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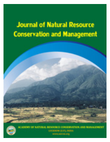

Soil physical properties and productivity of wheat as affected by minimum and conventional tillage in Rice-Wheat cropping sequence

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ABSTRACT

The rice-wheat cropping sequence is one of the most important systems in the Indo-Gangetic Plains of India. Recently, this system has shown signs of fatigue and a declining trend in productivity. To sustain productivity in structurally degraded soils with low organic matter content, it is essential to improve soil structure through the integrated use of organic manures, crop residues, and inorganic fertilizers. Considering the problems created by puddling for rice and its adverse effects on the subsequent wheat crop, there is a need to develop alternate tillage systems that enhance soil physical and structural attributes. This study evaluated the effects of minimum and conventional tillage on soil physical properties, particularly soil structural characteristics. Bulk density increased significantly from 0-7.5 cm to 7.5-15 cm but decreased at 15-30 cm under all treatments except minimum tillage with straw retention. Straw application and soil depth significantly influenced bulk density, which decreased over time under the imposed treatments. Hydraulic conductivity was also significantly affected by both depth and straw application, showing consistent trends across treatments. Cumulative infiltration varied between 93-96% in 2004-05 and 2005-06, with maximum values observed under minimum tillage with straw retention. Moisture storage was highest (15.1 cm) in the minimum tillage with straw retention treatment compared to the lowest values under conventional tillage with straw removal. The water storage function ($w = at^{-b}$) showed maximum variation in conventional tillage with straw retention ($R^2 = 0.971$). Moduli of rupture values increased with depth and were higher under conventional tillage treatments compared to minimum tillage. Wheat grain yields ranged from 3.7 to 4.1 t ha{ ^{1} across treatments.

Keywords: Alternate tillage system, Hydraulic conductivity, Drainage rate, Modulus of rupture

INTRODUCTION

The rice-wheat cropping system (RWCS) of the Indo-Gangetic Plains (IGP) has played a transformative and enduring role in safeguarding India's food security since the advent of the Green Revolution. By the mid-1990s, this production system accounted for nearly 75% of the country's total food grain output and continues to serve as the cornerstone of agricultural sustainability across Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal. The RWCS not only underpins national grain reserves but also sustains millions of farming households through assured productivity and market stability. Nevertheless, over the past two decades, clear signs of system fatigue and yield stagnation have emerged. These declining productivity trends have been attributed primarily to progressive soil structural degradation, depletion of soil organic carbon (SOC), and inefficient crop residue management practices that disturb the natural soil equilibrium (Duxbury *et al.*, 2000; Yadav *et al.*, 2000; Mishra *et al.*, 2015). In addition to physical deterioration, biological degradation has intensified due to the continuous mining of soil nutrients, reduced organic matter inputs, and disruption of soil microbial processes responsible for nutrient cycling and ecosystem functioning (Kushwaha *et al.*, 2020; Bhardwaj *et al.*, 2020; Upadhyay *et al.*, 2024). The cumulative effect of these constraints threatens the long-term resilience and sustainability of the RWCS in the IGP.

Conventional puddling, the dominant tillage practice for transplanted rice cultivation, has been identified as a major contributor to soil physical constraints within this system. While puddling facilitates weed control and reduces percolation losses in rice, it simultaneously breaks down soil aggregates, increases sub-surface compaction, and forms a dense plough pan. These alterations adversely affect soil structure and necessitate repeated and energy-intensive tillage operations for subsequent wheat establishment. As a consequence, wheat sowing is often delayed, leading to suboptimal crop stand, poor root proliferation, restricted soil aeration, and inefficient utilization of nutrients and irrigation water (Buehrer & Rose, 1943; Sharma & De Datta, 1985). Under the prevailing scenario of climate variability and terminal heat stress, such delays further exacerbate yield penalties. Recent empirical evidence indicates that conservation tillage practices combined with in-situ crop residue retention can substantially alleviate compaction, enhance soil porosity, improve water infiltration, and sustain wheat productivity even under climatic stress conditions (Chaudhary *et al.*, 2024). In parallel, the integration of organic amendments, such as farmyard manure, compost, and crop residues, has demonstrated significant improvements in soil aggregation, hydraulic conductivity, and microbial diversity within RWCS soils, thereby strengthening soil health and ecosystem services (Tripathi and Nayak, 2024; Frontiers in Microbiology, 2023).

Despite these promising advancements, important knowledge gaps persist, particularly regarding the comparative impacts of minimum tillage and conventional puddling on critical soil structural attributes under RWCS conditions in north-western India. Although numerous contemporary studies emphasize residue management and conservation agriculture frameworks, there remains a paucity of rigorous quantitative assessments focusing on soil physical parameters such as bulk density, infiltration rate, modulus of rupture, and drainage characteristics under contrasting tillage regimes. A systematic and context-specific evaluation of these parameters is essential to generate evidence-based recommendations that can reconcile productivity goals with soil health restoration and long-term system sustainability. Accordingly, the present study was undertaken with the following objectives: (i) to evaluate the effects of minimum and conventional tillage on key soil physical parameters, including bulk density, hydraulic conductivity, infiltration rate, modulus of rupture, and drainage rate; (ii) to assess the role of residue retention in moderating soil structural degradation under the RWCS; and (iii) to identify sustainable tillage practices that enhance soil physical quality, system resilience, and long-term productivity in the Indo-Gangetic Plains.

MATERIALS AND METHODS

Site characteristics

Field experiment was conducted at the Research Farm, Department of Soil Science (T. No 5, Field No E-3) Punjab Agricultural University, Ludhiana to study the effect of minimum and conventional tillage on some soil physical properties specifically structural properties in rice-wheat sequence.

Experimental site

The site is situated at 30°54′24″ N latitude and 75°47′30″ E longitudes with an altitude of 247 m above mean sea level, in the central plains of Punjab at Ludhiana under Indo-Gangetic Agro-climatic zone of India. It is characterized by sub-tropical and semi-arid type of climate. The soils have developed from alluvium under ustic soil moisture regime and belong to the family of Typic Ustochrepts (Sehgal and Sys, 1970). The area experiences an average annual rainfall of 800 mm, of which 80% is received during June to September months coinciding with kharif season (summer monsoon months) and remaining 20% in rabi (winter) season. The mean maximum and minimum temperatures during rice (July-October) were 35 and 18ºC, whereas during wheat (November-April), the temperatures were 22.6 and 6.7ºC. The soils are well drained with the groundwater table at 6.6m and 10m deep during the rainy and summer seasons.

Table 1. Soil chemical properties in 2004-06

Treatments	OC %	pH	EC dsm^{-2}	P kg ha^{-1}	K kg ha^{-1}
CTSRT	0.39-0.42	7.3-7.4	0.37-0.37	19.3-21.6	88.2-84.0
CTSRM	0.41	7.3	0.35 -0.36	19.4-22.4	87.5 -87.7
MTSRT	0.41	7.3	0.37 -0.38	18.4-19.5	84.2-84.0
MTSRM	0.39	7.4	0.30-0.37	18.6-19.5	83.3-89.7
CD (0.05)	NS	NS	NS	2.26	NS

Experimental details

The experiment was laid out with 16 plots (14×11m^2) to test four treatments each was replicated four times. However, out of 16 plots, 8 were conventionally tilled having four straw removed and four straw retained. Similarly, for 8 minimum tilled plots, four were straw removed and four were straw retained (Singh, 2008). A buffer of 1m was maintained between the two adjacent plots. Rice straw was incorporated 20 days before sowing of wheat crop. The treatments were imposed randomly within layout.

Soil characteristics

The soil of experimental site was non saline, low in organic carbon, available N and medium in available P and medium to high in available K (Table 1). However, the texture of soil is sandy loam.

Collection of samples

To determine bulk density, the soil samples were taken with the help of iron core of 5 cm diameter and height 5cm from the depths of 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm after harvest of wheat in 2004-05 and 2005-06.

Similarly, to determine hydraulic conductivity, soil samples were collected with the help of iron cores of internal diameter 5 cm and height 5 cm. These samples were drawn from depths of 0-7.5, 7.5-15, 15-22.5, and 22.5-30 cm.

However, to determine modulus of rupture, the soil samples were taken from 0-7.5 and 7.5-15 cm depths with the help of cores (Dimensions- diameter 5 cm and height 5cm). For computation of drainage rate, the soil samples were collected with the help of screw auger from the depths of 0-15, 15-30, 30-60, 60-90, 90-120 and120-180 cm respectively after an interval of 12 hours up to 240 hours continuously.

The soil moisture storage for each layer was computed using the information on mass water content, bulk density, and depth of each layer up to 180cm.

The collected soil samples were brought to the laboratory and analyzed for soil organic carbon (SOC) with wet digestion potassium dichromate (Walkley and Black, 1934) procedure and Aggregate stability i.e. mean weight diameter (MWD) by wet sieving method (Yoder 1936). The saturated hydraulic conductivity (Ks) was determined by constant head method (Reynolds, Elrick, and Youngs, 2002). However, bulk density (Db) was determined by core method (Blake and Hartge, 1986). Infiltration rate (IR) under each treatment was determined by double ring infiltrometers (Reynolds, Elrick, and Youngs, 2002) by maintaining 3 replications. However, the particle size analysis was carried out as per the international Pipette method of Day (1965). However, the detailed methodology is described below for each type of measurement and determination.

Methodology

Soil samples were taken after an interval of 20 days after wheat harvest. Soil bulk density was determined using cores (Internal diameter 5cm and depth 5cm). The soil samples were taken from 3-different spots in the same plot at varying depths with the help of a core sampler. Similarly, for hydraulic conductivity sampling, the same size cores were used. However, double ring infiltrometers were employed for *in- situ* infiltration measurement at 3-replicates in each plot. Modulus of rupture was evaluated at two different depths 0-7.5 and 7.5-15 cm of each treatment. The samples were taken using the iron cores. The 4- plots, each of size 2×2 m^2 were made in each imposed treatment combination. A known quantity of water was applied in a plot. After that plots were covered with polythene sheets. And later on, the drainage rate was computed.

Bulk density

The metallic core sampler of internal diameter 5cm and height of 5cm was taken and pushed manually and/or by using the jack system depending on soil hardness. Then the core was taken out with the help of a spade. The samples were taken in depth increments of 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm after the harvest of wheat crop from each plot.

Saturated hydraulic conductivity

Undisturbed soil samples in cores for different depths were obtained from selected sites to measure hydraulic conductivity with constant head permeater method (Klute, 1965).

In situ infiltration

The double ring infiltrometers method (Bertrand, 1965) was used to determine the infiltration at a place in the plot. The 3- sets of rings were fixed at a reasonable depth with the help of hammer and plate at different locations in the plot. The water was poured in the inner ring by keeping the polythene sheet at the base. After that, the observations were taken on the receding level of water in the inner ring with the help of hook gauge and foot scale. These observations on infiltration rate continued till constant steady state infiltration was obtained. This was achieved by giving suitable time interval in between two observations.

Drainage rate

After collection of soil samples from the relevant depth(s), the drainage rate was computed for each time period using the Ogata and Richards's equation (1957):

$$W = a\,(t)^{-b} \qquad \ldots(1)$$

Where, W is the water storage in cm; t is time in minutes; a, is the intercept and b, is the slope of the line.

Modulus of rupture

The modulus of rupture was determined as per the procedure described by Richard (1953). It was computed using the relationship

$$S = 3FL/2bd^2 \qquad \ldots(2)$$

Where, F is the breaking force applied at the centre of the briquette beam in dynes that equals weight of water used × 980; L is the distance between the two lower bars and support in cm; b is the width of the briquette in cm; d is the length of the briquette in cm. These parameters were actually measured in the field and then 'S' was calculated for each of the treatment.

Experimental Design

A randomized block design with four treatments was established:

- CTSR – Conventional tillage with straw removed
- CTSRT – Conventional tillage with straw retained
- MTSR – Minimum tillage with straw removed
- MTSRT – Minimum tillage with straw retained

Each treatment was replicated four times in plots measuring 14 × 11 m, separated by 1 m buffer strips. Rice straw was incorporated 20 days before wheat sowing.

Complete randomized design

The data was statistically analysed following the analysis of variance (ANOVA) technique by employing the Complete Randomized Design as per procedure of Gomez and Gomez (1984).

RESULTS AND DISCUSSION

Soil bulk density

Bulk density increased from 0-7.5 cm to 7.5-15 cm under all treatment combinations but decreased at 15-30 cm, except in the minimum tillage with straw retention (MTSRT) treatment (Fig. 1). The conventional tillage with straw removed (CTSRM) treatment exhibited the highest bulk density across most depths, with a maximum value of 1.86 Mg m^{-3} at 7.5-15 cm in 2004-05, which decreased to 1.58 Mg m^{-3} in 2005-06. The lowest bulk density was 1.44 Mg m^{-3} at 22.5-30 cm in CTSRM.

This increase in bulk density at 0-15 cm depth across treatments may be attributed to the formation of a compacted layer (plough pan). Similar findings were reported by Hobbs *et al.* (1994), who noted that puddling reduces soil aggregate size and promotes hardpan development. Wheel traffic during planting and harvesting also contributes to compaction, regardless of tillage system (Voorhees & Lindstrom, 1983).

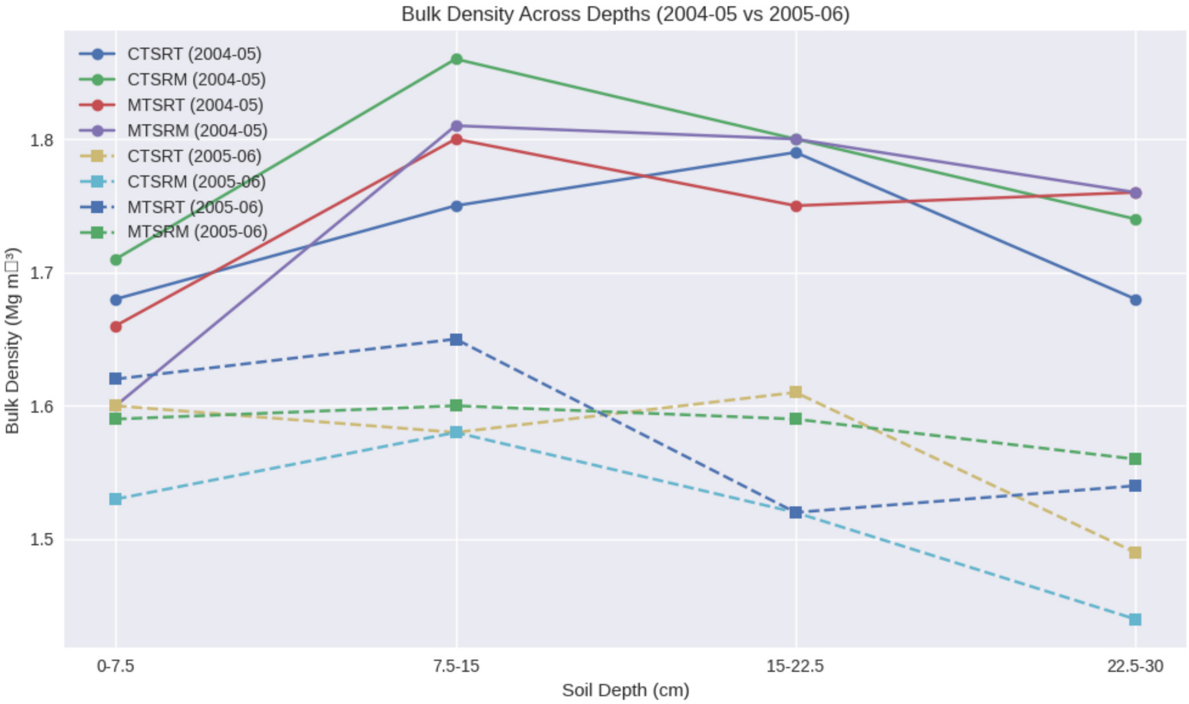

Fig. 1. Depth distribution of bulk density as affected by different treatments in 2004-05 versus 2005-06

Interestingly, puddling can either decrease or increase bulk density depending on soil structure. In poorly aggregated soils, puddling disperses particles and reduces bulk density, while in well-aggregated soils; it increases compaction (Bodman and Rubin, 1948; Ghildyal, 1978).

Depth distribution showed significant treatment effects. Bulk density tended to decrease in the surface layer (0-7.5 cm) and at 15-22.5 cm, except under MTSRM. In the surface layer, maximum bulk density was observed in MTSRT, while CTSRM recorded the lowest. At 7.5-15 cm, MTSRT again showed the highest values, whereas CTSRM/ MTSRT recorded the lowest. Across all treatments, bulk density generally decreased with depth.

Between 2004-05 and 2005-06, bulk density declined across all layers and treatments, likely due to increased organic carbon content, which improved soil aggregation. These results align with earlier studies (Aulakh *et al.*, 2001; Chang and Lindwall, 1989).

Overall, minimum tillage combined with straw retention (MTSRT) consistently reduced bulk density in the 0-15 cm layer compared to conventional tillage. This supports previous findings that residue incorporation improves aggregation and lowers compaction (Iqbal *et al.*, 2005; Singh *et al.*, 2007). Recent RWCS trials in north-west India confirm that conservation tillage reduces soil strength and enhances root proliferation, thereby improving wheat establishment under climatic stress (Chaudhary *et al.*, 2024). The observed decline in bulk density under MTSRT highlights the importance of residue-mediated organic matter inputs in maintaining soil structure, especially in sandy loam soils prone to compaction.

Hydraulic conductivity

Hydraulic conductivity as affected by tillage and residue management after wheat harvest is presented in Fig. 2. Within treatment combinations, residue management significantly influenced hydraulic conductivity. With increasing depth, conductivity generally increased compared to the 0-7.5 cm layer. However, in 2005-06, the lowest values were observed at 22.5-30 cm across treatments.

The expected trend of higher bulk density leading to lower hydraulic conductivity was not consistently observed. This inconsistency may be attributed to the relatively short duration of treatment imposition, as changes in soil physical attributes often require 6–7 years to stabilize (Sur *et al.*, 1981). Puddling, which is comparable to conventional tillage, alters pore size distribution by reducing macro-porosity and

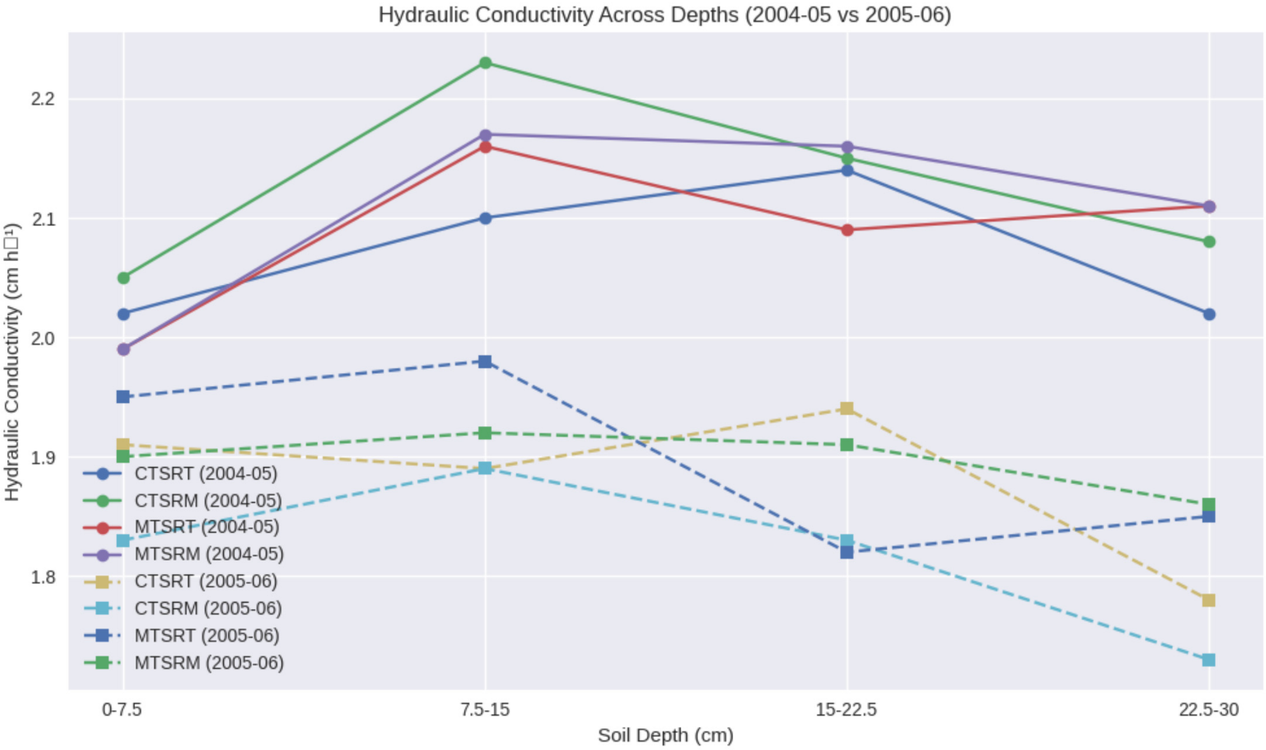

Fig. 2. Depth distribution of hydraulic conductivity as affected different treatments in 2004-05 versus 2005-06

increasing micro-porosity, thereby lowering conductivity (Aggarwal *et al.*, 1997). Conventional tillage after rice harvest typically decreases saturated hydraulic conductivity by destroying soil aggregates and eliminating transmission pores (Wickham and Singh, 1978; Bodman and Rubin, 1984). In puddled soils, particles align closely in vertical orientation, restricting water movement (Sharma and De Datta, 1985).

Hydraulic conductivity values were lowest at 22.5-30 cm depth under most treatments, except MTSRT. In the surface layer (0-7.5 cm), conductivity was highest under MTSRT in 2005-06. At 22.5-30 cm, maximum conductivity (1.86 cm h^{-1}) was recorded under MTSRM. These results indicate that MTSRT was superior in maintaining higher conductivity in the surface layer.

Overall, hydraulic conductivity decreased across all treatments from 2004-05 to 2005–06, reflecting the gradual nature of soil structural changes (Lal, 1989; Rhoton, 2000). Minimum tillage treatments, particularly with residue retention, consistently showed higher conductivity compared to conventional tillage. This supports earlier findings that puddling-induced hardpan formation reduces transmission pores (Tripathi *et al.*, 2003). Recent studies confirm that conservation tillage enhances pore continuity and water transmission, thereby reducing waterlogging risks in RWCS soils (Tripathi and Nayak, 2024).

Enhanced conductivity under MTSRT indicates improved water transmission and reduced risk of waterlogging, which is critical for wheat growth following rice. Residue retention not only moderates compaction but also sustains hydraulic properties essential for crop establishment.

Infiltration rate

The effects of different treatment combinations on infiltration are presented in Table 2.1 and 2.2 in years 2004-5 and 2005-6. The intercept parameter ('a') remained nearly constant across treatments (1.03-1.08), while the slope parameter ('n') followed the trend: MTSRT > MTSRM > CTSRT > CTSRM during 2004-05. Final infiltration values also reflected this order. The log I versus log T relationship showed the lowest intercept ('a' = 0.036) and the highest slope ('n' = 0.388) in the MTSRT treatment, with infiltration variation explained by 94.3% (Fig. 4).

Table 2.1. Infiltration equation parameters ($I=at^n$) as affected by different treatment combinations in 2004-05

Treatment	a	n	R^2	Final infiltration, cm
CTSRT	1.05	0.34	0.95	6.1
CTSRM	1.08	0.28	0.95	4.7
MTSRT	1.03	0.39	0.94	7.3
MTSRM	1.04	0.34	0.93	6.0

Table 2.2. Infiltration equation parameters ($I=at^n$) as affected by different treatment combinations in 2005-06

Treatment	a	n	R^2	Final infiltration, cm
CTSRT	1.03	0.37	0.95	6.6
CTSRM	1.00	0.33	0.95	5.4
MTSRT	1.06	0.36	0.94	6.4
MTSRM	1.02	0.34	0.96	5.7

In 2005-06, intercept values were slightly lower (1.02-1.06), while slope values ranged from 0.33-0.37, with R^2 values between 0.94-0.96 (Table 2.2). The CTSRT treatment recorded the highest final infiltration (6.6 cm), whereas CTSRM had the lowest (5.4 cm). The regression analysis confirmed that CTSRT was most effective in enhancing moisture movement through the soil profile.

The more pronounced decline in infiltration rate during 2004-05 compared to 2005-06 may have resulted from extensive surface cracking in rice fields, which facilitated rapid water entry (Sur *et al*., 1981; Singh *et al*., 2007). In residue-retained treatments, rapid initial absorption occurred due to the formation of a hanging water column, followed by gradual stabilization of infiltration rates.

Conservation tillage reduced evaporation losses by maintaining crop residue mulch. Lower bulk density in the surface layer and reduced soil crust formation enhanced infiltration and moisture retention (Dao, 1993). These findings are consistent with Ghuman and Sur (2001), who reported that residue management improves infiltration. More recent evidence confirms that residue retention enhances infiltration and water-use efficiency in RWCS soils under climate variability (Frontiers in Microbiology, 2023).

Overall, infiltration rates were significantly higher under minimum tillage with straw retention (MTSRT) compared to conventional tillage with straw removal (CTSRM). Improved infiltration under MTSRT ensures greater soil moisture availability during critical crop growth stages, thereby supporting higher yields and resilience under variable rainfall conditions.

Table 3. Soil moisture storage after 240 hours as affected by different treatment combinations in 2004-05

Treatment combination	Soil moisture storage in 180cm soil profile
CTSRM	13.7
CTSRT	14.3
MTSRM	12.5
MTSRT	15.3

Table 4. Soil moisture storage after 240 hours as affected by different treatment combinations in 2005-06

Treatment combination	Soil moisture storage in 180cm soil profile
CTSRM	11.3
CTSRT	13.7
MTSRM	14.2
MTSRT	15.1

Soil moisture storage after 240 hours

Soil moisture storage was highest in the MTSRT treatment, recording 15.3 cm in the 180 cm soil profile during 2004-05. In 2005-06, maximum storage (15.1 cm) was observed under MTSRM (Tables 3 and 4; Fig. 3). The lowest values were 12.5 cm in MTSRM (2004-05) and 11.3 cm in CTSRM (2005-06). Overall, minimum tillage with residue retention (MTSRT) consistently outperformed other treatments in retaining soil moisture, demonstrating its effectiveness in enhancing water storage capacity.

Residue retention improved soil porosity and aggregation, leading to greater infiltration and reduced evaporation losses. The MTSRT treatment stored 1.6 cm more water than CTSRT in 2004-05, and 4.1 cm more in 2005-06. These findings confirm that crop residue incorporation enhances soil water-holding capacity, consistent with earlier studies (Black and Siddoway, 1979; Singh *et al*., 2007).

Moisture storage trends varied with depth. Treatments MTSRM and CTSRM showed similar distributions, while MTSRT and CTSRT followed comparable patterns. Among all treatments, MTSRT retained the most water after 240 hours, likely due to improved residence time and enhanced aggregation (Aggarwal *et al*., 1997; Bhagat and Acharya, 1987). At 30 cm depth, MTSRM recorded the highest

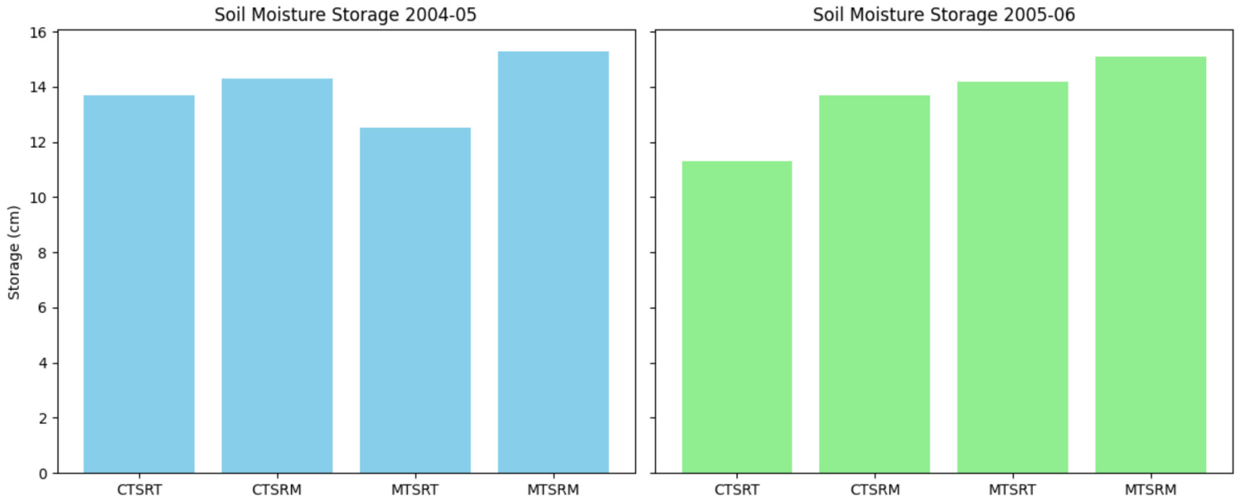

Fig. 3. Soil moisture storage in 180 soil profile up to 240 hours as affected by different treatments

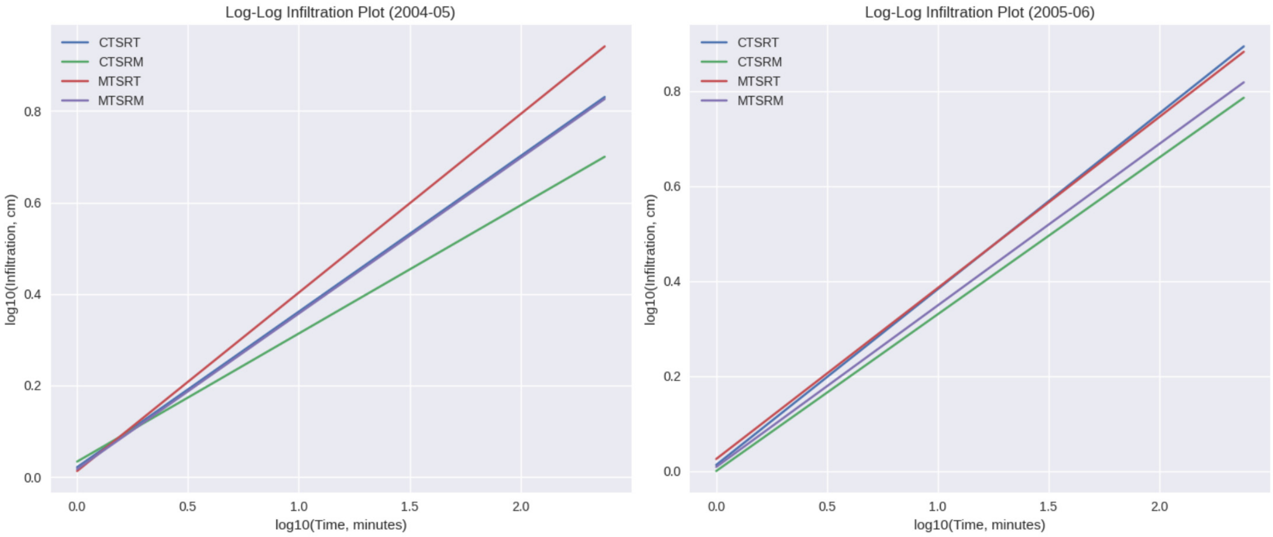

Fig. 4. Log of Infiltration (cm) as a function of log of time (minutes) as affected by conventional and minimum tillage imposed treatments in years 2004-5 and 2005-6

storage, followed by CTSRM, whereas CTSRM was least effective at 22.5 cm depth.

Residue retention improved soil structure by increasing organic carbon content and stabilizing aggregates. This enhanced porosity and permeability, thereby boosting water retention (Aggarwal *et al.*, 1997; Carter and Steward, 1996). Improved aggregation was also linked to microbial biomass and water-soluble carbohydrates, which positively influence infiltration and storage (Angers *et al.*, 1993a,b). The protective effect of crop residue mulch further supported moisture conservation (Lal, 1989; Ghuman and Sur, 2001).

Overall, the findings demonstrate that minimum tillage with residue retention (MTSRT) is the most effective practice for sustaining soil moisture storage in the rice–wheat system. By enhancing infiltration, reducing evaporation, and improving aggregation, MTSRT provides a clear advantage.

Modulus of rupture

The modulus of rupture values were significantly affected by tillage, straw management, and soil depth (Tables 13 and 14). However, the interactive effects of tillage × straw × depth were non-significant. Values were consistently higher under conventional tillage treatments compared to minimum tillage. With increasing depth, modulus of rupture values also increased, indicating greater soil strength in subsurface layers.

The CTSRT treatment recorded the highest values in both surface (8.2 × 10^{-4} KPa) and subsurface (8.4 × 10^{-4} KPa) layers, while MTSRT showed lower values (7.4 × 10^{-4} KPa in surface and 7.5 × 10^{-4} KPa in subsurface). Similarly, CTSRM exhibited higher rupture strength (7.6-7.7 × 10^{-4} KPa) compared to MTSRM (6.8–6.9 × 10^{-4} KPa).

Higher modulus of rupture values indicate stronger soil crusting and compaction, which can hinder seedling emergence, reduce root penetration, and ultimately lower grain yield .Previous studies have reported significant increases in penetration resistance from transplanting to harvest, adversely affecting moisture retention and crop establishment (Sharma *et al.*, 1988).

Residue retention under minimum tillage reduced soil strength, resulting in lower rupture values. This facilitated better seedling emergence and root growth, consistent with earlier findings that organic amendments reduce soil crust strength (Seker, 2003; Unger, 1982). The protective effect of crop residues improved soil friability, moderated compaction, and enhanced crop establishment.

Overall, MTSRT proved superior in moderating soil strength by lowering rupture values, thereby supporting sustainable wheat production. Reduced soil crusting under minimum tillage with residue retention ensures better seedling emergence, improved root penetration, and enhanced crop performance compared to conventional tillage treatments.

Drainage rate

The water storage as a function of time showed maximum variation under the CTSRT treatment (R^2 = 0.971), followed by CTSRM/MTSRM (R^2 = 0.937) and MTSRT (R^2 = 0.933)). Soil water drained most rapidly under CTSRM, as indicated by the steepest slope (b = –0.107), while drainage was slowest under MTSRT, with a gentler slope (b = –0.089) (Tables 5-12). This demonstrates that MTSRT was the most effective treatment for retaining moisture in the field. In 2005–06, similar trends were observed. Water drained quickly under MTSRM, with slope parameter b = –0.104, whereas MTSRT again showed slower drainage, confirming its superior moisture retention capacity.

Table 5. Depth distributed parameters of Ogata and Richards equation ($W=at^{-b}$) through conventional tilled Straw removed treatment in 2004-05

Depth, cm	a	b	R^2	Soil moisture storage after 240 hrs, cm
0-15	3.30×10^2	-0.0196	0.966	1.6
15-30	3.40×10^2	-0.0180	0.947	2.0
30-60	3.72×10^2	-0.0177	0.936	2.2
60-90	4.32×10^2	-0.0187	0.933	2.3
90-120	4.73×10^2	-0.0176	0.927	2.6
120-180	4.82×10^2	-0.0160	0.892	3.0
			Total	13.7

Table 6. Depth distributed parameters of Ogata and Richards equation ($W=at^{-b}$) through conventional tilled straw removed treatment in 2005-06

Depth, cm	a	b	R^2	Soil moisture storage after 240 hrs, cm
0-15	2.04×10^2	-0.0171	0.939	1.7
15-30	1.69×10^2	-0.0168	0.947	1.8
30-60	2.14×10^2	-0.0167	0.935	1.9
60-90	2.67×10^2	-0.0177	0.925	2.0
90-120	3.14×10^2	-0.0185	0.945	1.8
120-180	3.47×10^2	-0.0185	0.928	2.1
			Total	11.3

Table 7. Depth distributed parameters of Ogata and Richards equation ($W=at^{-b}$) through conventional tilled straw retained treatment in 2004-05

Depth, cm	a	b	R^2	Soil moisture storage after 240 hrs, cm
0-15	2.10×10^3	-0.0266	0.981	1.7
15-30	2.56×10^3	-0.0268	0.963	2.1
30-60	2.47×10^3	-0.0271	0.938	2
60-90	2.89×10^3	-0.0239	0.979	2.5
90-120	3.13×10^3	-0.0236	0.972	2.8
120-180	3.94×10^3	-0.0235	0.946	3.2
			Total	14.3

Table 8. Depth distributed parameters of Ogata and Richards equation ($W=at^{-b}$) through conventional tilled straw retained treatment in 2005-06

Depth, cm	a	b	R^2	Soil moisture storage after 240 hrs, cm
0-15	3.01×10^2	-0.0172	0.897	2.3
15-30	3.33×10^2	-0.0180	0.898	2.4
30-60	3.83×10^2	-0.0203	0.947	1.7
60-90	5.33×10^2	-0.0195	0.953	2.2
90-120	6.41×10^2	-0.0196	0.936	2.4
120-180	6.40×10^2	-0.0190	0.893	2.7
			Total	13.7

Table 9. Depth distributed parameters of Ogata and Richards equation ($W=at^{-b}$) through minimum tilled removed straw treatment in 2004-05

Depth, cm	a	b	R^2	Soil moisture storage after 240 hrs, cm
0-15	1.09×10^2	-0.015	0.938	1.6
15-30	1.35×10^2	-0.0152	0.921	1.8
30-60	1.48×10^2	-0.0144	0.927	2.0
60-90	1.77×10^2	-0.0144	0.916	2.2
90-120	1.64×10^2	-0.0135	0.889	2.3
120-180	1.88×10^2	-0.0134	0.850	2.6
			Total	12.5

Table 10. Depth distributed parameters of Ogata and Richards equation ($W=at^{-b}$) through minimum tilled straw removed treatment combination in 2005-06

Depth, cm	a	b	R^2	Soil moisture storage after 240 hrs, cm
0-15	6.02×10^2	-0.0174	0.901	2.9
15-30	7.49×10^2	-0.0213	0.928	1.9
30-60	7.20×10^2	-0.0207	0.937	2.2
60-90	10.22×10^2	-0.0198	0.938	2.8
90-120	10.85×10^2	-0.0192	0.924	3.1
120-180	10.43×10^2	-0.0190	0.858	3.2
			Total	15.1

Table 11. Depth distributed parameters of Ogata and Richards equation ($W=at^{-b}$) through minimum tilled straw retained treatment in 2004-05

Depth, cm	a	b	R^2	Soil moisture storage after 240 hrs, cm
0-15	8.45×10^2	-0.0197	0.975	2.5
15-30	6.72×10^2	-0.0204	0.921	2.3
30-60	1.35×10^3	-0.0194	0.991	2.7
60-90	1.15×10^3	-0.0213	0.961	2.4
90-120	1.86×10^3	-0.0196	0.994	3
120-180	1.99×10^3	-0.0245	0.903	2.4
			Total	15.3

Table 12. Depth distributed parameters of Ogata and Richards equation ($W=at^{-b}$) through minimum tilled straw retained treatment in 2005-06

Depth, cm	a	b	R^2	Soil moisture storage after 240 hrs, cm
0-15	1.21×10^3	-0.026	0.981	1.3
15-30	2.72×10^3	-0.0209	0.926	2.2
30-60	1.68×10^3	-0.0266	0.993	1.4
60-90	1.19×10^3	-0.0186	0.997	3.2
90-120	2.18×10^3	-0.0217	0.958	3.1
120-180	4.65×10^3	-0.0159	0.870	3
			Total	14.2

Table 13. Modulus of rupture (Kpa × 10^{-4}) as affected by different treatment combinations and depths in 2004-05

Treatment combination	Depth, cm	
	0-7.5	7.5-15
CTSRT	8.8	9.0
CTSRM	8.3	8.4
MTSRT	7.8	8.1
MTSRM	7.4	7.5
CD (0.05)	Tillage	0.628
	Straw	0.421
	Depth	0.676
	Tillage × Straw	NS
	Tillage × Straw × Depth	NS

Table 14. Modulus of rupture (Kpa × 10^{-4}) as affected by different treatment combinations and depths in 2005-06

Treatment combination	Depth, cm	
	0-7.5	7.5-15
CTSRT	8.25	8.38
CTSRM	7.66	7.77
MTSRT	7.36	7.50
MTSRM	6.78	6.89
CD (0.05)	Tillage	0.715
	Straw	0.496
	Depth	0.083
	Tillage × Straw	NS
	Tillage × Straw × Depth	NS

These findings highlight the contrasting effects of tillage and residue management on soil water dynamics. Conventional tillage with straw removal accelerates drainage due to reduced aggregation and pore continuity, while minimum tillage with residue retention slows drainage by enhancing soil structure, increasing organic matter, and stabilizing aggregates. Improved aggregation under MTSRT increases meso-pores and micro-pores, which hold water longer and reduce rapid losses.

Overall, MTSRT proved to be the most effective treatment for conserving soil moisture by moderating drainage rates. By slowing water loss, it ensures greater availability of moisture for wheat growth following rice, thereby supporting sustainable productivity in the rice-wheat cropping system.

Overall ranking of treatments

The overall ranking of treatments with respect to hydraulic performance and mechanical strength is presented in Table 15. The overall best treatment is CTSRT2004-05 that combines strong infiltration and better soil moisture storage with high soil strength. However, high soil strength is otherwise

Table 15. Overall ranking of treatments (best → worst), combining both hydraulic performance parameter (*soil* moisture storage) and mechanical strength (modulus of rupture)

Rank	Treatment & Year	Hydraulic Performance	Soil Moisture Storage	Mechanical Strength	Overall Notes
1	CTSRT 2004–05	Very high *a* (2.1–3.9×10^3)	14.3 cm	Strong (8.8–9.0)	Best balance of infiltration + strength
2	MTSRT 2004–05	High *a* (8.4×10^2–1.9×10^3)	15.3 cm (highest)	Moderate (7.8–8.1)	Excellent hydraulics, slightly weaker strength
3	MTSRT 2005–06	Very high *a* (1.2–4.6×10^3)	14.2 cm	Moderate) (7.4–7.5	Strong hydraulics, moderate strength
4	CTSRT 2005–06	Moderate *a* (3.0–6.4×10^2)	13.7 cm	Strong (8.3–8.4)	Strength-focused, hydraulics moderate
5	MTSRM 2005–06	Moderate *a* (6.0–10.8×10^2)	15.1 cm	Weak (6.8–6.9)	Good hydraulics, poor strength
6	CTSRM 2004–05	Moderate *a* (3.3–4.8×10^2)	13.7 cm	Moderate (8.3–8.4)	Balanced but not outstanding
7	CTSRM 2005–06	Lower *a* (1.7–3.5×10^2)	11.3 cm (lowest)	Moderate (7.7–7.8)	Weak hydraulics, average strength
8	MTSRM 2004–05	Low *a* (1.1–1.9×10^2)	12.5 cm	Weak (7.4–7.5)	Weakest overall

detrimental to deep root penetration and root growth. Similarly, in terms of highest water storage and infiltration capacity and better hydraulic leaders are MTSR treatment in both years 2004-05 and 2005-06. The strongest mechanical soil mechanical stability in terms of soil strength indicators is CTSRT treatments. However, the overall weakest in low infiltration and poor soil strength is MTSRM. In other terms, poor soil strength is beneficial better root growth and deep penetration of plant roots

Grain yield of Wheat

Across all treatments and both study years, the wheat grain yields ranged from 3.7 to 4.1 t ha^{-1}. While specific yield values for each individual treatment are visualized in Figure 5, the text indicates that yields generally reflected the improvements or degradations in soil physical properties caused by the tillage regimes.

Higher modulus of rupture values (indicative of soil crusting and compaction) observed in certain treatments were noted to potentially lower grain yield by hindering seedling emergence and root penetration.

Howver, the discussion links the productivity results shown in Fig. 5 to the underlying soil physical conditions.The variation in wheat yield is attributed to the effects of tillage and residue management on soil structure. Specifically, minimum tillage with residue retention (MTSRT) was identified as the most effective practice for sustaining productivity. The lower soil strength (modulus of rupture) under MTSRT facilitated better seedling emergence and root proliferation compared to conventional tillage.This improved establishment is a key driver for the stable yields observed in conservation-based treatments. In addition , by enhancing infiltration and slowing drainage rates, MTSRT ensured greater soil moisture availability during critical growth stages, which supported higher yields and resilience under variable conditions. Whereas In contrast, conventional tillage with straw removal (CTSRM) resulted in higher bulk density, stronger soil crusting, and faster drainage. These factors negatively affected crop establishment and soil quality, explaining the lower performance in these treatment groups.

CONCLUSION

The study demonstrated that tillage and residue management practices significantly influence soil physical properties and wheat productivity in the rice-wheat cropping system of the Indo-Gangetic Plains. Minimum tillage combined with straw retention (MTSRT) consistently improved soil structure by reducing bulk density, enhancing hydraulic conductivity, increasing infiltration, moderating soil strength, and retaining greater soil moisture compared to conventional puddling practices. However, conventional tillage with straw removal (CTSRM) resulted in higher bulk density,

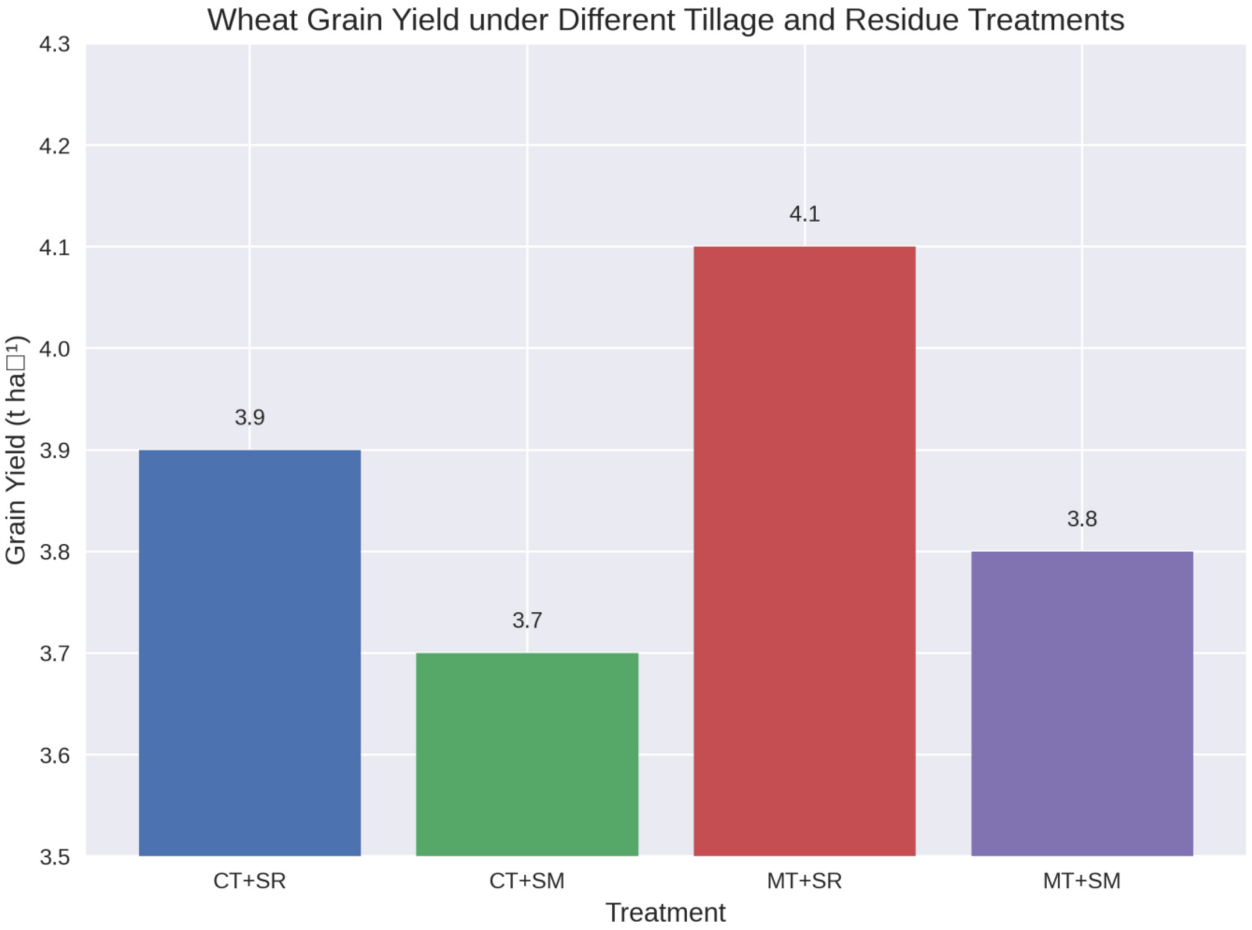

Fig. 5. Grain yield of wheat as affected by different tillage and residue treatments

reduced infiltration, stronger soil crusting, and faster drainage, all of which negatively affected soil quality and crop establishment. In contrast, residue retention under minimum tillage improved aggregation, porosity, and water-use efficiency, thereby sustaining soil health and productivity.

Overall, the findings confirm that minimum tillage with residue retention (MTSRT) is the most effective management practice for maintaining soil physical quality and ensuring long-term sustainability of the rice–wheat system. Adoption of conservation tillage practices with residue incorporation can mitigate soil degradation, enhance resource-use efficiency, and support stable wheat yields under climatic variability in north-west India.

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