Physical and Chemical Properties of a Sandy Loam Soil Under Irrigated Rice-Wheat Sequence in the Indo-Gangetic Plains of South Asia

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Abstract

Resource conservation technologies (RCTs) such as zero tillage (ZT), dry direct seeded rice (DSR) and crop residues as mulch are known to increase productivity and profitability of rice-wheat system (RWS) in South Asia. There are, however, few studies on assessing the effect of RCTs on physical and chemical properties of soil under RWS.

A field experiment on a sandy loam soil was conducted on RWS for two years at Modipuram, India involving six treatment combinations of three tillage and crop establishment methods in rice, (i) conventional puddled transplanted rice (CT-PTR), (ii) conventional dry tillage followed by direct seeding of rice (CT-DSR), and (iii) zero tillage followed by direct seeding of rice (ZT-DSR), and two green manuring options (with and without intercropping of *Sesbania aculeata*, -S or +S). In the succeeding wheat, rice residue (RR) was retained in sesbania green manure treatments and it was removed from no sesbania plots. Wheat was direct sown after ZT (DSW) in all the plots. Substituting PTR/DSW without crop residues with ZT-DSR/DSW plus residue cycling reduced electrical conductivity from 0.146 dS m^{-1} to 0.128 dS m^{-1} and increased soil organic C from 5.72 g kg^{-1} to 6.25 g kg^{-1} in 0-15 cm layer. Similarly, water-stable aggregates (WSAs) >0.25 mm were 28% higher and their mean weight diameter increased by 11.9% in ZT-DSR/DSW plus residues compared to PTR/DSW without crop residues plots. On average, there was a 23.6% increase in large (4.75-8.00 mm) aggregates and a reduction of 15.8% in finer (0.106–0.25 mm) aggregates in residue retention treatments over the no-residue treatments. In plots without puddling (ZT-DSR), the infiltration rates were higher (2.97-3.34 mmh^{-1}) than in the CT-PTR (2.41-2.62 mmh^{-1}). Residue retention compared to residue removal not only increased available K contents from 110.5 to 129.2 kg ha^{-1} but also showed favorable effects on soil matric potential and soil temperature during the wheat season. These beneficial effects on soil quality in just two years after introducing conservation tillage and residue management practices demonstrate potential to improve the long-term productivity and profitability of the RWS. However, the increased rate of infiltration under ZT with residue retention needs new irrigation techniques to minimize the loss of water through percolation during rice season.

Keywords: Direct-seeded rice; Zero tillage; Crop residue management; Soil physical properties; Soil chemical properties; Puddled transplanted rice; Crop residue; Wheat

Introduction

The rice (*Oryza sativa* L.) wheat (*Triticum aestivum* L.) system (RWS) is the major annual crop rotation covering about 13.5 million ha in South Asia with a major fraction (78%) in the Indo-Gangetic Plains (IGP) of India [1]. It is one of the most important crop rotations for food self-security in India, contributing about 40% of the country's total food grains. Rice and wheat crops differ in response to tillage due to differences in their optimum growing conditions. Puddling is the most common practice of rice establishment to prepare the seedbed, control weeds and reduce water infiltration rate in rice fields [2]. The traditional practice of growing rice (puddled transplanting, PTR) and wheat (conventional till, CT) each involving four to six tillage operations widely practiced by farmers in South Asia is highly input- and energy-intensive [3-6]. Puddling in rice is known to cause subsoil compaction (traffic pan), destroys soil structure in surface soil, and lowers permeability in the subsurface layer, resulting in restricted root penetration, poor soil nutrient-moisture-crop root interactions, and low productivity of the following wheat crop [7-10]. A traffic pan is, however, important to preserve surface water in rain fed and irrigated rice on permeable soils with a low groundwater table [11].

Limited practices of using organic manure, legume, and green manure based cropping patterns have led to depletion of SOM content in soils under RWS [12]. The depletion of SOC and N can be managed by including an N-fixing green manure (e.g., *Sesbania aculeata*) in the crop rotation, which can fix N in the range of 60-120 kg N ha^{-1} in 50-60 days [12]. However, in high intensive cropping systems, the situation may not induce the farmers to set apart six to eight weeks exclusively for a green manure with small direct benefits because N fertilizer (urea) is highly subsidized [12]. Requirement of sufficient irrigation for raising a green manure crop also stands in the way. Under these situations, green manure crops can be grown as an intercrop in both direct seeded rice (DSR) as well as transplanted crop. Sesbania as "brown manuring" can be practiced to control weeds, increase soil N supply on decomposition

of live mulch and crop yields in DSR [13]. Studies showed that grain yield of DSR with sesbania brown manuring was generally higher than without brown manuring [13,14].

In addition, burning/removal of crop residues, which is widely practiced in the rice-wheat system, not only adversely affects soil organic matter reserves and nutrient flows but also pollutes the environment [8,15]. The use of crop residues and ZT may be the most promising way to improve the soil quality and sustain/ improve crop production in RWS.

The ZT without straw retention generally increases the risk of yield loss [16]; thus, it should be applied in combination with crop straw retention if high yield is targeted [17]. Field experiments with ZT in wheat at several locations in the Indo-Gangetic plains have shown encouraging results in terms of increase in yield (due to more timely sowing of wheat) and profitability due to reduced cultivation costs, build-up of SOC in the surface soil and improvement in soil physical conditions [1,4,18,19]. Demonstrated that omission of puddling in DSR improved physical soil properties such as bulk density, penetration resistance, aggregation stability and cracking behavior, average mean weight diameter and water stable aggregates in rain fed rice [20]. Literature review by suggested that for exploiting the advantages of conservation agriculture (CA) on crop production, site-specific CA practices should be applied in different crops according to the annual air temperature and precipitation [21]. Therefore, a better understanding of the impact of tillage and residue management systems on soil physical properties, soil temperature and soil water availability is necessary for the further development of conservation tillage practice to improve crop yields under RWS in different soils and agro-ecological conditions in the IGP of India.

Management practices that are known to enhance resource-use efficiency and crop productivity with lower environmental footprints are crucial to enhancing the sustainability of an intensive cropping system such as rice-wheat in South Asia [22-24]. Over the past couple of decades, resource-conserving tillage (e.g., zero tillage, ZT) along with complementary crop establishment (CE) methods (e.g., dry direct seeding of rice, DSR) and crop residue recycling (e.g., mulching) have received increasing attention to (i) improve crop productivity, (ii) improve soil health, (iii) reduce the cost of production, and (iv) maintain or improve air quality [1,3,4,9]. In a comprehensive multi-location study, large benefits in crop productivity, economics, resource use, and global warming intensity have been reported [22]. As the conservation tillage practices have been reported to improve soil quality in non-rice-based cropping systems [25], they could also be a solution of poorly managed soil condition in RWS of northwestern India. Although conservation agriculture (CA) based practices have been evaluated in wheat, precise information on rice is still lacking [4]. The effects of puddling on soil properties depend on texture and type of clay mineral, structure, organic matter content, and sesquioxide content, and cultivation is done under variable conditions of climate (air temperature and precipitation), soils and management [11]. In addition, past studies have largely ignored the role of tillage and residue in the RWS, and systematic studies to monitor changes in soil quality parameters are lacking. This study was therefore, designed to evaluate the effect of CA based management practices (ZT, DSR, residue management and brown manuring) on key soil quality parameters in a RWS in northwestern India.

Materials and Methods

Experimental site

A field experiment was conducted for two cycles of rice-wheat sequence in 2005-06 and 2006-07 on a sandy loam soil on the research farm (29°4' N and 77°46' E, 237 m above mean sea level) of the Indian Institute of Farming Systems Research (IIFSR), Modipuram, India. The climate of the area is semi-arid, subtropical, characterized by very hot summers and cold winters. The hottest months are May and June, when maximum temperature reaches 45–46°C, whereas, during December and January, the coldest months of the year, the temperature often goes below 5°C. The average annual rainfall is 863 mm, 75-80% of which is received through the northwest monsoon during July-September. There was no large variation in air temperature, sunshine hours and rainfall during the wheat season during the two years of the study, but rainfall during the rice season in 2005 was higher (815 mm) than in 2006 (449 mm).

According to initial samples collected in 2005, the soil (0–15 cm) is Taxonomically classified as Inceptisol (Typic Ustocrept), alluvial soils developed under warm soil temperature regime and ustic soil moisture regime with 620, 205, and 165 g kg^{-1} sand, silt, and clay content, respectively [26,27]. It had pH 8.1(1:2, soil: water ratio), electrical conductivity (EC) 0.40 dS m^{-1}, 8.3 g organic C kg^{-1} [28], 0.88 g total N kg^{-1} (Kjeldahl digestion), 0.36 cmol Olsen-P kg^{-1} (0.5 M NaHCO$_3$ extractable) and 1.38 cmol 1 M NH$_4$OAc-extractable K kg^{-1} [29,30].

Experimental details and management

The experiment was laid out in a randomized complete block design with six treatments involving combinations of three tillage and crop establishment treatments (i) conventional puddling (wet tillage) followed by transplanting of rice (CT-TPR), (ii) conventional dry tillage followed by direct seeding of rice (CT-DSR), and (iii) zero tillage followed by direct seeding of rice (ZT-DSR) and two treatments of sesbania (*Sesbania aculeata*) as green manure (intercropped with rice, +S in T2, T4 and T6, and not intercropped, −S in T1, T3 and T5). Land preparation for CT-TPR included pre-puddling dry tillage (two cross harrowing and two passes of tyne plough) and puddling was done twice in 8-10 cm of standing water using a tractor-mounted disc harrow followed by planking. Land preparation for CT-DSR included two harrowing (12-15 cm depth) and two passes of tyne plough (12-15 cm depth) followed by planking. The DSR, both CT and ZT, was planted using a seed-cum-fertilizer planter.

After rice, zero till wheat was directly sown (ZT-DSW) in all plots. In −S treatments (T1, T3 and T5) rice residue was removed (−RR) but retained (+RR) in +S treatments (T2, T4 and T6) in wheat. Wheat residue was removed (−WR; T1, T3 and T5), but incorporated (15 cm stubbles) with puddling or dry tillage (+WR; T2 and T4), or left on the soil surface (+WR; T6). The treatments were replicated three times. The plot size was 6 m wide and 20 m long (120 m²). The treatment details with tillage and residue management operations are given in Table 1. The treatments were repeated in the same plots for two years.

Crop residue and *sesbania aculeata* management

Rice was harvested manually after leaving 30 cm anchored crop stubbles in residue-retained plots and after threshing loose residue uniformly spread back before wheat seeding in treatments T2, T4 and T6. Rice residue amounted to about 8 Mg ha^{-1} (dry weight basis, averaged across all treatments) at harvest. On the other hand, in the rice residue removal plots (T1, T3 and T5), the crop was harvested from the ground level (at 2-3-cm height). The wheat crop was harvested at 15 cm height in residue retention plots (T2, T4 and T6) adding about 2.25 Mg ha^{-1} of stubbles and rest of the wheat straw was removed. Although wheat stubble was retained on the soil surface in rice ZT plots (T6), they were incorporated into the soil in the CT-PTR (T2) and CT-DSR

Treatment no	Crop	Tillage method	Crop establishment method	Sesbania as an intercrop in rice	Crop residue removed or retained	Abbreviation
T1	Rice	Conventional till (two-disc harrowing+two-cultivator) or puddling (two-disc harrowing + laddering) (CT)	Transplanting of rice (TPR)	No sesbania (–S)	Wheat residue; Crop harvested from the ground (at 2-3 cm) and removed (–WR)	CT-TPR (–S,–WR)
	Wheat	Zero till (ZT)	Direct-/drill-seeded wheat (DSW)	-	Rice residue removed (–RR)	ZT-DSW (–RR)
T2	Rice	CT (puddling) as in T1	TPR	Sesbania intercropped for 30 days. (+S)	Wheat residue (15-cm anchored stubbles incorporated during puddling (+WR)	CT-TPR (+S,+WR)
	Wheat	ZT	DSW (Turbo Happy Seeder*)	-	Rice residue retained as mulch in wheat (+RR)	ZT-DSW (+RR)
T3	Rice	CT (dry tillage; two-disc harrowing+two-cultivator+planking)	Direct-/drill-seeded rice (DSR)	–S	–WR	CT-DSR (–S,–WR)
	Wheat	ZT	Same as in T2	-	–RR	ZT-DSW (–RR)
T4	Rice	CT (dry tillage) as in T3	DSR (drill)	+S	Wheat residue (15-cm anchored stubbles incorporated during dry tillage (+WR)	CT-DSR (+S,+WR)
	Wheat	ZT	Same as in T2	-	Rice residue retained as mulch in wheat (+RR)	ZT-DSW (+RR)
T5	Rice	ZT	DSR	–S	–WR	ZT-DSR (–S,–WR)
	Wheat	ZT	Same as in T2	-	–RR	ZT-DSW (–RR)
T6	Rice	ZT	DSR	+S	Wheat residue (15-cm anchored stubbles retained on soil surface (+WR)	ZT-DSR (+S,+WR)
	Wheat	ZT	Same as in T2	-	Rice residue retained as mulch in wheat (+RR)	ZT-DSW (+RR)

*The Turbo Happy Seeder is a power-operated machine that is capable of placing seed and fertilizer in a single operation by managing any crop residue (up to 10 t ha−1) just in front of the seed and fertilizer tines.

Table 1: Description of treatments used in the study.

(T4) plots. In residue removal plots (T1, T3 and T5), the wheat crop was harvested at ground level and residue was not returned to the plots.

In T2, T4 and T6, seeds of *Sesbania aculeata* (50 kg ha^{-1}) were broadcasted immediately after the transplanting or seeding of DSR and were raised for 30 days as an intercrop with rice followed by knocking it down using 2, 4-D herbicide and leaving it on the soil surface. Sesbania at 30 days had an average of 1 Mg ha^{-1} of dry biomass.

Seeding and seed rate

Rice (PHB-71) was transplanted manually in T1 and T2 in the last week of June in both the years, and direct drill-seeded in T3–T6 using a ZT seed and fertilizer planter in the first week of June in both the years. The seed nursery for transplanting was raised the same day as that of direct seeding to maintain the same date of seeding in all treatments. The seeding rate for raising the nursery for transplanted rice was 15 kg ha^{-1}, and was 25 kg ha^{-1} for direct seeding. Wheat (PBW 343 at the rate of 100 kg ha^{-1}) was sown in the first week of November in all plots.

Water application and management

In puddled transplanted rice (T1 and T2), the plots were flooded (70 mm of irrigation water) initially for 2 weeks to establish the seedlings, and subsequent irrigations (70 mm of irrigation water) were applied when the soil matric potential (using a tensiometer) decreased to about −20 kPa in the 15-18 cm soil layer. To the direct-seeded rice (T3–T6), light irrigations (50 mm of irrigation water) were given at a day after seeding and then at 4-day to 5-day intervals for 3 weeks after germination, followed by subsequent irrigations (70 mm of irrigation water) when the soil matric potential decreased to about −20 kPa in the 15-18 cm soil layer.

To wheat, five irrigations (60 mm each) were applied at crown root initiation (21 days after seeding, DAS), maximum tillering (35–50 DAS), flowering (50–70 DAS), dough (85–100 DAS), and late dough (115–125 DAS) stages in all the treatments.

Fertilizer application

In rice, all plots received 150 kg N (as di-ammonium phosphate and urea)+26 kg P (as di-ammonium phosphate)+50 kg K (as muriate of potash) + 8.75 kg Zn (as $ZnSO_4$) ha^{-1}. Full doses of P and K and a one-fourth dose of N were applied using a zero-tillage seeder with fertilizer drill planter at the time of seeding in DSR, and these were broadcast manually at the time of transplanting in TPR. The remaining N was applied in three equal splits at 35 to 40, 45 to 50, and 60 to 70 DAS, respectively. Zinc was broadcast at seeding in DSR and at transplanting in PTR plots. In wheat, all treatments received 120 kg N+26 kg P+50 kg K ha^{-1}; the whole of P and K and one-half of N were applied using a zero-tillage seeder with fertilizer drill at sowing. The remaining one-half of N was applied in two equal splits at just before first irrigation (CRI) and second irrigation (tillering), respectively.

Weed management

Weeds in ZT-DSR and ZT-DSW plots before the seeding were killed by spraying glyphosate at 900 g a.i. ha^{-1}. In DSR (CT/ZT) plots, pendimethalin (1000 g a.i. ha^{-1}) was applied at 2 DAS, followed by one post-emergence spray of 2,4-D ester (500 g a.i. ha^{-1}) at 30 DAS to knock down sesbania and broadleaf weeds. In CT-TPR, butachlor (1000 g a.i. ha^{-1}) was applied 2 days after transplanting (DAT). One hand weeding was also done in TPR and DSR (CT/ZT) to keep the plots weed-free. In wheat, grassy and broadleaf weeds were controlled

by spraying sulfosulfuron+metsulfuron methyl at 35 g a.i. + 4 g a.i. ha^{-1} at 25 to 30 DAS.

Soil sampling and measurement of soil properties

Soil chemical properties: Soil cores (7.6 cm in diameter) in triplicate from each plot were obtained from 0–15- to 15–30 cm soil depths after the wheat harvest in April 2007 (2 years after the initiation of the field experiment). The soil subsamples from each depth of each plot were then mixed to form one composite sample and air-dried. Roots and litter were removed from the soil samples before air drying. Subsamples from all the plots were ground to pass through a 2-mm sieve, and stored in plastic jars for analysis. The soil samples were analyzed for organic C [28], 0.5 MNaHCO$_3$-extractable P [29], and 1 N neutral NH$_4$OAC-extractable K by emission spectrophotometry [30].

Soil physical properties: Soil samples for the determination of soil physical parameters were collected after the wheat harvest in April 2007. Soil parameters, such as bulk density (D$_b$), aggregate size distribution, mean weight diameter (MWD) of aggregates, soil penetration resistance (SPR), and steady-state infiltration, were determined. Other soil properties measured were soil thermal regime during the rice and wheat seasons and soil matric potential during the wheat season.

Soil aggregate analysis: Duplicate undisturbed soil subsamples (0-15-cm depth) were collected with the help of a spade, air-dried, and passed through 8 mm and 4.75 mm sieves, by gently breaking apart the clods. Samples retained on 4.75 mm sieves were used for analysis and clods, aggregates, and residues >8 mm in diameter were discarded. The air-dried samples were placed in plastic bags, stored at ambient temperature, and transferred to the laboratory for analysis. Aggregate size distribution of the soil was determined by the wet-sieving method using a Yoder apparatus, as described by Kemper et al. [31]. The air-dried soil sample (50 g) was placed on a 4.75 mm sieve and submerged in water on a nest of six sieves (4.75, 2.0, 1.0, 0.5, 0.25, and 0.106 mm) for 10 minutes before the start of wet-sieving action. The sieve nest was then clamped and secured to the drum. The sieve assembly was oscillated up-down by a pulley arrangement for 20 min at a frequency of 30–35 cycles/min with a stroke length of 4 cm in salt-free water inside the drum. The water-stable aggregates (WSA) retained on the sieves were collected carefully by gentle washing using a washing bottle into pre-weighed containers, oven-dried at 105°C for 48 h, and weighed. The water-stable aggregates were expressed as percentage aggregation (aggregates >0.25 mm in size), mean weight diameter, and size distribution. The MWD of aggregates was calculated as:

$$MWD = \Sigma \, xi \, wi,$$

Where wi is the proportion of each aggregate class in relation to the bulk soil and xi the mean diameter of the aggregate class (mm) [31].

Infiltration rate: Double-ring infiltrometers were used to measure the infiltration rate of water into the soil by recording the amount of water needed to maintain a constant level in the inner ring as a function of time [32]. The infiltrometers were pushed into the soil to 10 cm depth. Infiltration measurements were made at two separate randomly selected points in each plot and a constant water level (20 cm) was maintained in both the rings of the infiltrometer. Measurements were continued until a steady-state infiltration rate was achieved. Infiltration measurements were made at two separate randomly selected points in each plot.

Bulk density and soil penetration resistance: The soil bulk density was determined by collecting soil cores at 0-5-, 6-10-, 11-15-, and 16-20 cm depth, and using 3 cm-long and 5 cm-diam metal cores by placing the core in the middle of each soil layer at the same time as the soil resistance was measured [33]. Bulk density was obtained from the gravimetric weights of the cores after oven drying, and from core volume.

Soil penetration resistance was determined to a maximum depth of 45 cm of soil at every 5 cm depth interval when the profile moisture content was near field capacity using a manual cone penetrometer (Eijkelkamp Agrisearch Equipment). The soil moisture percent variance was less than 5% at soil penetration resistance measurement and it was 15.85-16.39, 16.42-16.94, 14.07-14.55 and 14.38-14.91% at 0-5, 6-10, 11-15 and 16-20 cm, respectively. The cone had a 30° apex angle and base of the cone had 1-cm^2 surface area. Simultaneously, soil samples from the same depths were also collected for gravimetric soil moisture determination.

Soil temperature: Soil temperature at 5 cm depth was measured daily at 0700 h (minimum) and 1500 h (maximum) during both the rice and wheat seasons using a digital soil thermometer (HI 93510 Thermistor thermometer, Hanna Instruments, Inc., USA). Since the soil temperature trends in different treatments during the two seasons were not different, weekly temperatures averaged over two years for rice and wheat were calculated.

Soil matric potential: Soil matric potential during crop growth was measured by Jet-fill gauge-type tensiometers (Eijkelkamp Agrisearch Equipment). The tensiometers with ceramic cups were installed vertically, in a hand-augered hole, to a depth of 0.18 m after establishment of the wheat crop. Tensiometer readings were monitored daily in the morning during the crop season, but, for simplicity, weekly averaged data are presented and discussed.

Statistical analysis

The data were subjected to analysis of variance (ANOVA) and analyzed using the general linear model (GLM) procedures of the statistical analysis system [34]. Treatment means were compared by Tukey's honest significant difference (HSD) test. Unless stated otherwise, differences were considered significant only when P<0.05. The crop residue mean effects were separated by factor of -residue (T1, T3 and T5) and +residue (T2, T4 and T6) treatments and compared by HSD.

Results and Discussion

Soil fertility parameters

Of the soil fertility parameters monitored, only EC, organic C, and NH$_4$Ac K were influenced by various tillage and residue treatments, and the effects were restricted to the 0-15 cm soil layer (Table 2). Soil pH (varying from 7.72 to 7.80 in both soil layers) and Olsen-P (varying from 14.7 to 14.9 kg ha^{-1} in 0-15 cm and from 10.4 to 11.6 kg ha^{-1} in 15-30 cm) remained unchanged (data not shown) in all the treatments. In contrast, most of other studies have found that the pH of the topsoil was lower for ZT than for CT [25,35]. The greater SOM accumulation in the topsoil with ZT led to acidity from decomposition (largely due to the organic acid and CO$_2$) [35,36]. It has also been proposed that greater leaching under ZT was responsible for the higher removal of bases, which led to a lowering of pH [37,38]. The rather small effects on soil pH were associated with the shorter duration of our study. On the other hand, it is also likely that pH did not change because of improved buffering under ZT, especially where residue is mulched [38]. Thus, tillage may not directly affect soil pH but its effects on pH will depend

[a] Treatment	EC (dS m^{-1})	Organic carbon (g kg^{-1})	NH_4O Ac extractable K (kg ha^{-1})	Aggregate size distribution (%)		
				8.00–4.75 (mm)	4.00–2.00 (mm)	0.106–0.25 (mm)
T1	0.146a	5.72b	110.5b	9.5b	8.4b	22.13
T2	0.124b	5.88b	126.2a	10.6b	10.1ab	16.93
T3	0.127b	5.78b	111.3b	9.2b	10.7ab	20.47
T4	0.127b	5.97ab	125.4a	10.5b	11.1ab	20.13
T5	0.134ab	5.78b	109.4b	11.3b	10.9ab	20.67
T6	0.128b	6.25a	129.2a	16.0a	12.5a	16.20
No residue	0.135a	5.76b	110.4b	10.0b	10.0a	21.09a
Residue	0.126b	6.03a	126.9a	12.4a	11.2a	17.76b
Source	Analysis of variance (ANOVA)					
Replication	0.042	NS	NS	NS	NS	NS
Treatment	0.002	0.001	<0.001	<0.001	0.048	NS
Residue	0.002	<0.001	<0.001	<0.001	NS	0.027

Table 2: Effect of different tillage/crop establishment and residue retention on soil electrical conductivity (EC), organic carbon, ammonium acetate extractable K, and aggregate size distribution (%) in 0-15 cm layer at wheat harvest after two cycles of rice-wheat cropping.

on the prevailing climatic condition, soil type and management factors (e.g., depth of placement of fertilizers). Consistent with our study, [39] reported that EC and pH were not affected by the tillage practices.

Likewise, the low amount of total P (10-12 kg P ha^{-1}) recycled through crop residues was not enough to show a detectable change in Olsen-P after two years. Consistent with our results, [39] found no increases in the soil P levels in the surface layer in ZT and straw incorporation treatments compared to CT with no straw, possibly because the amounts of P in the residues were low compared with the total levels in the soil and some of the residue P may have fixed by clay minerals in the alkaline soil. Controversial results have been observed for tillage and residue management effects on soil P availability. While, Jiang et al. [40] and Hu et al. [41] reported that residue retention increased the total P content, Wang et al. [42] found a decrease in the total P content at the 0- to 0.10 m depth after 11 years of residue retention.

The EC in T1 with soil puddling without residue in rice [CT-TPR (‑S, ‑WR)] was, on average, higher by 13.35% than in other treatments (except T5). Organic C, on the other hand, was higher by 7.94% in T6 than in other treatments (T2, T3 and T5) except T4. Overall, residue mulch had positive effects on EC, which decreased by 6.6% and on organic C and NH_4-AC K, which increased by 4.7% and 15.0%, respectively (Table 2). Normally, greater percolation of water because of the high infiltration rate with residue mulch is responsible for the higher removal of bases, leading to a lowering of EC in sandy loam soil [43]. However, reported that EC was not affected by the tillage practices in maize-based rotation, where amount of irrigation water input was much lower than that in our study with RWS [39].

Increases in C concentrations, especially in surface soil, in response to ZT and residue mulch are known [44-46]. From a literature review, showed that in 40 of 78 cases, the SOC content was higher in ZT compared to CT; in 7 cases it was lower and in 31 of the cases there was no significant difference [47]. Higher mineralization rate could be implicated for reduction in organic C and total N under CT plot due to soil structure deterioration following tillage. Zero tillage reduces breakdown of macro-aggregates where C is sequestered [48,49]. Therefore, the higher C in T6 (ZT-DSR+S, +WR/ZT-DSW+RR) in this study is consistent with published reports. However, these differences in C concentration disappeared when calculated on a total content basis because of the reduction in bulk density in T6 (data not shown). Found that tillage impacts on changes in SOC were larger in tropical moist and tropical dry compared to temperate moist and temperate dry climates [50].

Unlike P, treatments showed significant effect on NH4-Ac K content in soil. Irrespective of tillage and crop establishment, all the treatments in which residue was mulched increased NH4-Ac K. The treatments without residue (T1, T3 and T5) and those with residue (T2, T4 and T6) did not differ among themselves. Crop residues are rich sources of K and its major fraction is released within a short time after their application to the soil [51].

Soil physical parameters

Soil bulk density (D_b): The effect of tillage, CE, and residue management on D_b was significant at all depths (Figure 1). Generally, irrespective of treatments, D_b increased with an increase in depth. At the 0‑5-cm and 6‑10-cm soil depths, D_b was higher in T5 (ZT-DSR (‑S,‑WR)/ZT-DSW (‑RR)) than in T2 (CT-PTR (+S,+WR)/ZT-DSW (+RR)), whereas it was not significantly different from the rest of the treatments except T4 (CT-DSR (+S,+WR)/ZT-DSW (+RR)) at 6‑10 cm depth (Figure 1). The difference in D_b between CT-DSR and ZT-DSR was not significant at 0‑5 cm and 6‑10 cm soil depths, whereas, at both 11‑15 cm and 16‑20 cm soil depths, T3 and T4 had 4‑5% higher D_b than T5 and T6 (Figure 1). Several studies have reported higher D_b under ZT at the soil surface compared with tilled soil [49,52,53]. Our results are in variance with the findings of other researchers who showed lower Db with ZT and residue retention than with CT in top layers, particularly in fine-textured soils, which is attributed to the development of an organic-rich mulch and possibly enhanced faunal activity, and no difference or higher Db in CT in the deeper layers [54-57]. The presence of crop residues over the soil surface prevents aggregate breakdown by direct raindrop impact as well as by rapid wetting and drying of soils. There are also reports showing slight or no differences in D_b values between CT and ZT in the surface soil layers [58-60]. At 11–15-cm and 16–20-cm depths, D_b was significantly higher in T1, T2, T3 and T4 than in ZT-DSR (T5 and T6). Compared to initial values, D_b at lower depths generally increased in CT-PTR (T1 and T2) and CT-DSR (T3 and T4) plots. A plow pan may be formed by puddling/tillage immediately underneath the tilled soil, causing higher D_b in this horizon in tilled conditions. Sharma [8], Yang et al. [54], Tripathi et al. [61] reported that puddling is known to increase D_b in soil immediately below the plow layer due to (i) destruction of soil aggregates The greater Db in 15-30 cm layer of the CT treatment indicates the development of a compacted "hard pan" beneath tillage depth, caused by the compacting and shearing action of tillage implements [7,54,62]; (ii) filling of macro-pores with finer soil particles, which ultimately reduces the porosity; and (iii) direct physical compaction caused by implements. Puddling provides favorable conditions for soil compaction and reducing
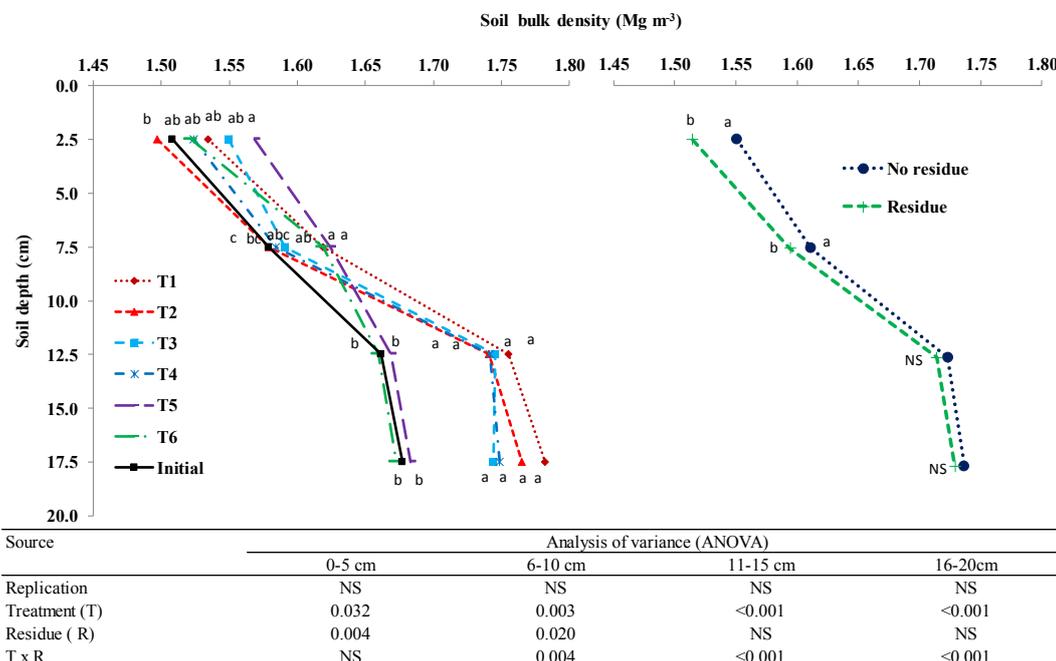
Figure 1: Effect of different tillage/crop establishment and residue retention on soil bulk density at wheat harvest after two cycles of rice-wheat cropping. T1, CT-PTR (–S,–WR)/ZT-DSW (–RR); T2, CT-PTR (+S,+WR)/ZT-DSW (+RR); T3, CT-DSR (–S,–WR)/ZT-DSW (–RR); T4, CT-DSR (+S,+WR)/ZT-DSW (+RR); T5, ZT-DSR (–S,–WR)/ZT-DSW (–RR); T6, ZT-DSR (+S,+WR)/ZT-DSW (+RR). Within a horizontal, means followed by the same letter are not significantly different at $P \leq 0.05$. NS stands for non-significant [6].

percolation losses, which decreases with a decrease in moisture content [53].

Overall, D_b in the no-residue (T1, T3 and T5) plots was significantly greater than in plots with residue retention (T2, T4 and T6). Reported lower D_b with residue incorporation than with either residue burning or residue removal, particularly in the 0–5 cm layer [63,64].

Soil aggregation: Treatment 6 (ZT-DSR (+S+WR)/ZT-DSW (+RR)) attained significantly higher water-stable macro-aggregates (8.0–4.75 mm and 4.0–2.0 mm size) than those of the rest of the treatments (T1–T5). Aggregates of less than 1.0 mm in size, though, tend to be in greater proportion with puddling or dry tillage, and there were no significant differences among treatments. This confirms that avoiding tillage favors macro-aggregation by either binding the micro-aggregates or protecting them against destruction, or both [9,53,65]. ZT increases soil aggregation by reducing soil disturbance and increasing soil organic matter, and possibly the growth of fungi that bind soil particles and micro-aggregates together [66]. Pooled over tillage and CE treatments, residue retention increased the proportion of larger aggregates (8.0–4.75 mm) by about 24.0% (Table 2). ZT without residue mulch (T5) was not sufficient to improve structural stability probably because of a lack of organic carbon input. Zhang et al. [67] reported that zero tillage with residue mulching had the lowest proportion of smaller WSA (<0.83 mm diam) and greatest proportion of larger (>12.7 mm diam) aggregates, compared to corresponding aggregates in conventional tillage without residue, indicating improvement in soil structure when tillage was omitted and crop residues were retained [68].

Likewise, T6 without tillage and residue mulch exhibited the greatest proportion of >0.25 mm-size aggregates, whereas T1 and T3 with tillage and no residue resulted in the lowest proportion of >0.25 mm-size aggregates (Figure 2). The beneficial influence of T6 was also

reflected in its mean weight diameter (MWD) of aggregates, which was significantly higher than that of other treatments (Figure 2). The effect of tillage and crop residue on WSA with an increase in MWD from wet sieving has been reported for a wide variety of soils and agro-ecological conditions [46,48,53,69]. Since organic matter is a key factor in soil aggregation, the management of previous crop residues is important to soil structural development and stability. In our study, the increase in SOC with ZT and residue retention would support higher soil aggregation in ZT with residue. Under ZT conditions in northern China, 5 years of residue mulching increased the topsoil water-stable aggregate (≥ 0.25 mm) by 104.5%, and increased the topsoil SOM content by 31.4 % compared with soils without mulching [70].

Singh et al. [63] reported an increase in the aggregate stability and MWD of aggregates with residue amendment due to an increase in SOC after 5 years of rice-wheat cropping on a sandy loam soil. Small changes in SOC can influence the stability of macro-aggregates.

Soil penetration resistance: Soil penetration resistance (SPR) was significantly influenced by tillage, CE methods, and residue management up to 25 cm depth, except at 15 cm depth (Figure 3). Irrespective of treatment, SPR increased with the increase in depth up to 20 cm. In surface soil (5 cm depth), SPR was significantly higher in T5 [ZT-DSR (–S, –WR)/ZT-DSW (–RR)] compared to the other treatments. At 10-cm depth, SPR was significantly lower in T4 (CT-DSR (+S, +R)/ZT-DSW (+RR)) than in T5 (ZT-DSR (–S, WR)/ZT-DSW (–RR)), whereas the rest of the treatments did not differ from either T4 or T5. This differs from the results of [71], who reported lower SPR in ZT than in CT in the surface (0–15 cm) layer. The changes in SPR also depend on the method of residue management (incorporation vs. surface mulch). Although several researchers have reported a decrease in SPR due to straw incorporation in the surface layer, a similar trend was observed in our study when residue was
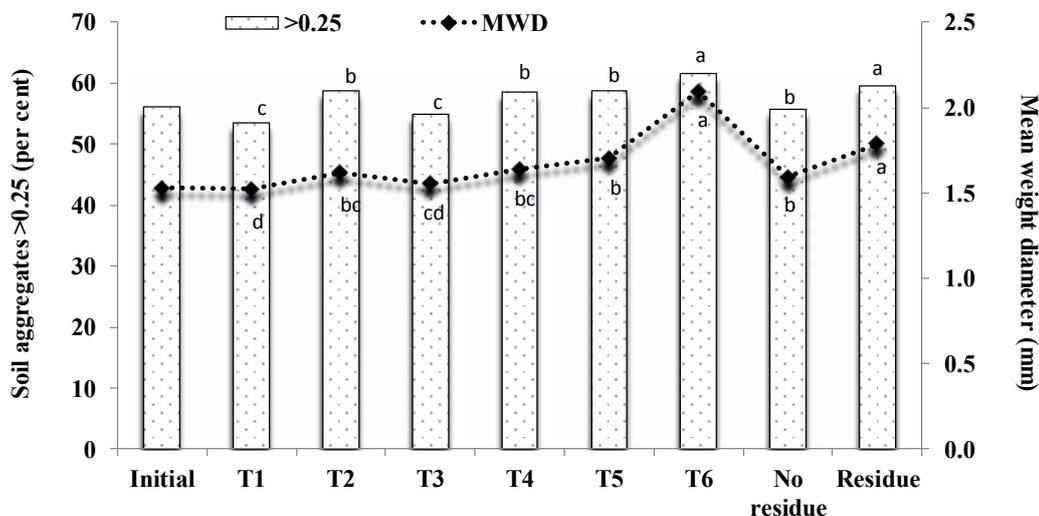
Source	Analysis of variance (ANOVA)	
Replication	NS	NS
Treatment (T)	<0.001	<0.001
Residue (R)	<0.001	<0.001
R x T	<0.001	<0.001

Figure 2: Effect of different tillage/crop establishment and residue retention on soil aggregates (>0.25 mm) and mean weight diameter (mm) at wheat harvest after two crop cycles of rice-wheat cropping. T1, CT-PTR (–S,–WR)/ZT-DSW (–RR); T2, CT-PTR (+S,+WR)/ZT-DSW (+RR); T3, CT-DSR (–S,–WR)/ZT-DSW (–RR); T4, CT-DSR (+S,+WR)/ZT-DSW (+RR); T5, ZT-DSR (–S,–WR)/ZT-DSW (–RR); T6, ZT-DSR (+S,+WR)/ZT-DSW (+RR). Within a horizontal, means followed by the same letter are not significantly different at $P \leq 0.05$. NS stands for non-significant [10].
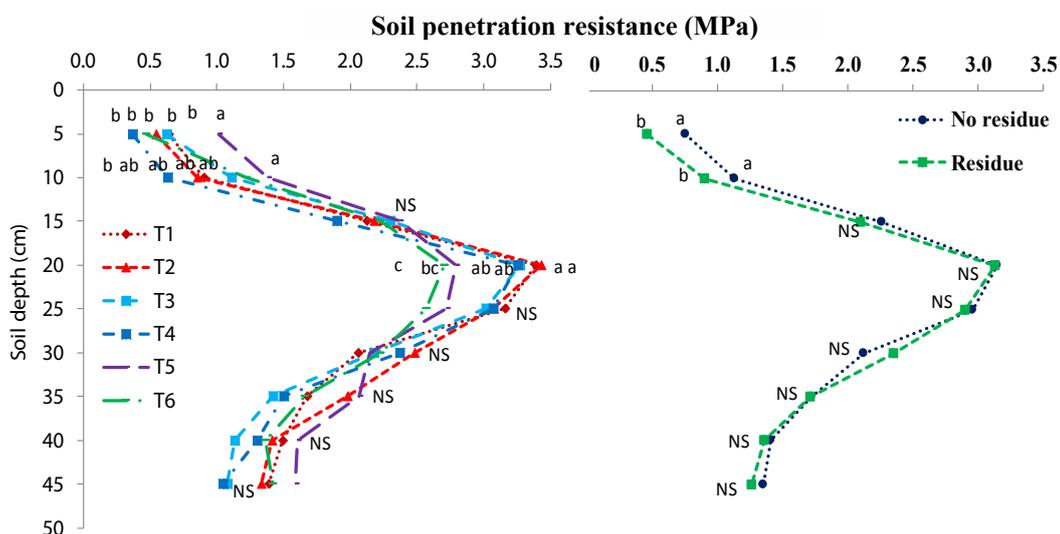
Source	Analysis of variance (ANOVA)								
	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm	45 cm
Replication	NS	NS	NS	NS	NS	0.001	0.004	NS	NS
Treatment (T)	0.002	0.008	NS	0.002	NS	NS	NS	NS	NS
Residue (R)	0.001	0.032	NS	NS	NS	NS	NS	NS	NS
T x R	0.018	0.010	NS	0.001	NS	NS	0.010	NS	NS

Figure 3: Effect of different tillage/crop establishment and residue retention on soil penetration resistance at wheat harvest after two cycles of rice-wheat cropping. T1, CT-PTR (–S,–WR)/ZT-DSW (–RR); T2, CT-PTR (+S,+WR)/ZT-DSW (+RR); T3, CT-DSR (–S,–WR)/ZT-DSW (–RR); T4, CT-DSR (+S,+WR)/ZT-DSW (+RR); T5, ZT-DSR (–S,–WR)/ZT-DSW (–RR); T6, ZT-DSR (+S,+WR)/ZT-DSW (+RR). Within a horizontal, means followed by the same letter are not significantly different at $P \leq 0.05$. NS stands for non-significant [23].

retained at the surface under ZT at 5.0 cm soil depth. SPR in T1, T2, T3 and T4 at 20 cm depth was significantly different from that in the T5 and T6 [6,71], (T3 and T4) (Figure 3). At 20 cm depth, SPR was about 0.62 MPa lower in T5 and T6 than in T1 and T2. Beyond 30 cm depth, however, different treatments did not influence SPR. SPR is directly related to D_b and inversely related to soil water content [72]. Also in our case, higher SPR below tillage depth (especially in the 15- to 25 cm soil layers) under puddling (T1 and T2) was associated with higher D_b, as soil water content was similar in different treatments at the time of SPR measurements. Published studies corroborate these results that SPR remains higher under puddling than under ZT [9,53,73] reported that ZT and residue management had a positive effect on soil physical parameters, notably soil aggregation, D_b, SPR, and infiltration rate. In medium-textured soils, the critical mechanical impedance for wheat root development is around 1.75 to 2.00 MPa [74]. In our study, SPR in the 10–30 cm layers was greater than the critical value (1.75 MPa) for wheat root development under all the treatments.

Infiltration rate (IR): The steady-state IR measured at wheat harvest was significantly affected by different treatments (Figure 4). It was consistently higher with an average of 3.1 mm h^{-1} in DSR (T3-T6) compared with an average value of 2.7 mm h^{-1} in TPR (T1-T2). Puddling in T1 and T2 decreased IR directly by destroying soil aggregates, increasing D_b, and causing subsoil compaction (as discussed in preceding sections). Our results support earlier findings [9,53], which also reported higher steady-state IR under ZT than in CT on different soil types. Other studies have found higher infiltration rates under ZT than CT because of the presence of fast draining macro-pores created in ZT plots and increased large (>2 mm) aggregate stability [75,76].

However, in a Gray Luvisol, found that the steady-state infiltration rate was not significantly affected by tillage and residue management [77].

Reported that ZT resulted in higher IR (initial as well as steady state) where residue was retained than where residue was removed [71,78]. In our study, the pooled average result shows that residue retention had significantly higher IR than the residue removal treatment. This is probably due to the more stable aggregates resulting from improved soil porosity and water retention in ZT with residue
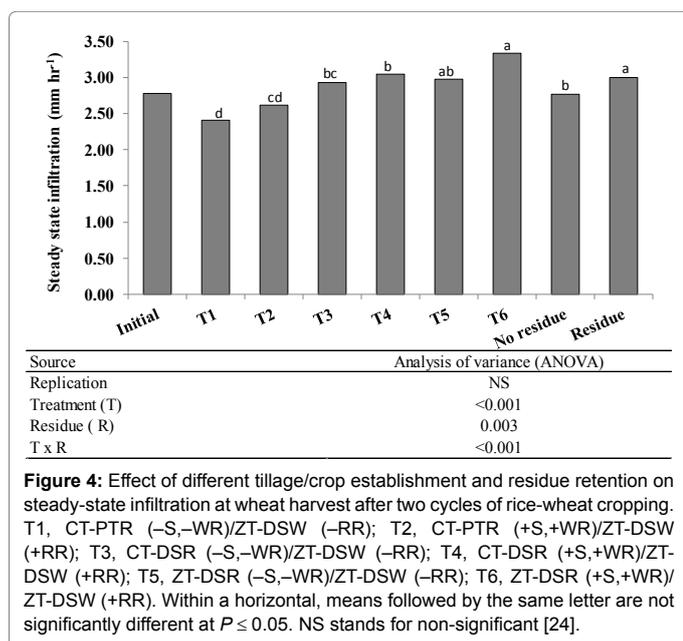
retention than in CT and ZT without residue [46,69]. The higher rate of infiltration in ZT with residue retention treatment compared to TPR may not be desirable in rice when using flood irrigation because of high percolation losses of water. The solution to such a problem lies in the use of soil matric potential based irrigation approach and sub-surface drip irrigation method in RWS reported similar infiltration rates for CT and ZT plots, probably due to the similarity of soil physical properties in the upper layer [59,79]. However, when water infiltrated into deeper soil layers, ZT plots showed significantly higher infiltration rates than the ZT plots. Consequently, final (steady state) infiltration rate for ZT plots were 4-times that of the CT plots (4.25 mm min^{-1}).

Soil matric potential (SMP): There was no significant effect of tillage and CE on SMP in both rice and wheat; hence, a combined analysis was done to examine the effects of sesbania and residue retention. SMP at 15-18-cm soil depth was not affected by residue mulch treatment in rice during the initial 11 weeks after sowing (Figure 5a). Residue mulch increased SMP by 2–6 MPa compared with no residue 12 to 14 weeks after rice planting. The effect of residue mulch on SMP in wheat was significant (*P*<0.05). SMP was higher by 3 to 8 MPa (average of 5.7 MPa) with residue than without residue throughout the 14-week period after the sowing of wheat (Figure 5b). The effect of mulch on SMP was stronger during the early growth period than in the latter part of the season. This is expected because the mulch had a greater effect in conserving soil moisture during the initial growth period in comparison with the latter part of the crop season. Decomposition of rice residue over time and the application of a first post-sowing irrigation (75 mm) at 3–4 weeks after sowing possibly decreased the positive effect
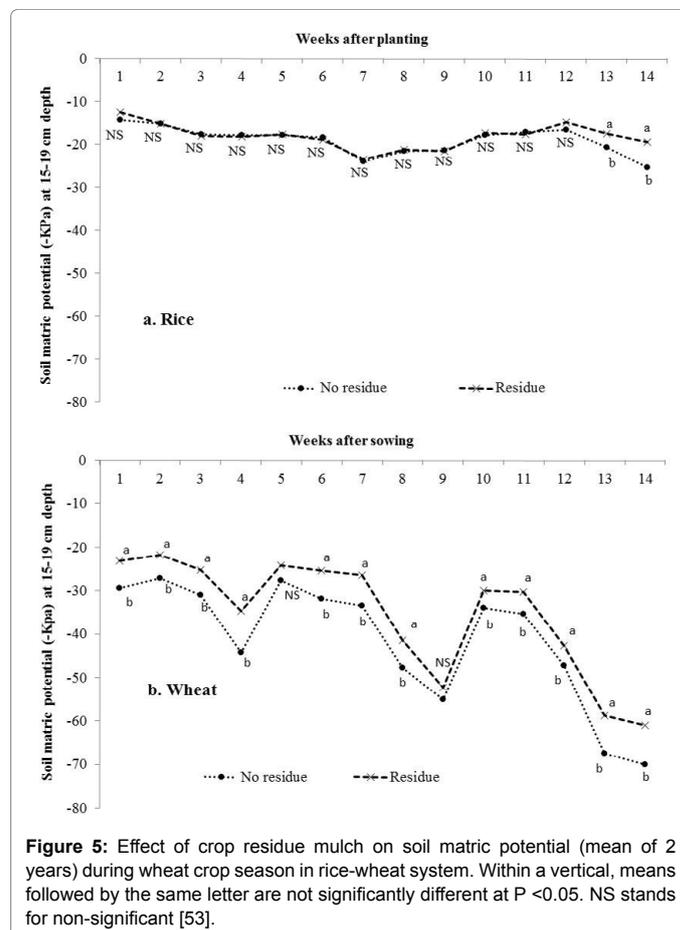

Figure 4: Effect of different tillage/crop establishment and residue retention on steady-state infiltration at wheat harvest after two cycles of rice-wheat cropping. T1, CT-PTR (–S,–WR)/ZT-DSW (–RR); T2, CT-PTR (+S,+WR)/ZT-DSW (+RR); T3, CT-DSR (–S,–WR)/ZT-DSW (–RR); T4, CT-DSR (+S,+WR)/ZT-DSW (+RR); T5, ZT-DSR (–S,–WR)/ZT-DSW (–RR); T6, ZT-DSR (+S,+WR)/ZT-DSW (+RR). Within a horizontal, means followed by the same letter are not significantly different at *P* ≤ 0.05. NS stands for non-significant [24].

Figure 5: Effect of crop residue mulch on soil matric potential (mean of 2 years) during wheat crop season in rice-wheat system. Within a vertical, means followed by the same letter are not significantly different at P <0.05. NS stands for non-significant [53].

of residue retention on SMP. Earlier reports have shown higher water holding capacity or moisture content in the topsoil (0–10 cm) under ZT and straw mulching than after ploughing/puddling [55,80-82]. Soil management practices that increase the soil organic matter content could have a positive impact on the soil water holding capacity [83]. Therefore, replacement of traditional tillage with conservation tillage will improve soil water storage and increase water use efficiency [84].

Soil thermal regime: Tillage and CE had no effect on soil thermal regimes in both crops and years. Hence, the time trends of two-year averages showing residue effects for rice and wheat are shown in Figures 6 and 7, respectively. Both minimum and maximum soil temperatures were significantly lowers by 0.4-0.8°C and 1.4-1.8°C, respectively, with residue vis-à-vis without residue during early (3 weeks) rice establishment (Figure 6). No such effect of residue mulching was noted thereafter until 11 weeks after planting, except that minimum soil temperature was 0.5°C higher during week 11 in the residue treatment. In contrast to reported observations of lower temperatures in ZT with straw mulch compared to the CT system [53], no such effect was observed in our study on irrigated rice. This was perhaps due to the lower mass of residue (1-1.5 t ha^{-1}) retained in rice coupled with high soil moisture conditions maintained during the rice growth season in comparison to other upland crops.

Soil temperature at 0700 h and at 1500 h during the wheat season varied between 8.1 and 18.5°C and 15.5 and 23.1°C, respectively (Figure 7). During the initial 6 weeks after sowing of wheat, the minimum temperature was 1.12 to 2.21°C higher with residue than without residue, and thereafter the soil temperature remained similar until week 8. The trend was reversed between the two treatments during weeks 9 to 11 when the minimum soil temperature was 1.74°C lower with residue (Figure 7). The maximum soil temperature was always lower with residue than without residue. Early in the crop cycle (4 weeks after seeding), maximum temperatures were 2.2 to 2.8°C lower with residue
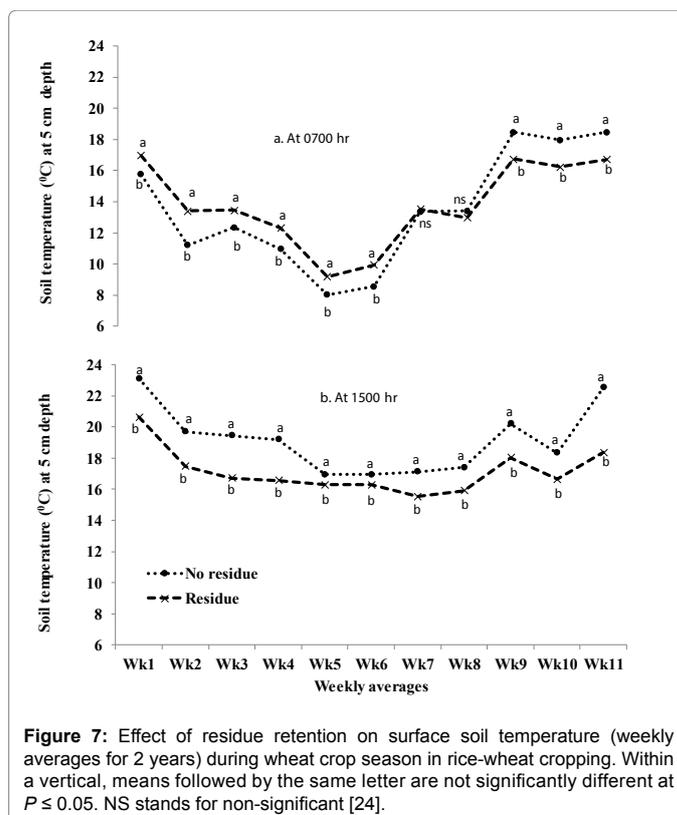

Figure 6: Effect of residue retention on surface soil temperature (weekly averages for 2 years) during rice crop season in rice-wheat cropping. Within a vertical, means followed by the same letter are not significantly different at P≤0.05. NS stands for non-significant [23].
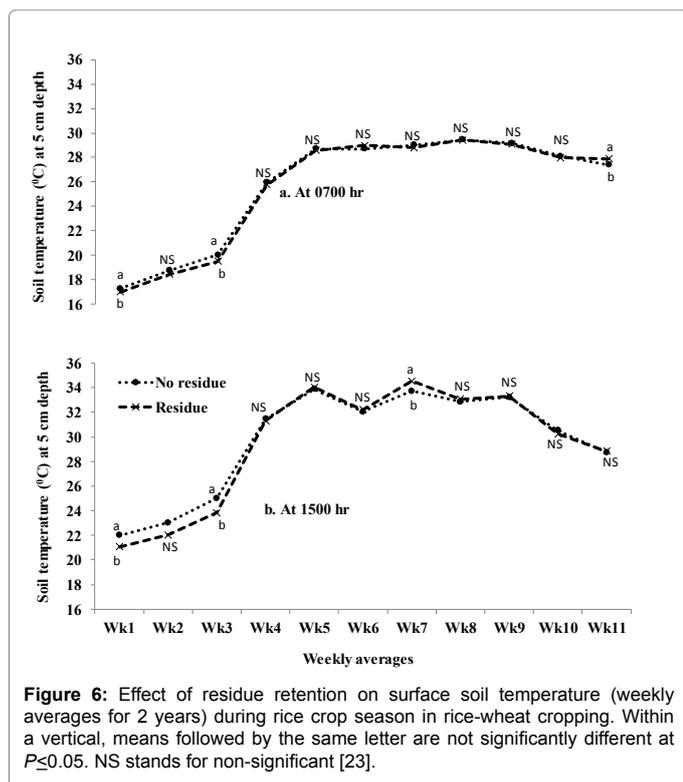

Figure 7: Effect of residue retention on surface soil temperature (weekly averages for 2 years) during wheat crop season in rice-wheat cropping. Within a vertical, means followed by the same letter are not significantly different at P ≤ 0.05. NS stands for non-significant [24].

than without residue (Figure 7). Residue mulch decreased maximum soil temperatures by 1.7 to 4.2°C during the latter part of the cropping season (weeks 9 to 11). Similar increases in minimum temperature and decreases in maximum temperature with residue mulch, particularly at the beginning of the crop cycle, have been reported [19,80,81,85]. Our data, which are more comprehensive than previously published data, clearly show that residue mulch modifies the soil temperature and provides an optimum soil thermal regime with lower fluctuations for better crop growth and development.

Conclusion

Our results from a rice-wheat rotation demonstrated that avoiding puddling and dry tillage, and adopting brown manuring in rice followed by zero till (ZT) wheat with residue retention improved soil structural stability, soil infiltration, soil penetration resistance, soil thermal regime, and soil organic C. These improvements were significant in the surface 0-15 cm layer, but the differences were small at the 15-30 cm depth. The residue mulch provides an optimum soil thermal regime, allowing better seedling emergence and subsequent rooting. The improvements in soil physical properties and water infiltration under ZT with residue retention have profound implications for crop production in rice-wheat system in the northwestern India, which is presently experiencing soil degradation and decreasing water availability. However, from a sustainable development perspective, long-term studies are needed on the impact of alternate tillage and crop establishment, and residue management practices on crop productivity, soil properties, and accompanying factors such as greenhouse gas emissions in different soil types and climatic conditions.

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