavy soils. Puddling provides reduced percolation, strong weed control and a stable anaerobic rooting environment condition that conservation practices still struggle to reproduce (Kumar and Ladha 2011; Gathala et al. 2015). This rice yield penalty remains the central barrier to CA adoption in South Asian rice–wheat systems.

Despite these contrasting crop-level responses, overall system productivity (REY) remained unchanged because of economic complementarity among crops. Mungbean, the highest-value crop (2.5–3× the price of rice), maintained stable yields across all treatments, providing important income support. Wheat's 7–12% yield gains under MT × R^+, combined with its higher market price (1.2 × rice), helped offset the revenue loss from rice. This buffering effect, where legumes and responsive cereals compensate for transitional yield declines, shows how diversified rotations can preserve profitability during CA adoption.

The ability to maintain system-level returns while building substantial soil health capital (including 291% higher K and 114% higher total N) indicates that short-term trade-offs do not necessarily threaten farm viability. However, narrowing the rice yield gap remains essential for large-scale adoption of CA in rice-based systems and further refinement of conservation tillage practices is required to achieve higher rice yields.

4.6 Weed management

Higher weed pressure under minimum tillage represents a manageable transitional challenge rather than a fundamental limitation to conservation agriculture adoption in smallholder systems. The observed increase is consistent with known ecological shifts under reduced soil disturbance, where weed seeds remain concentrated near the soil surface and established root systems regenerate more readily (Nichols et al. 2015). In the present study, weed pressure under MT declined progressively from 50.0 in 2018–2019 to 33.3 by 2022–2023, indicating partial system adaptation over time. Residue retention further contributed to weed suppression, reducing weed pressure by approximately 15–20% from the second year onward, although weed biomass under MT × R^+ remained higher than under CT.

These results emphasise the need for targeted weed and pest management strategies specifically designed for CA systems, rather than reliance on residue retention alone or on strategies being used for conventional practices. While weed pressure under MT was higher than under CT and under R^- compared with R^+, this provides a strong rationale for developing crop-specific integrated weed management (IWM) and IPM approaches compatible with CA. Such strategies include the use of effective pre- and post-emergence herbicides, selection of crop varieties with strong early vigour, optimised planting density and row spacing to enhance crop competitiveness and strategic crop sequencing to disrupt weed life cycles (Chauhan and Mahajan 2021). Smallholder farmers may increase reliance on manual weeding in CA systems, allowing effective weed control without substantial soil disturbance.

Although the present study did not include an economic analysis, regional evidence suggests that weed control under MT may involve additional short-term costs (approximately USD 20–30 ha^{-1}), primarily due to increased labour requirements or dependence on herbicide use (though not used in the present study) (Ozpinar 2006; Kumar et al. 2020; Singh et al. 2022). However, these costs also underline an opportunity for innovation, particularly through the development of locally adapted IPM packages that integrate chemical, cultural, and mechanical options while minimising input use. The absence of a clear decline in weed pressure over time in this study further suggests that active weed management will remain an essential component of CA, reinforcing the importance of continued refinement of weed control strategies to ensure both agronomic and economic sustainability.

4.7 Broader implications for CA in rice-based systems

The multivariate analysis (Fig. 8) shows that conservation practices generate a distinct “soil health syndrome,” where chemical, physical and biological improvements occur together rather than in isolation. The clear separation of MT × R^+ from all other treatments in the ordination plot (Fig. 8) indicates that these changes are tightly interconnected: higher organic matter supports larger and more active microbial communities, which in turn drive stronger nutrient cycling, creating a reinforcing positive feedback loop. This integrated, system-wide shift not just small improvements in individual parameters, captures the true transformation that sustained CA can deliver.

To assess the interrelationships among soil fertility parameters and crop productivity, a Pearson correlation analysis was conducted using post-harvest soil chemical properties (OM, TN, P, K, S, Zn, B) and the yields of wheat and rice equivalent yield under different tillage and residue management treatments. The correlation matrix (Fig. 9) reveals remarkably strong positive correlations among most soil chemical parameters ($r = 0.91–1.00$), indicating a high degree of synchrony among organic matter, macronutrients and micronutrients in response to long-term CA. These strong correlations reflect treatment-driven co-variation rather than independent soil processes, as variables were jointly influenced by long-term tillage and residue management. In particular, SOM was highly correlated with K ($r = 0.99$), Zn ($r = 0.99$) and B ($r = 0.99$), reflecting its central role in enhancing nutrient retention and availability. Total N also exhibited strong correlations with P, S and Zn ($r \geq 0.91$), highlighting its association with both macro- and micronutrient cycling. The correlation between soil properties and wheat yield was consistently strong ($r = 0.84–0.94$), while rice equivalent yield also showed moderate-to-high correlations with OM ($r = 0.79$), TN ($r = 0.92$) and P ($r = 0.78$). These results indicate that long-term minimum tillage with residue retention is associated with synergistic improvements in soil fertility that translates into enhanced wheat and system-level productivity (Fig. 9).

5. Conclusions

This five-year field study demonstrates that minimum tillage combined with partial residue retention can substantially improve soil health and sustain system-level productivity in an intensive wheat–mungbean–rice rotation of the western Gangetic Plains. Consistent with the study objectives, MT × R^+ progressively enhanced SOC (by 36%), total N% (114%), available K by 291%, available macro- and micronutrients, and beneficial microbial populations, indicating a shift towards more biologically driven nutrient cycling.

Crop responses differed across the rotation. Wheat showed a clear and increasing yield advantage (around 15%) under MT × R^+, reflecting improved soil moisture and nutrient availability. In contrast, rice yields under non-puddled MT were lower than under conventional puddling in later years, confirming that rice establishment remains the principal constraint to CA adoption in rice-based systems. Despite these crop-specific responses, overall system productivity was maintained, as gains in wheat and stable mungbean performance compensated for reduced rice yields. The large increase in soil K under MT × R^+, addressing a widespread regional deficiency, represents a particularly important long-term benefit of residue retention. Weed pressure was higher under minimum tillage, especially during early years, but declined gradually (from 50% higher to 30% higher) and was partially mitigated by residue retention. These results indicate that weed management will remain an active component of CA systems, requiring crop-specific and CA oriented integrated weed and pest management strategies rather than passive reliance on residue cover alone.

Overall, the findings confirm that CA can sequester SOC, restore soil fertility and maintain productivity in rice-based rotations, provided that continued innovation in non-puddled rice establishment and CA-adapted weed management is pursued. The substantial soil health gains observed underline CA as a long-term investment in resilient and resource-efficient agricultural systems in South Asia.

Declarations

Author Contributions: Conceptualisation, N.S. and M.K.A.; methodology, N.S. M.K.A.; soft-ware, N.S., M.K.A. and N.U.M.; validation, N.S., M.K.A., N.U.M., RN, M.H.R. and M.S.K.; formal analysis, N.S., M.K.A., M.S.I. and N.U.M.; investigation, N.S., M.K.A., N.U.M., RN, M.H.R. and M.S.K.; resources, N.S., N.U.M., RN, M.S.I., M.H.R. and M.S.K.; data curation, N.S., M.K.A. and M.S.I.; writing—original draft preparation, N.S., M.K.A., A.Z. and M.S.I.; writing—review and editing, N.S., M.K.A., N.U.M., RN, M.H.R., A.Z. and M.S.K.; visualisation, N.S. and M.K.A.; funding acquisition, N.S.. All authors have read and agreed to the published version of the manuscript.

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Ethics, Consent to Participate and Consent to Publish declarations:
Ethics approval and field permission: The genotypes were sourced from publicly released varieties maintained by the Bangladesh Agricultural Research Institute (BARI) and the Bangladesh Rice Research Institute (BRRI). All plant materials were cultivated in designated institutional research fields following national agronomic and biosafety guidelines. No specific collection permits or licenses were required.

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Figures

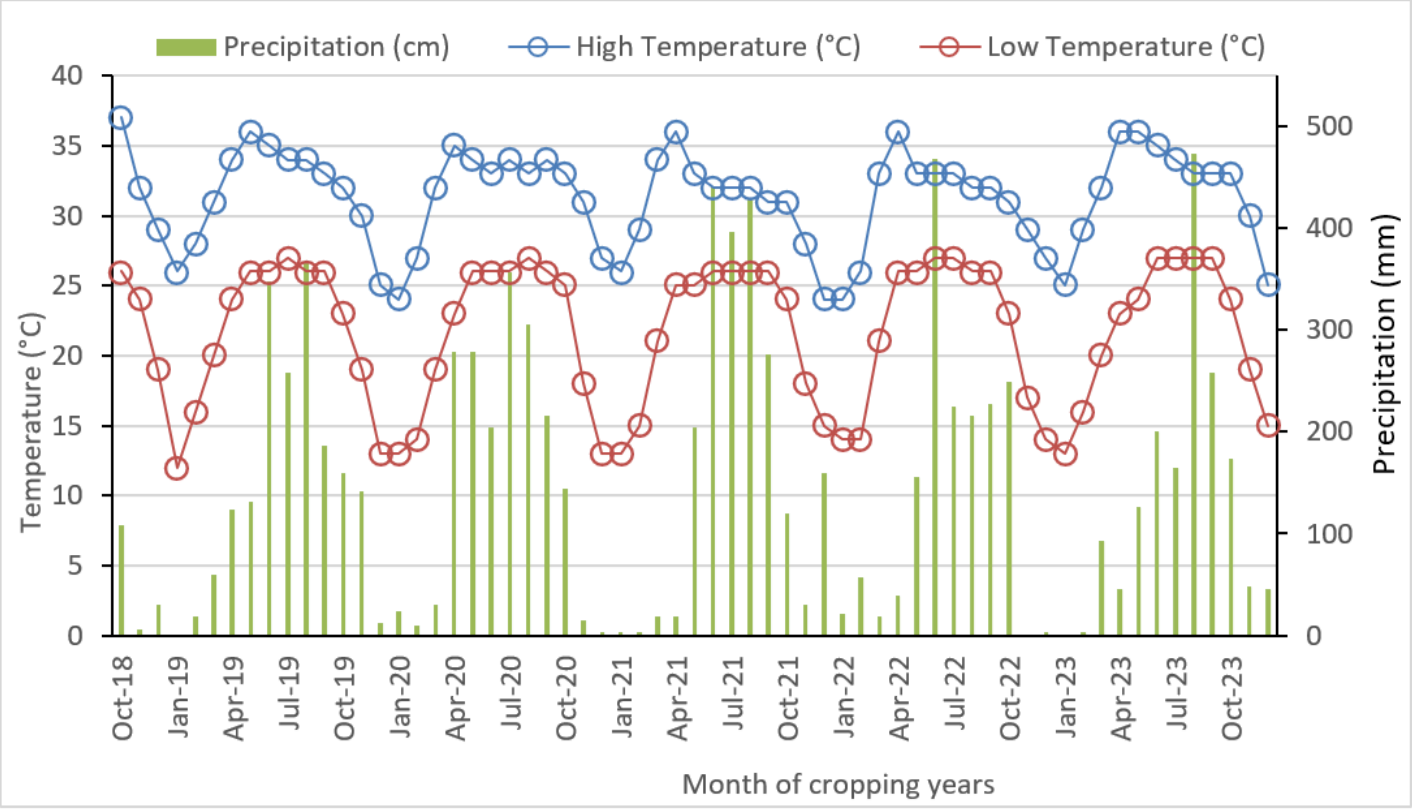


Figure 1

Monthly precipitation and temperature patterns at the experimental site in Jashore, Bangladesh during the five-year study period (October 2018-October 2023). Bars represent monthly precipitation; lines show mean maximum and minimum temperatures.

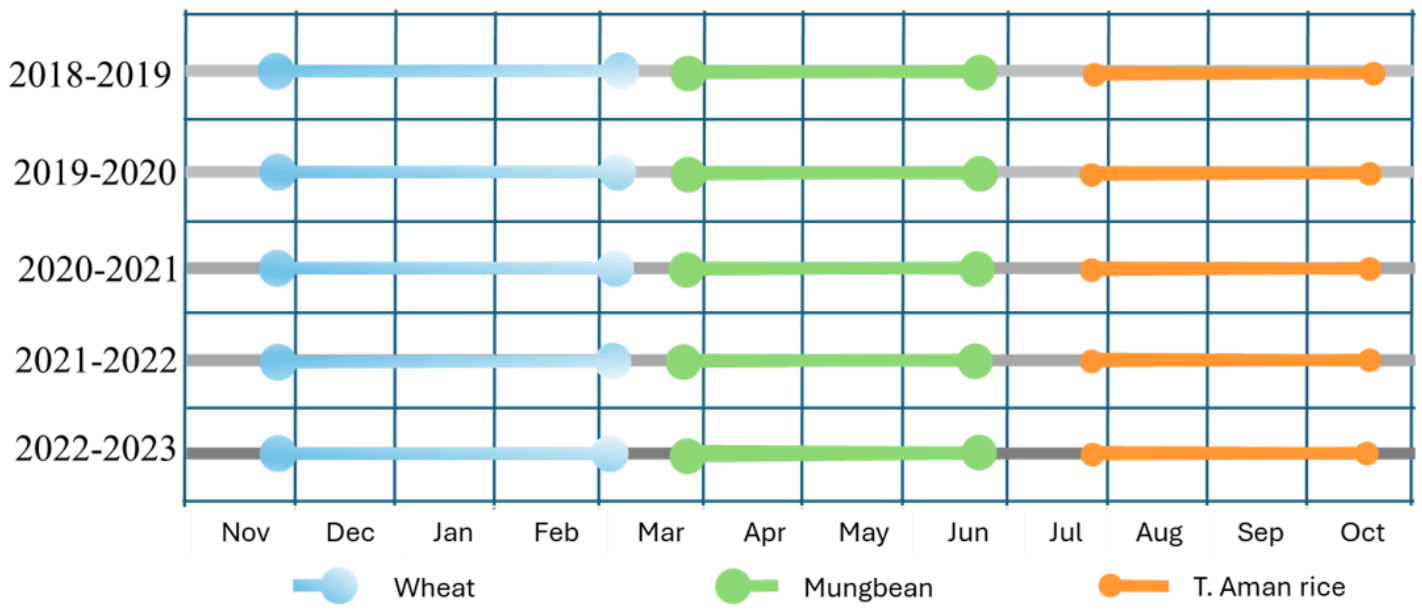


Figure 2

Crop calendar shows the sowing, fallow, growing and harvesting periods of wheat (*Triticum aestivum* L.) mungbean (*Vigna radiata* L. Wilczek) and rice (*Oryza sativa* L., ecotype T. aman) crops from 2018-2019 to 2022-2023.

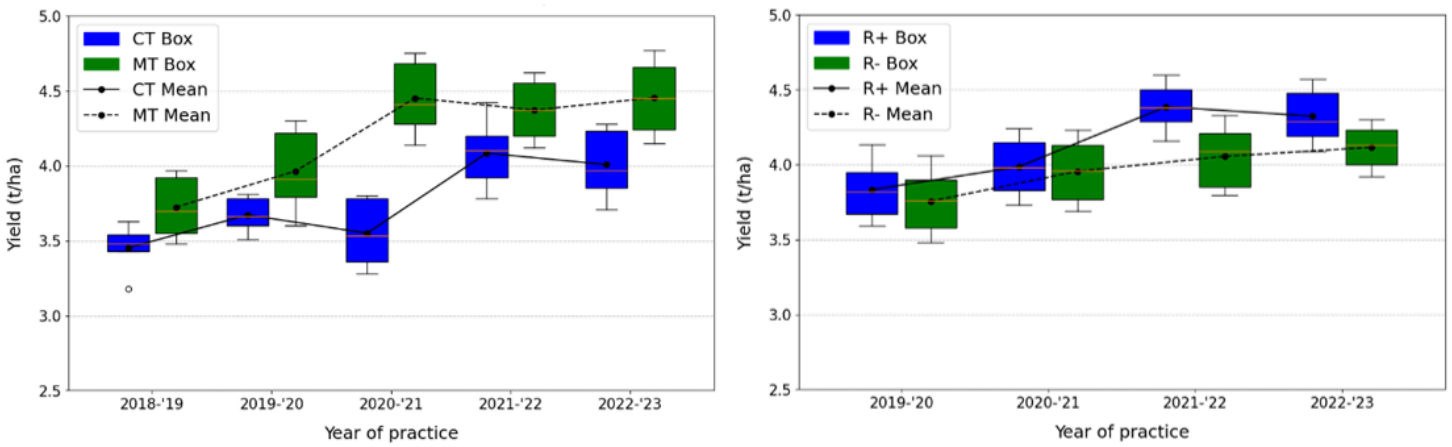


Figure 3

Effects of tillage practices and residue retention on wheat (*Triticum aestivum* L.) grain yield (t ha^{-1}) over the study period. Here, CT denotes conventional tillage/crop establishment, MT denotes minimal tillage crop establishment, R+ indicates residue retention and R− indicates residue removal.

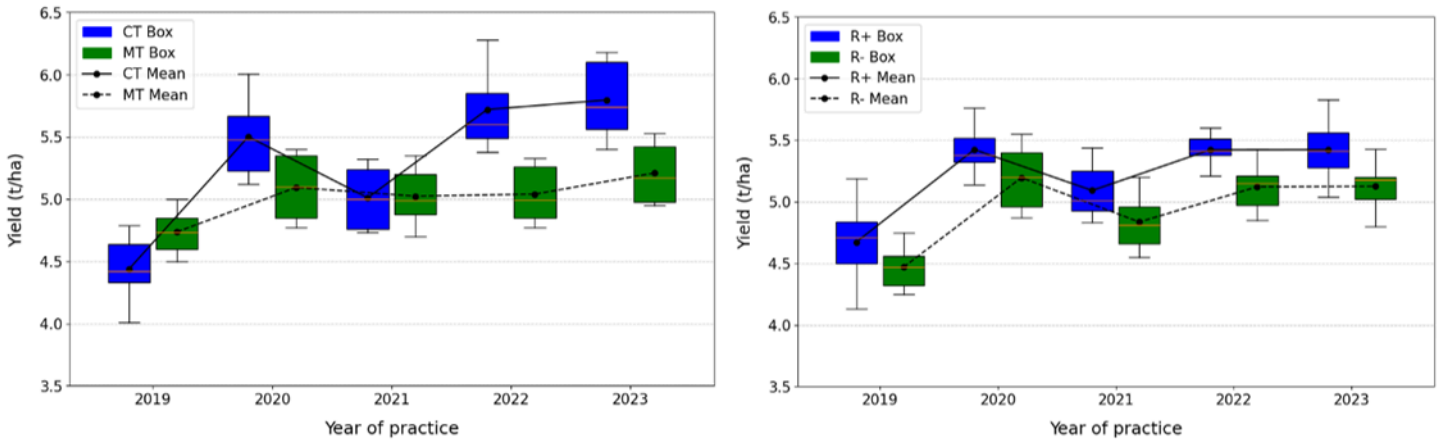


Figure 4

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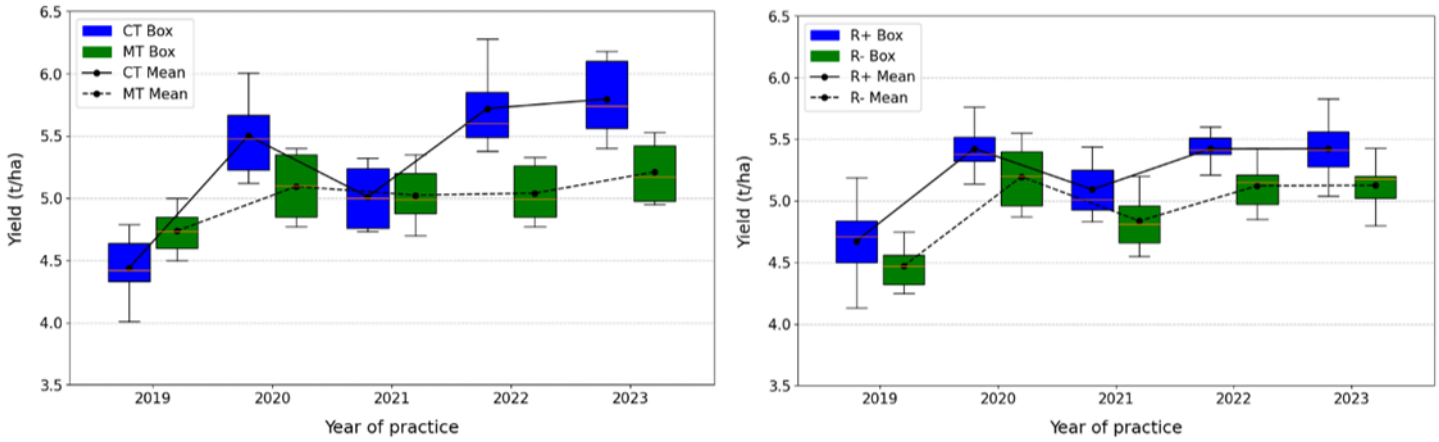


Figure 4

Effects of tillage practices and residue retention on grain yields of T. Aman (*Oryza sativa* L) rice. Here, CT denotes conventional tillage/crop establishment, MT denotes minimal tillage crop establishment, R+ indicates residue retention and R− indicates residue removal.

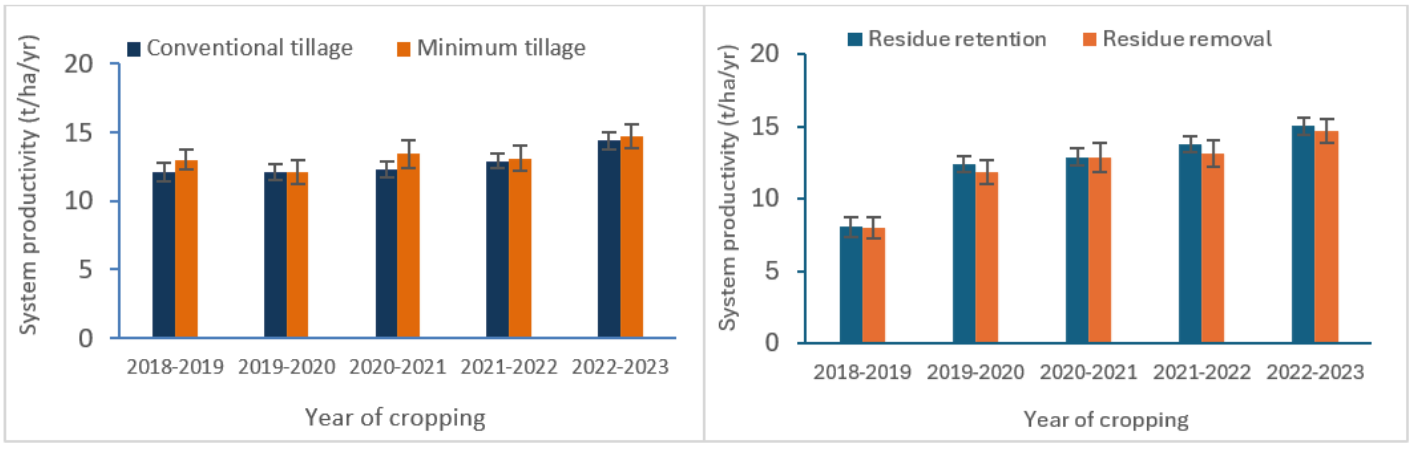


Figure 5

Effects of tillage practices and residue retention on rice equivalent yield (t ha-1 year-1).

Note: Market prices of rice, wheat and mungbean were US$ 0.16 kg-1, US$ 0.21 kg-1 & US$ 0.41 in 2018-19, respectively; were US$ 0.20 kg-1, US$ 0.21 kg-1 & US$ 0.49 in 2019-20, respectively; were US$ 0.23 kg-1, US$ 0.25 kg-1 & US$ 0.58 in 2020-21 and 2021-22, respectively; were US$ 0.23 kg-1, US$ 0.25 kg-1 and US$ 0.66 in 2022-23, respectively.

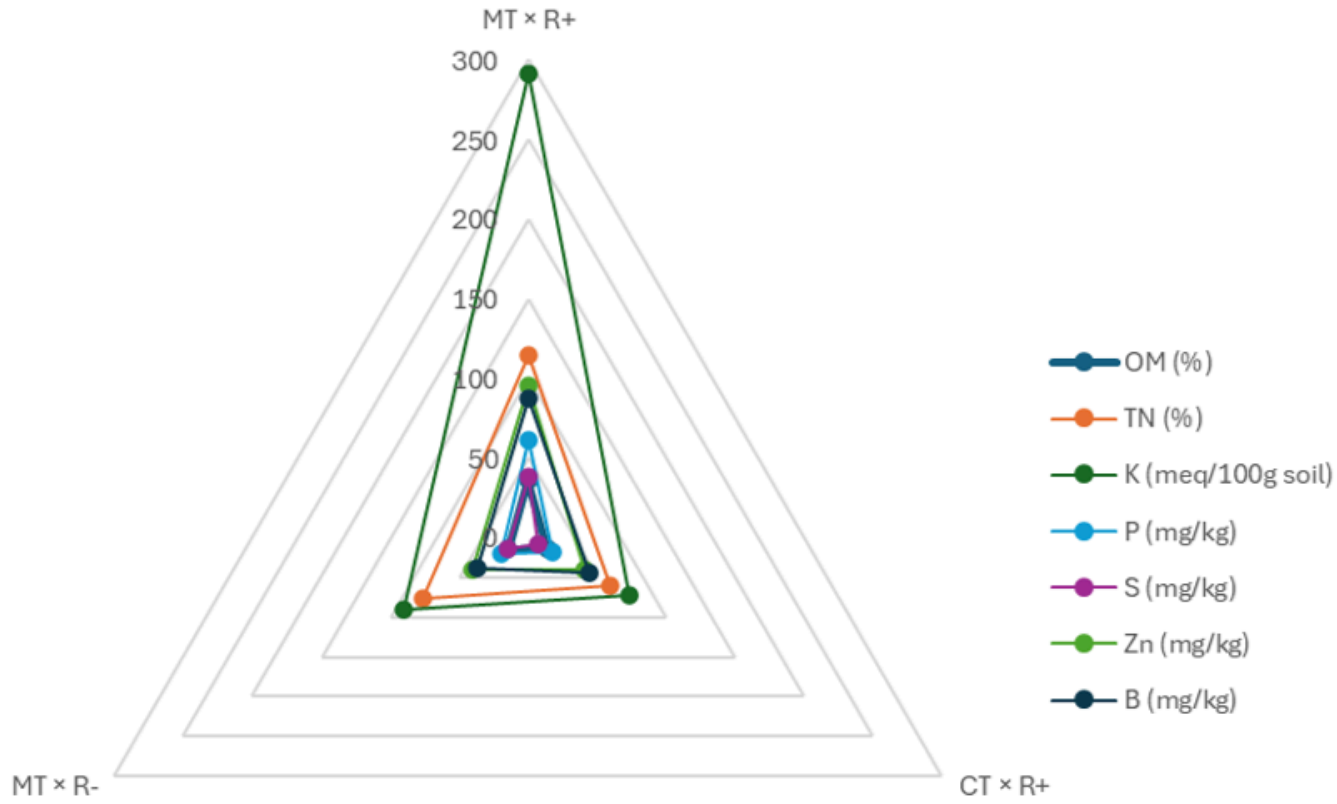


Figure 6

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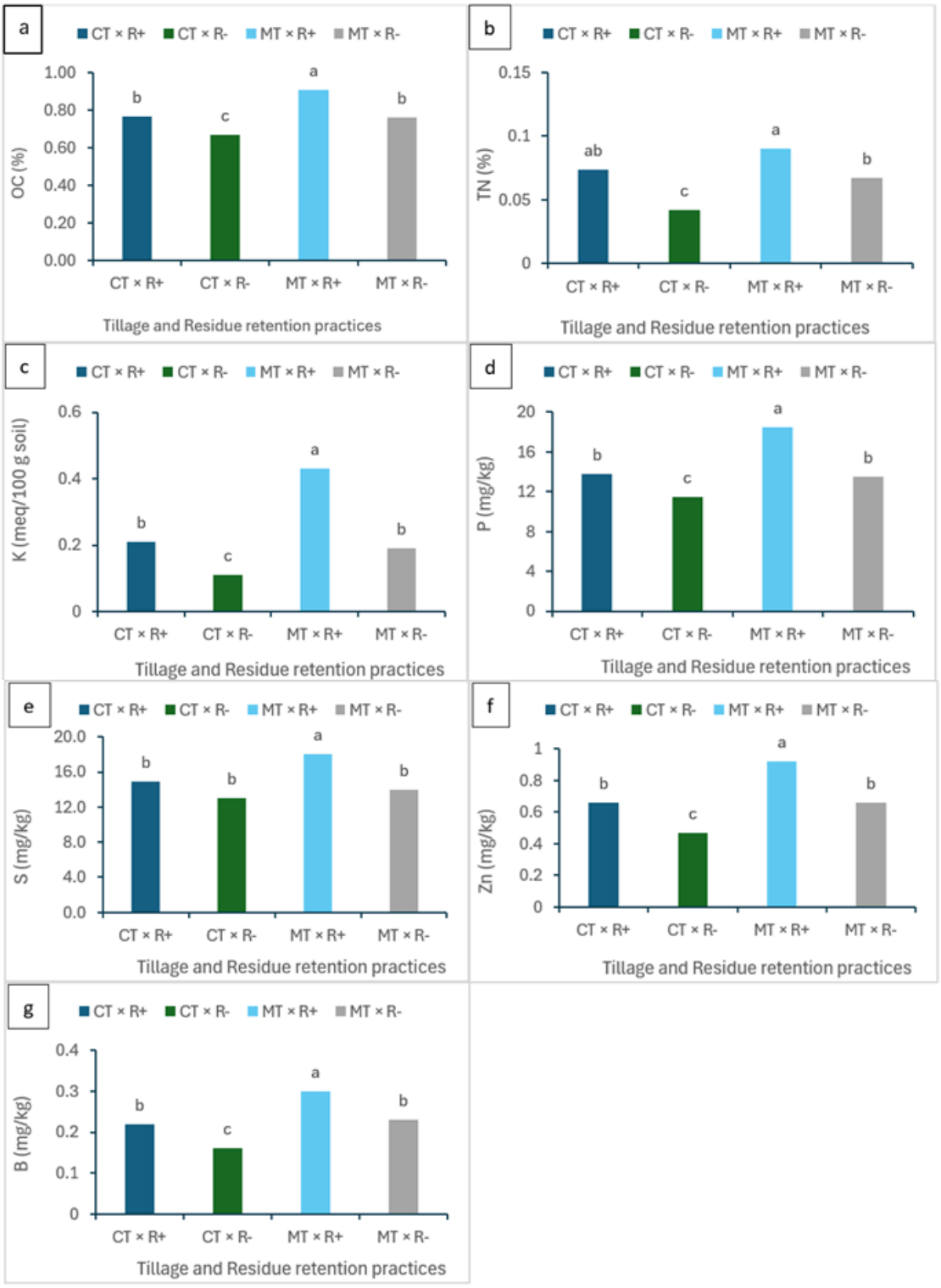


Figure 6

(a-g). Effects of tillage practices and residue retention levels on soil organic carbon, total nitrogen, available phosphorus, potassium, sulphur, zinc and boron contents after 5-cropping years. Here, CT denotes conventional tillage/crop establishment, MT denotes minimal tillage crop establishment, R+ indicates residue retention and R– indicates residue removal.

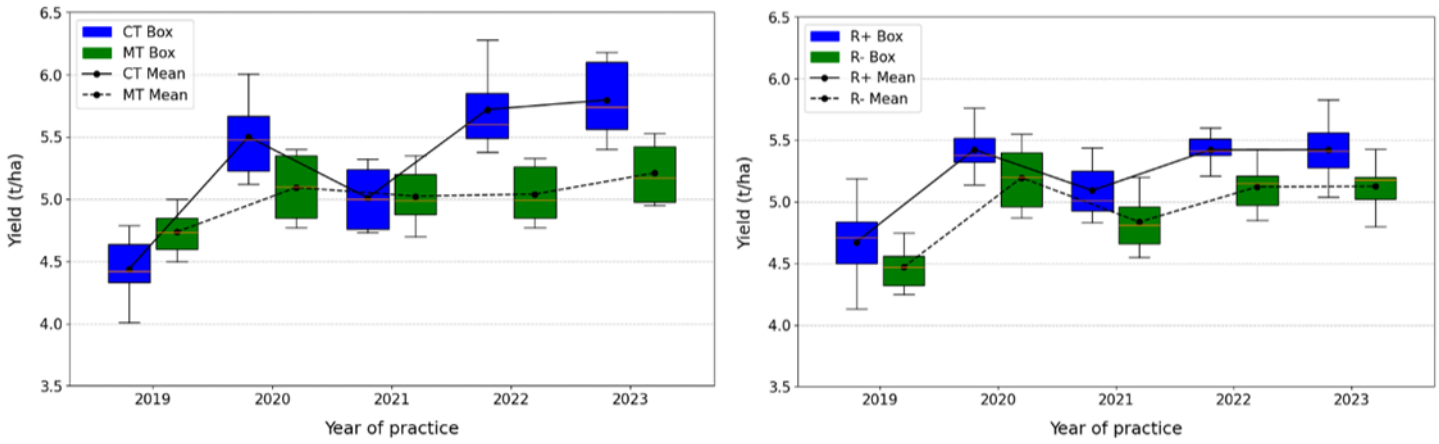


Figure 7

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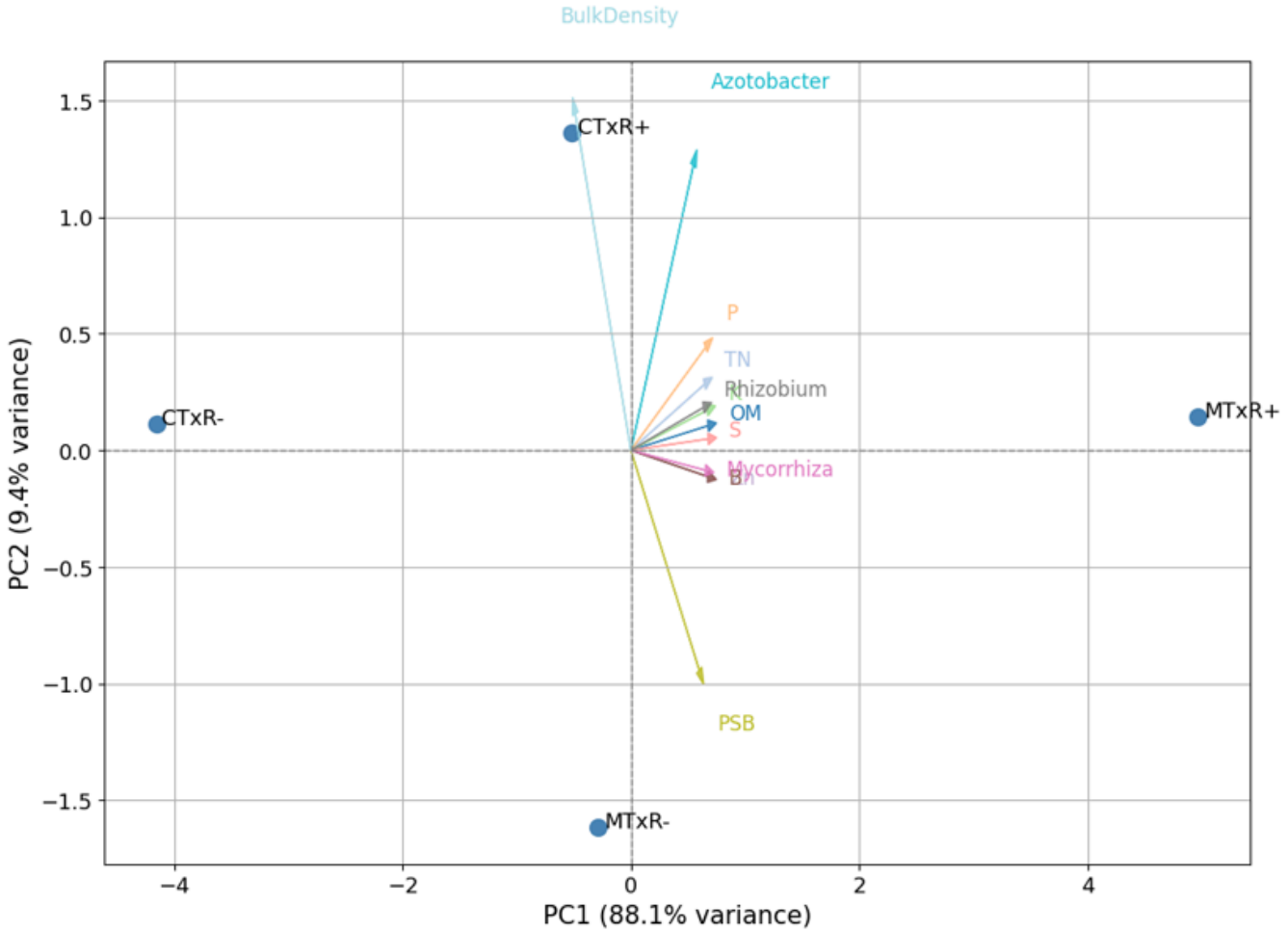


Figure 7

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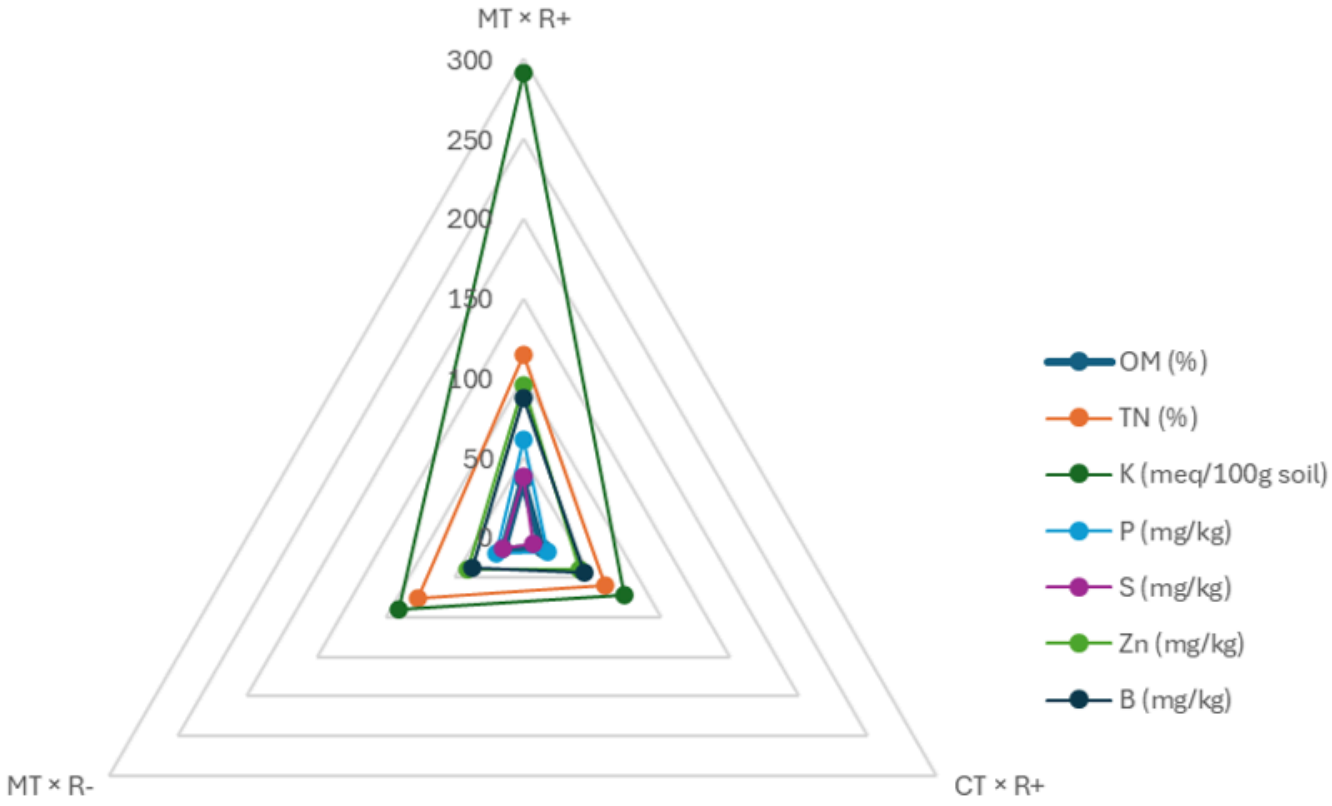


Figure 7

Percent improvement of plant nutrients and soil organic matter in minimum tillage and conventional tillage with residue and minimum tillage without residue in comparison with conventional tillage without residue retention after 5-cropping years. Here, CT denotes conventional tillage/crop establishment, MT denotes minimal tillage crop establishment, R+ indicates residue retention and R− indicates residue removal.

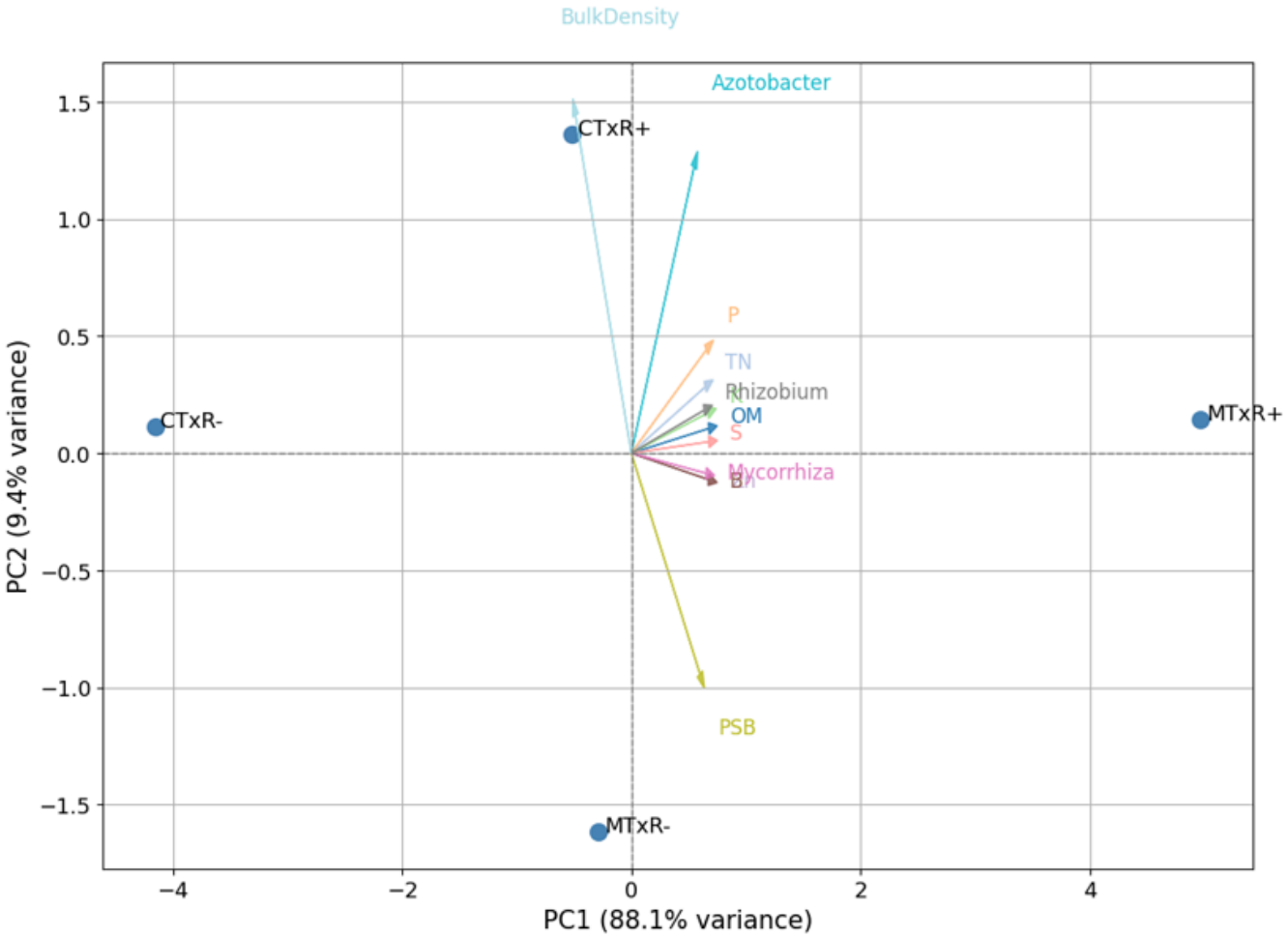


Figure 8

Principal Component Analysis (PCA) biplot showing treatment clustering and variable contributions for soil properties, microbial counts and bulk density after five years of wheat–mungbean–rice cropping system under different tillage and residue retention practices. Treatments include conventional tillage (CT), minimum tillage, residue retained (R^+) and residue removed (R^-). Principal Component 1 (PC1) explains 88.1% of the total variance, while PC2 explains 9.4%. Arrows represent the direction and magnitude of the contributions of each soil and microbial variable.

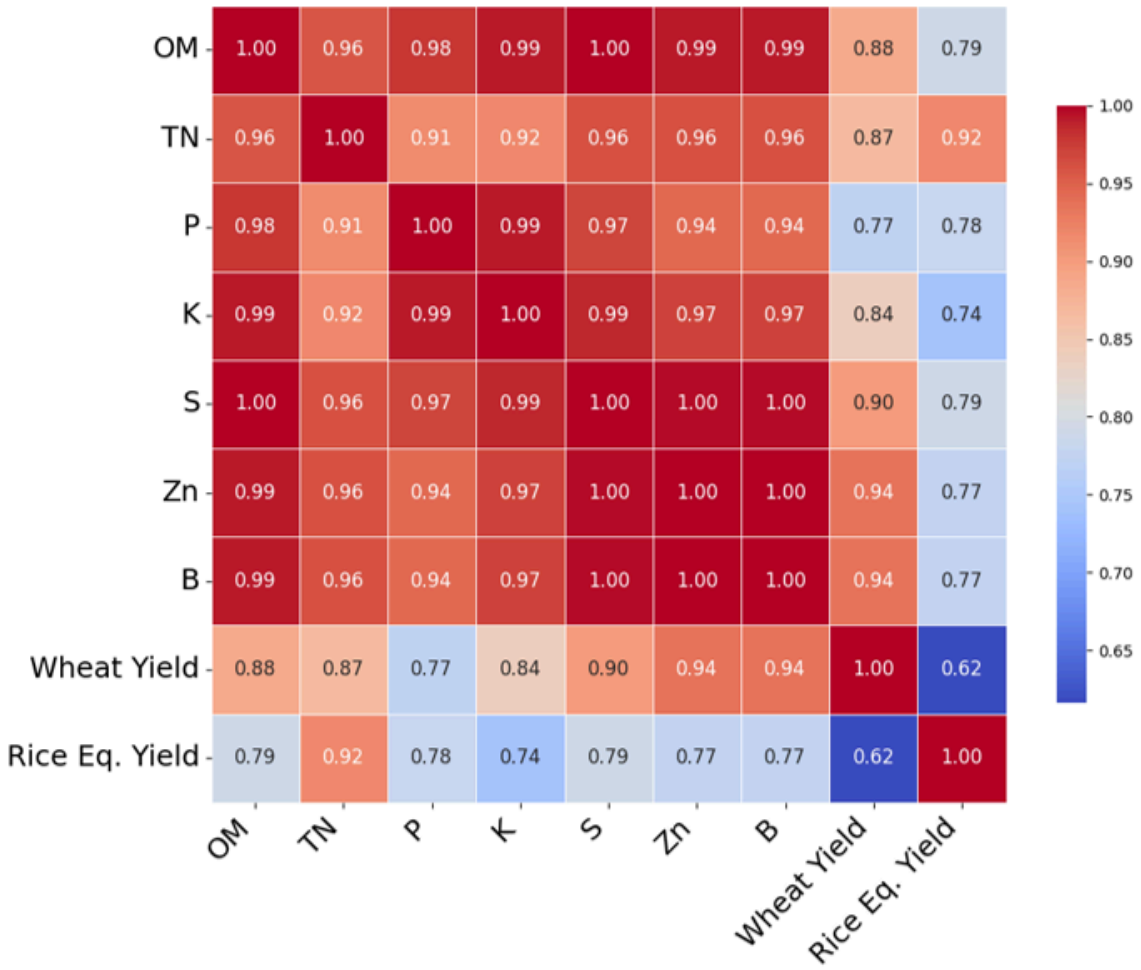


Figure 9

Pearson correlation matrix among soil chemical properties (OM, TN, P, K, S, Zn, B) and crop yields (wheat and rice equivalent yield) after five years of wheat–mungbean–rice cropping under different tillage and residue management practices. Most soil properties showed strong positive correlations ($r > 0.8$) with crop yields, especially rice equivalent yield and wheat yield.