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Effect of Different Tillage and Residue Management Options on Soil Water Transmission and Mechanical Behavior

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Abstract: Understanding the variability in the mechanical and hydrological soil characteristics resulting from diverse tillage and residue management practices is essential for evaluating the adoption of conservation strategies to preserve soil's physical well-being. Zero-tillage techniques combined with residue retention or incorporation have gained widespread recognition for their capacity to conserve soil and water resources, reduce energy consumption, and enhance soil quality and environmental sustainability. Nevertheless, the choice of tillage and residue management options may vary depending on the geographical locations and specific soil conditions. To assess the impacts of four distinct tillage and residue management approaches, a two-year experiment (2020–2021 and 2021–2022) was conducted: T1: conventional tillage followed by wheat sowing after the removal of rice straw (CT-RS); T2: zero tillage with wheat sowing using a Happy Seeder while retaining rice straw (ZT+RS); T3: conventional tillage followed by wheat sowing after rice straw incorporation using a reversible mouldboard plough (CT+RS); T4: minimum tillage with wheat sowing using a Super Seeder with rice straw incorporation (MT+RS); the effects were recorded on the physical soil properties. Our findings indicate that zero tillage combined with residue retention (T2) had a positive influence on various physical soil attributes. Notably, significant differences were observed among the tillage and residue management options, particularly in terms of the bulk density with T1 exhibiting the highest values and the lowest being in T2, whereas the soil penetration resistance was lowest in T3 compared to T1. In the case of T3, sandy loam and clay loam soils had the highest measured saturated hydraulic conductivity values, measuring 5.08 and 4.57 cm h^{-1} and 4.07 and 3.73 cm h^{-1}, respectively. Furthermore, T2 (zero tillage with residue retention) demonstrated the highest mean weight diameter (MWD) and maximum water stable aggregate. These results collectively underscore the positive effects of adopting zero tillage and retaining residue (T2) on soil structure and quality, particularly concerning the mechanical and hydrological soil properties.

Keywords: soil structure; penetration resistance; bulk density; moisture content; residuemanagement; soil water transmission

Citation: Singh, V.; Gupta, R.K.; Kahlon, M.S.; Toor, A.S.; Singh, K.B.; Al-Ansari, N.; Mattar, M.A. Effect of Different Tillage and Residue Management Options on Soil Water Transmission and Mechanical Behavior. *Land* **2023**, *12*, 1895. https://doi.org/10.3390/land12101895

Academic Editors: Ognjen Žurovec, Nani Raut and Sabrija Čadro

Received: 23 August 2023
Revised: 28 September 2023
Accepted: 30 September 2023
Published: 9 October 2023

1. Introduction

Soil characteristics, environmental quality, and crop productivity are significantly influenced by tillage and residue management [1]. While tillage is an age-old practice, often considered as beneficial for plant growth, extreme and unnecessary ploughing with no residue retention can harm the soil physical characteristics, lower the concentration of organic carbon in soil (SOC), and reduce crop productivity [2]. As a result, there is a focus on adopting conservation tillage with residue retention or incorporation to enhance soil quality, reduce soil erosion risks, and increase soil organic matter (OM), soil structure, water storage capacity, infiltration rate, biodiversity, ecosystem stability and energy use efficiency [3,4]. A significant cropping pattern in the Indo-Gangetic Plains of South Asia is the rice-wheat cropping system (RWCS). It is practised on 10.0 million hectares (Mha) and is essential for the region's food security [5]. In Punjab, wheat was cultivated over 3.52 Mha during 2018–19, while rice occupied an area of 3.14 Mha during 2019–20 [6]. RWCS has made a significant contribution to India's becoming self-sufficient in the production of food grains; however, the conventional RW cultivation method has been used for the last 50 years, which has led to a drop in the soil's natural ability to supply nutrients, overutilization of groundwater along with a dropping of the water table, the obstruction of system productivity and dwindling profits, the emergence of new weeds, the risk of health hazards and the degradation of soil microbial population, etc., which are risking the sustainability of RWCS [7]. Wheat straw is preferably used for consumption as fodder for animals. Contrarily, due to dangerous levels of oxalates [8] and silica [9], more than 90% of rice straw is burned in the field before the planting of wheat crops [10] as it cannot be utilised as fodder. After the rice is mechanically harvested, the remaining straws impede wheat seeding efforts and frequently delay wheat planting [11]. Consequently, almost all residues are always burned in the open by farmers to facilitate residue-free and timely wheat sowing [12]. Burning rice residue leads the soil to lose 4 to 60% of its sulfur, 21% of its potassium, 25% of its phosphorus, and 80% of its nitrogen [13]. Meanwhile, environmental contamination increases as a result of the loss of soil organic matter (SOM) caused by residue fire [14].

The *in-situ* incorporation, mulching and removal of residue with minimum or no tillage are the foremost crop residue management options. According to Sandhu et al. [15], the application of crop residues with higher C/N ratios to the soil surface during conservation agriculture has been reported to slow down decomposition in North-west India, resulting in long-term beneficial effects on soil moisture conservation, soil thermal regime, and carbon sequestration. Farmers in north-western India typically employ Happy Seeder technology for the surface retention of rice residue and soil integration after rotavator or mouldboard plough plowing as treatments for in situ rice residue management [16]. This has prompted the creation of a zero-tillage machine called the Turbo Happy Seeder that could plant crops into thick layers of crop residues without burning them. Compared to ZT techniques, which keep the soil intact, a plough till causes physical disruption and pulverization, producing a loose and fine soil structure [17,18]. In other words, different plowing techniques can affect how well soil can store and transmit water and manage aeration by changing the number, shape, continuity, and size of pore networks. Adopting ZT might increase the edaphic environment and input utilization efficiency by improving the soil's porosity and accessible water capacity [19]. ZT soil often has a more continuous pore network due to bio pores produced by earthworms, root channels, and vertical fractures [20]. Additionally, when compared to ZT treatments, CT increases the proportion of micro-aggregates (fractions of 0.05–0.25 mm and 0.05 mm) while decreasing the proportion of macro-aggregates (0.25–2 mm). Compared to CT soils, ZT soil has more macroaggregates [21,22]. Tillage intensifies the effects of freezing–thawing and drying–rewetting, making macroaggregates more vulnerable to physical disturbance [23,24]. The retention of residue, however, enhances the edaphological environment [25], facilitates the soil temperature [26], increases the soil porosity and rate of water infiltration during heavy rains [27,28], and reduces soil erosion and runoff [29]. The hypotheses of this study were: (1) ZT, along with residue, enhances the soil structure in the soil as compared to CT; (2) in comparison with ZT, the adoption of CT degrades the physical quality of the soil.; and (3) the adoption of ZT with residue increases the water transmission and decreases the mechanical resistance (e.g., bulk density and soil penetration resistance). The aim of this study was to investigate how changes in the mechanical and hydrological properties of the soil were impacted by various tillage and residue management options.

2. Materials and Methods

2.1. Study Site Description

Experiments conducted at Punjab Agricultural University's Research Farm of Soil Science Department, Ludhiana (N 30°56′ latitude, E 75°52′ longitude, 247 m altitude) examined sandy loam and clay loam over two years (2020–2021 and 2021–2022). In our study area, weather conditions were subtropical semiarid, with hot summers and cold winters characterized by 652 mm of precipitation on average each year. During the summer, the maximum air temperature frequently surpasses 38 °C and occasionally reaches 45 °C due to dry spells in May and June. There are frosty periods during the winter months of December and January, when the minimum temperature drops below 0.5 °C. During the Rabi seasons 2020–21 and 2021–22, the Meteorological Observatory at Punjab Agricultural University, Ludhiana, recorded the following weather conditions in Figure 1. An initial description of the soil characteristics is provided in Table 1. Four different rice residue management techniques were used as the principal treatments in a split-plot design experiment with a 50 m^2 plot size and three replications. Table 2 provides a thorough explanation of the treatments. In the experiment, the rice crop was manually transplanted at a 15 × 20 cm spacing in puddled conditions. In the wheat season, the plots with rice residue retention treatments were harvested with a combine fitted with a straw management system (PAU SMS). The plots with no rice residue retention were manually harvested at the ground with a sickle. The sowing of wheat crops was performed in the first fortnight of November in both years with 100 kg of seed per hectare with a properly-calibrated seed-cum-fertilizer Happy Seeder, a seed-cum-fertilizer drill and a super seeder machine as mentioned in Table 2. Phosphorus at the rate of 65 kg P_2O_5 per hectare was drilled through di-ammonium phosphate (46% P_2O_5). Potassium at the rate of 30 kg per hectare was broadcasted through muriate of potash (60% K_2O) before the sowing of rice crops; potassium was not applied during the wheat sowing. Wheat seeds were treated with 15 mL of Tebuconazole (Raxil) and 160 mL Chlorpyriphos (Dursban) for 40 kg of seed for protection against smuts and termites, respectively. The clodinafop (post-emergence) herbicide was applied after 35 days of sowing equally in all plots. During the experiment period, the wheat crops were manually harvested in the second fortnight of April. The bundle weight from every plot biomass was recorded after drying for four days under sunlight, and threshing was carried out.

Table 1. Description of initial soil properties of the experimental sites.

Soil Properties	Sandy Loam	Clay Loam	Method
	Soil Chemical Properties		
Clay %	11.1	33.2	[30]
Silt %	17.4	26.7	
Sand %	71.5	40.1	
Soil pH	7.25	8.45	[31]
Soil EC (dS/m)	0.22	0.25	[31]
SOC (%)	0.43	0.54	[32]
Available N (kg/ha.)	202	235	[33]
Available P (kg/ha.)	22.5	25.8	[34]
Available K (kg/ha.)	149	168	[35]
Available Zn (mg/kg)	2.17	2.47	[36]
Available Fe (mg/kg)	22.8	25.7	
Available Mn (mg/kg)	10.4	14.2	
Available Cu (mg/kg)	1.12	1.49	

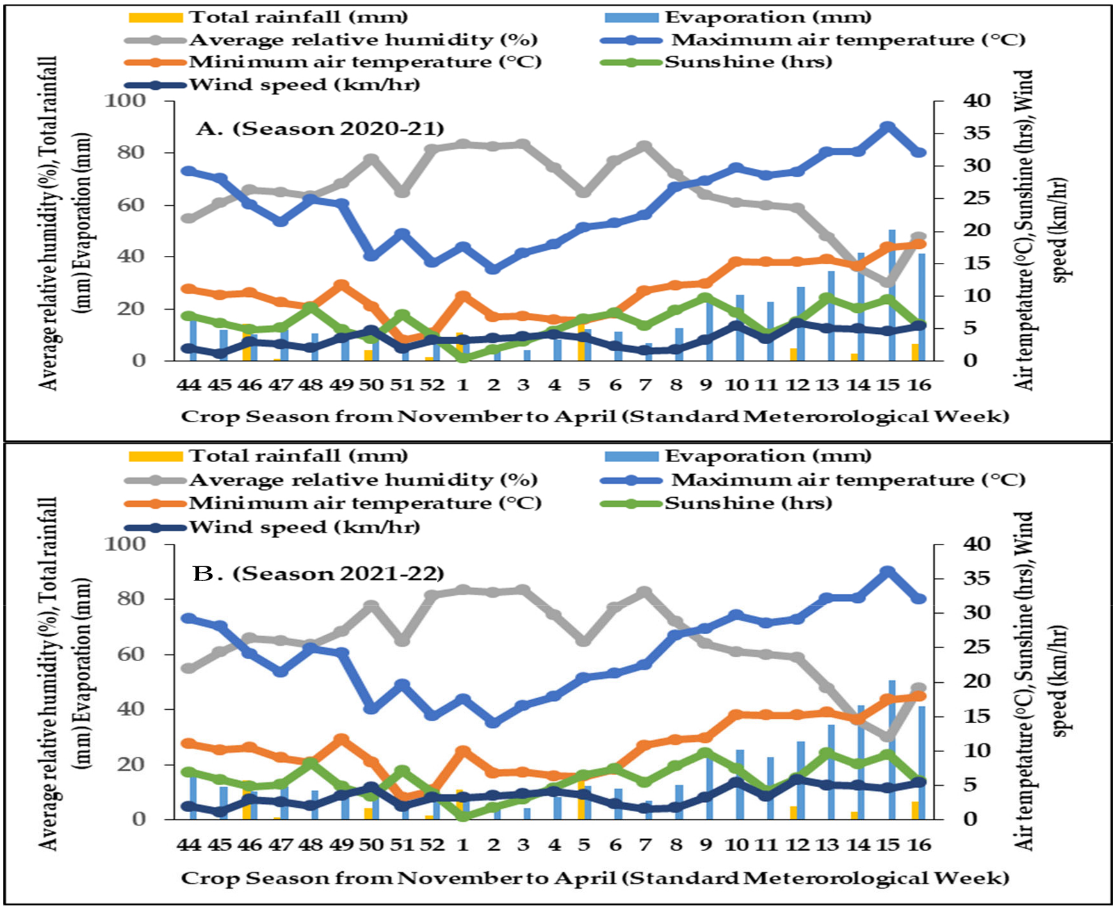

Figure 1. Graphical representation of crop season from November to April according to weekly meteorological data during wheat crop seasons of 2020–21 (**A**) and 2021–22 (**B**).

Table 2. Description of the treatments of wheat sowing in the experiment at both sites.

Abbreviation	Treatment Detail	Method of Crop Establishment	Short-Term
		Main Treatment	
T1	Conventional till wheat after the removal of rice residue	After removing the rice straw, wheat was sown using conventional tillage. Two harrow passes to a 10 to 15 cm depth and two rotavator passes were used to prepare the field. A seed-cum-fertilizer drill was used to sow wheat, leaving 20 cm between each row.	CT (−RS)
T2	Zero till wheat retaining full residue of rice crop as mulch	Wheat was directly sown with a Happy Seeder zero till machine (seed-cum-fertilizer) by retaining rice residue on the surface as mulch without disturbing the straw of the previous rice crop.	ZT (+RS)
T3	Conventional till wheat by incorporating full residue of previous rice crop +T1	After incorporating rice straw, wheat is sown using a reversible mouldboard deep plough up to 25–30 cm (two disc harrowing operations about 18–20 days prior to the sowing of wheat). The field was then irrigated to hasten the decomposition of the straw. The wheat was then sown using the T1 method.	CT (+RS)
T4	Minimum (single pass of machine) till wheat by incorporating full residue of previous rice crop	Wheat was seeded after the incorporation of rice straw using a super seeder machine (roto-seeder) with a single pass up to a 15 cm soil depth on the same day of sowing, along with fertilisers.	MT (+RS)

2.2. Determination of Soil Physical Properties

2.2.1. Bulk Density (ρ_b) and Penetration Resistance

Using the Blake and Hartge [37] approach, a core sampler with the dimensions of 8.0 cm in diameter and 7.5 cm in height was used to determine the bulk density of soil at depths of 0–15 and 15–30 cm at wheat harvesting after two years:

$$\rho_b = \frac{M_s}{V_t} \tag{1}$$

where M_s and V_t denote the soil's dry mass and volume of the core sampler used, respectively.

Using a digital cone and handheld penetrometer (CP40II; Rimik Electronics, RFM Australia), the penetration resistance (PR) was measured up to 40 cm with 10 cm increments. The PR was determined at four different locations within a plot at wheat harvesting after two years.

2.2.2. Determination of Infiltration Rate (IR) and Cumulative Infiltration (CI)

In situ, the determination of the infiltration rate was made using a locally made double-ring infiltrometer having the dimensions of 30 cm height for both the outer and inner rings; however, the internal diameter was 50 cm for the outer ring and 30 cm for the inner ring [38]. Water filled both the outer and inner rings. For 240 min, the infiltration rate and cumulative infiltration were determined. The water in the outer and inner rings was refilled when the pounded water dropped up to a 5 cm depth from the soil surface.

2.2.3. Mean Weight Diameter and Water Stable Aggregates

Wet sieving technique was used to assess the state of soil aggregation [39]. After drying in the air and being sieved through an 8 mm sieve, those soil peds from the top layer (0–15 cm) were collected over the 4 mm sieve. Four sets of five (12.7 cm wide and 5 cm height) Yoder wet sieving sieves were used in this experiment. The sieve pores ranged in size from 2.0, 1.0, 0.5, 0.25 and 0.1 mm. Over the top sieve of the set, the soil peds were equally dispersed, and the capillary was moistened for approximately 10 min. After that, for 30 min, the sieve set was stirred. After that, the sieves were dried at 105 °C in the oven until they reached a constant weight. The following formula was used to assess the water stable aggregates (WSA) [40] and mean weight diameter (MWD) [41]:

$$MWD = \sum_{i=1}^{n} d_i \times w_i \tag{2}$$

$$\mathrm{WSA} > 0.25\ \mathrm{mm}(\%) = \frac{\sum_{i=1}^{n} \mathrm{w_i}}{\text{weight of soil peds}} \times 10 \tag{3}$$

where n is the number of size fractions, d_i is each size range's average diameter, and w_i is the weight of aggregates in a specific size range as a percentage of the total dry weight of the soil samples taken.

2.2.4. Volumetric Water Content (θ)

A pressure plate device (Soil Moisture Equipment Co. New York, NY, USA) was used to investigate the parameters of the soil moisture retention using an applied pressure of 0.3, 5, 10 and 15 × 10^2 kPa [42]. The samples for the moisture determination were taken with a locally made screw auger (Falcon Ltd., Ludhiana, Punjab, India) at 0–7.5, 7.5–15, 15–22.5, and 22.5–30 cm depths. After measuring the soil's fresh weight and oven-drying the samples for 24 h at 105 °C, the water content was calculated on a mass basis.

The volumetric water content was calculated by dividing the mass water content by the bulk density of the soil:

$$\theta = D_b \times \omega \tag{4}$$

where θ is the volumetric water content, D_b is the soil bulk density, and ω is the water content on a mass basis.

2.2.5. Saturated Hydraulic Conductivity

The saturated hydraulic conductivity was calculated using the constant head method. Unobstructed soil cores of 7.5 cm in length and 8 cm in diameter were taken from depths of 0 to 7.5 and 7.5 to 15 cm. The samples were saturated in the lab. In order to stop water leakage, grease was placed at the jointing area on top of the first core after joining the saturated soil sample and core with another core. Siphons attached to a constant head device (Mariotte apparatus) were used to pour water on top of the sample slowly. The volume of water that filtered through the sample was gauged periodically. The following equation was used to analyze the hydraulic conductivity:

$$K_s = \left(\frac{Q}{At}\right) \times \left(\frac{L}{H+L}\right) \tag{5}$$

where K_s = the saturated hydraulic conductivity (cm h^{-1}); Q = the volume of percolate collected (cm^3); A = the cross-sectional area of the soil column (cm^2); t = time (h); L = the length of the soil column (cm); H = the depth of water above soil (cm).

2.3. Statistical Analysis

The data was analyzed using a split-plot design as described by Gomez and Gomez [43] using IRRISTAT version 92 (IRRI 1992) to determine the effects of tillage and residue management options on changes in the mechanical and hydrological soil properties. The statistical significance was determined for means that varied at $p < 0.05$ and was determined using the least significant difference (LSD) test to compare the means.

3. Results and Discussion

3.1. Soil Bulk Density and Penetration Resistance

Significant variations in the soil bulk density were observed at two depths (0–15 and 15–30 cm) for different land and residue management practices in Table 3. At the end of the cropping season, a lower bulk density was observed at 0–15 and 15–30 cm depths in both soils in the T2 treatment (With the wheat sown with the Happy Seeder machine), which was comparable with the mouldboard plough sown wheat (T3). This was due to better soil loosening and increased soil porosity by maintaining the rice residue as surface mulch. Maximum bulk densities of 1.56 and 1.53 Mg m^{-3} were recorded in the clay loam and sandy loam soils under the T4 treatment at the 0–15 cm depth; however, a hard pan formation brought the bulk density under the T4 treatment to a level with the T1 treatment in the clay loam and sandy loam soils at the 15–30 cm depth due to the compaction and shearing action of the tillage ploughed up to 15 cm. Lower bulk density in the ZT method showed that the no-till system assisted in reducing sub-soil compaction. As a result of CT, rice and wheat crops developed a plough sole beneath the usually-tilled layer. Sharma et al. [44] and Tripathi et al. [45] reported similar results, illustrating that puddling increases the bulk density in the soil immediately below a plough layer caused by destroying soil aggregates and filling macropores with finer soil particles, resulting in a reduction in porosity. When the moisture content drops, puddling creates favourable conditions for soil compaction and reduced percolation losses [46]. The residue retained during the wheat season enhanced the aggregation of soil particles and improved the soil organic matter, thereby reducing the bulk density at different depths in the T2-treated soils. Our findings were consistent with other research reports where ZT and residue retention led to a lower bulk density than CT in the top layer. These differences are due to the development of an organic-rich mulch, which perhaps increased the faunal activity or biological activity in the soil, particularly earthworms and higher microbial activity, resulting in an increased soil aggregation [47,48]. Parvin et al. [49] revealed that shallow tillage considerably increased the bulk density compared to mouldboard ploughing, and similar findings were recorded in our study on the sandy and clay loam soils. Moreover, Ji et al. [50] discovered that the bulk density of mouldboard was 4.2% lower than conventional tillage. Mulching maize stover at 5 and 10 Mg ha^{-1} for the first year reduced *pb* on a silt loam soil from 1.42 Mg m^{-3} (control) to 1.26 and 1.22 Mg m^{-3}, respectively, according to Blanco-Canqui et al. [51].

Table 3. Effect of residue management options on soil bulk density (Mg m^{-3}) and penetration resistance (MPa) in sandy loam and clay loam soils.

Residue Management Options	Bulk Density (Mg m^{-3})				Penetration Resistance (M Pa)							
	Sandy Loam		Clay Loam		Sandy Loam				Clay Loam			
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–10 cm	10–20 cm	20–30 cm	30–40 cm	0–10 cm	10–20 cm	20–30 cm	30–40 cm
T1	1.56a* ±0.03**	1.74a ±0.04	1.52a ±0.05	1.70ab ±0.05	1.21a ±0.11	2.57a ±0.11	2.50a ±0.10	2.55a ±0.09	1.16a ±0.10	2.41a ±0.12	2.50a ±0.11	2.48a ±0.11
T2	1.54b ±0.03	1.70c ±0.03	1.50a ±0.04	1.66c ±0.05	1.22a ±0.10	2.24c ±0.10	2.16c ±0.10	2.12c ±0.10	1.18a ±0.11	2.17c ±0.12	2.07c ±0.11	2.08c ±0.10
T3	1.54b ±0.03	1.71b ±0.04	1.50a ±0.04	1.67bc ±0.04	1.05b ±0.09	1.95d ±0.11	1.93d ±0.10	2.06c ±0.10	1.02b ±0.10	1.84d ±0.11	1.91d ±0.12	1.87d ±0.10
T4	1.56a ±0.03	1.75a ±0.04	1.53a ±0.04	1.71b ±0.04	1.26a ±0.09	2.44b ±0.12	2.37b ±0.11	2.45b ±0.11	1.21a ±0.11	2.33b ±0.12	2.36b ±0.12	2.28b ±0.10

* By using the Dun-Can Multiple Range Test (DMRT), mean values within a column that is followed by a different letter differ significantly at $p < 0.05$. ** values show standard deviation.

3.2. Penetration Resistance

At the end of the research investigation, different residue management techniques substantially influenced the soil penetration resistance (PR), showing an increasing trend with an increase in soil depth up to 40 cm (Table 3). This effect was seen in both sandy and clay loam soil. The variation in the PR also depends on the residue management options (e.g., the incorporation or retention of surface mulch). Several researchers reported a decrease in the PR resulting from straw incorporation in the surface layer, which was also observed in our research investigation. Residue incorporated with an MB Plough (T3) recorded the lowest penetration resistance from a 0 to 40 cm depth, while the second lowest was recorded in the T2 treatment (e.g., rice residue was retained on the surface as mulch) after two years, irrespective of the soil types. A lower PR in the T3 treatment might be due to the breakdown of the hardpan by deep ploughing. The maximum PR was recorded in shallow tillage (T1) followed by the T4 treatment at 10–20 cm in both the sandy loam and clay loam soils. The highest PR values were reported under CT and the lowest values were reported with an MB plough, according to Zhao et al. [52] and Pervaiz et al. [53]. The PR values at the 0–20 cm layers were below the required value for optimal growth of wheat roots regardless of the residue management techniques used [54]. The findings of Blanco-Canqui et al. [47], who similarly got a decreased PR under ZT-based management techniques, were supported by our findings. Mulching with a crop residue enhances the biological activity and SOC content, which reduces the PR in the soil. Our results were similar to those of Materechera and Banda [55] and Unger [56]. Regardless of the soil type, the penetration resistance (PR) decreased as the water table increased [57].

3.3. Mean Weight Diameter and Water-Stable Aggregates

An increase of the macro-aggregates was exhibited with a maximum MWD in the sandy loam (0.66 and 0.61 mm) and in the clay loam (0.67 and 0.63 mm), and the WSA (59.76% and 44.82%) in the sandy loam and (67.42% and 52.43%) in the clay loam soil, in contrast to the other tillage techniques in the T2 treatment at depths of 0–15 and 15–30 cm, respectively, which might be caused by residue retention and an enhanced organic matter decomposition (Table 4). Our data support the assessment of Chaudhary et al. [58] that ZTW had a much larger MWD than CTW. Similar findings were recorded by Hou et al. [59] and Andruschkewitsch et al. [60]. The increased organic matter under the T2 plot may have improved the microbial activity and worked as a cementing agent, increasing the MWD and WSA values by producing polysaccharides that might link soil particles into aggregates [61]. The incorporation of straw helped in the formation and stability of aggregates by increasing microbial cells and the excreted microbial products and decomposition products released during the death of the microorganisms. The T4 treatment recorded the second highest MWD on the sandy loam (0.54 and 0.50 mm) and on the clay loam soil (0.55 and 0.50 mm) at depths of 0–15 and 15–30 cm, respectively. Similarly, the WSA also showed the second-highest value in the T4 treatment. The amount of WSA increased due to the use of residual mulch [62]. Rice residue incorporated on the sandy and clay loam soils using a reversible MB plough in the T3 treatment revealed the lowest mean weight diameter of 0.37 and 0.39 mm at a 0–15 cm depth and 0.34 and 0.35 mm at a 15–30 cm depth on both the sandy loam and clay loam soils, respectively, which also resulted in the lowest water-stable aggregate. The MWD may have decreased as a result of the freezing-thawing periods and frequent drying-rewetting, which increased the susceptibility of macroaggregates to physical disruption [24].

Table 4. Effect of residue management options on mean weight diameter (mm), water stable aggregate (%) and saturated hydraulic conductivity (cm/h) in sandy loam and clay loam soils.

Residue Management Options	Mean Weight Diameter (mm)				Water Stable Aggregate (%)				SHC (cm/hr)			
	Sandy Loam		Clay Loam		Sandy Loam		Clay Loam		Sandy Loam		Clay Loam	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
T1	0.43c* ±0.03**	0.37c ±0.03	0.45c ± 0.04	0.37c ±0.03	54.7c ±3.28	40.2c ±4.32	60.2c ±3.34	45.2c ±4.09	3.18d ±0.14	2.47d ±0.16	3.08d ±0.10	2.19d ±0.11
T2	0.66a ±0.03	0.61a ±0.03	0.67a ± 0.04	0.63a ±0.03	59.8a ±3.07	44.8a ±3.15	67.4a ±3.45	52.4a ±4.04	4.37b ±0.15	3.65b ±0.15	3.84b ±0.09	3.58b ±0.11
T3	0.37d ±0.04	0.34d ±0.03	0.39d ±0.03	0.35d ±0.04	42.9d ±3.79	27.8d ±4.20	48.7d ±3.87	32.7d ±4.15	5.08a ±0.14	4.07a ±0.14	4.57a ±0.11	3.73a ±0.12
T4	0.54b ±0.02	0.50b ±0.03	0.55b ±0.03	0.50b ±0.03	57.4b ±3.31	42.4b ±3.51	63.5b ±3.47	48.5b ±4.12	4.01c ±0.15	2.95c ±0.15	3.73c ±0.12	2.68c ±0.12

* By using Dun-can's Multiple Range Test (DMRT), mean values inside a column that is followed by a different letter are different significantly at $p < 0.05$. ** values show standard deviation.

Mechanical tillage lowers the activity and species variety of organisms in the ploughing layer, disturbs aggregation, and induces SOM mineralization. These tillage-related changes reduce the adhesion of soil particles and diminish the WSA [63]. Various sizes of WSA were produced under the effect of natural settings; subsequently, the ZT practice was not artificially disrupted, suggesting that the soil aggregation degree was higher. After five years of rice-wheat farming on sandy loam soil, the aggregate stability and MWD of aggregates treated with residues were improved by a higher SOC, according to Singh et al. [64]. The stability of macro-aggregates can be impacted by slight variations in the SOC.

3.4. Infiltration Rate and Cumulative Infiltration

The likelihood of erosion is decreased by the addition of crop residue to the soil or as surface cover in the blocks of mulch [65]. The T3 treatment (deep ploughed treatment) had the highest final infiltration rate (cm h^{-1}), followed by the T2 treatment, and the T4 treatment had the lowest final infiltration rate (cm h^{-1}) (Figure 2) due to the presence of a substantial number of macropores and enhanced microbial activity [66].

The presence of abundant macro porosity led to a quicker passage of water through the soil, and Moroke et al. [67] also noted greater values for the infiltration rate during deep tillage (e.g., in T3) in compared to conventional tillage. Furthermore, an increase in the infiltration rate was observed with an increase in the tillage depth by Alamouti and Navabzadeh [65,68], due to decreased bulk density. The minimum value of the infiltration rate (cm h^{-1}) was recorded in conventionally tilled plots (e.g., the T1) during the research investigation. According to McGarry et al. [69], ZT with residue retention produced more stable aggregates than conventional tillage, which reduced the aggregate disintegration and decreased the potential of surface crust formation. This resulted in a greater infiltration rate and cumulative infiltration. Using rice straw from 0 to 15 Mg ha^{-1}, Barzegar et al. [70] found linear increases in infiltration rate and water retention. According to Ogban et al. [71], mulched ZT (e.g., in T2) plots had considerably greater equilibrium infiltration rates and cumulative infiltration than mulched CT plots. The data showed the occurrence of a steady state of cumulative infiltration and the infiltration rate on clay loam soil, which was significantly affected by different rice residue management treatments (Figure 2). The causes for better soil infiltration under residue treatments include a higher SOC content, greater soil aggregate stability and improved soil porosity, all of which are important in enhancing soil's physical and hydrological properties [72]. The final value of the infiltration rate (cm h^{-1}) on the clay loam soil exhibited a similar trend as in the sandy loam soil during the final year of the study. Compared to no residue, Chalise et al. [73] found that retention of residue increased soil infiltration by 66%. Due to increased infiltration under CA-based systems, the ZT with residue retention may have helped create continuous soil pores from the surface to the depth of the soil [46,74]. According to Gangwar et al. [75], crop residues left on the soil surface prevent soil crusting, soil sealing, and evaporation, which increase soil infiltration. Additionally, according to Johnson et al. [76], soil infiltration was two times greater when there was a total return of residue of >7 Mg ha^{-1} compared to a lower return of residue of 2 Mg ha^{-1}.

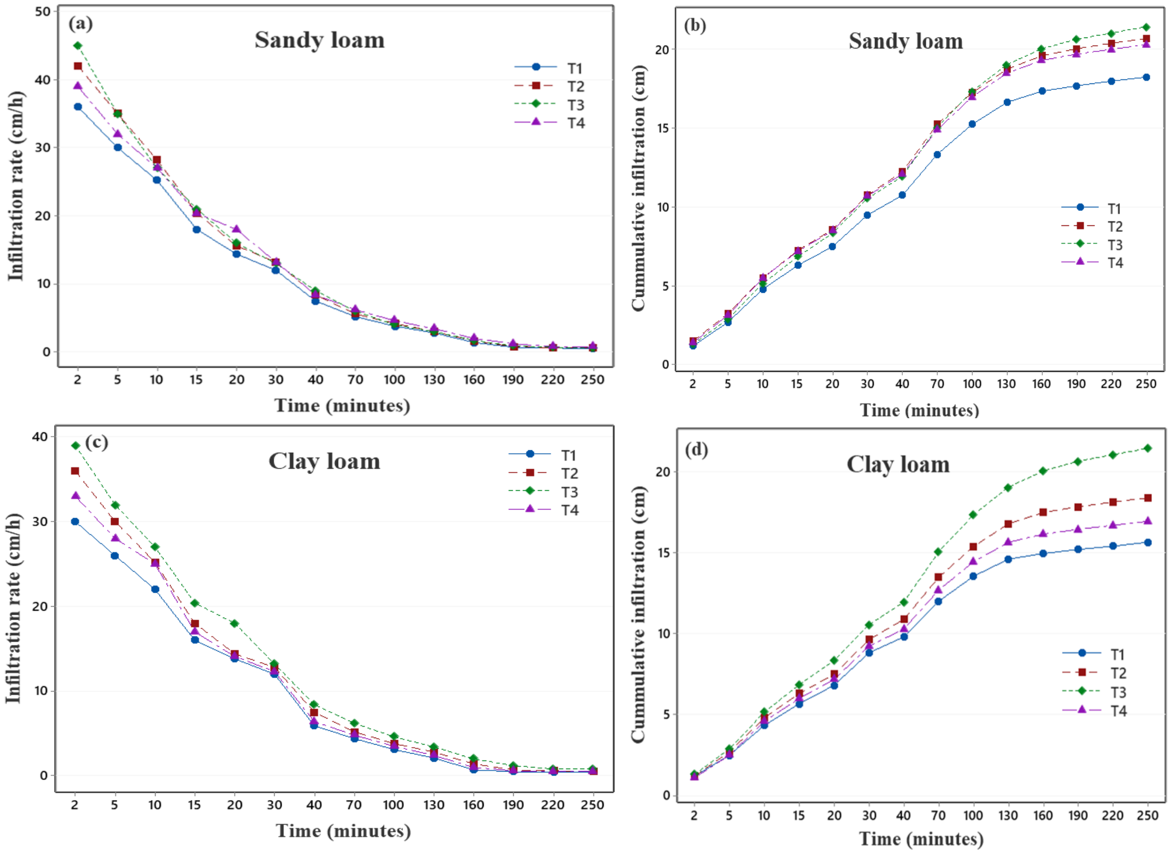

Figure 2. Infiltration rates and cumulative infiltration in sandy loam (**a**,**b**) and clay loam (**c**,**d**) soils as affected by tillage and residue management options.

3.5. Saturated Hydraulic Conductivity

In the T3 treatment (i.e., deep ploughing below the hardpan of soil), the highest values of K_s (5.08 and 4.57 cm h^{-1}) and (4.07 and 3.73 cm h^{-1}) were recorded in the sandy loam and clay loam soils, respectively, at both depths (Table 4). At 15–30 cm, the bulk density increased; therefore, the K_s decreased, which might be attributed to the decline in the soil macro-porosity [77] at both sites. The second highest value of K_s (4.37 and 3.84 cm h^{-1}) at 0–15 cm and (3.65 and 3.58 cm h^{-1}) at 15–30 cm was recorded in the T2 treatment on the sandy loam and clay loam soil surfaces, respectively, leading to a favourable effect on the K_s owing to an organic matter addition that improved the soil macro-aggregates. The T2 treatment was found to be statistically at par with the rice straw incorporated with the super seeder (T4) followed by the lowest K_s value in the T1 treatment (i.e., surface ploughed after residue removal) at both sites. According to Fuentes [78] and Hu et al. [79], tillage operations and practices could occasionally cause temporal surface changes in the hydraulic properties. Six et al. [80] indicated that the mechanical disintegration of aggregates during tillage subsequently resulted in decreased saturated hydraulic conductivity in CT. According to Tripathi et al. [45], crop residue removal lowers saturated hydraulic conductivity in all tillage systems. A higher value of K_s under deep tillage has also been reported by Shaver et al. [81], due to a greater macro-porosity under DT that facilitated enhanced water transmission compared to other tillage treatments. Jabro et al. [82] also observed higher Ks in deeply tilled soil. The researchers attributed the rise in K_s to more macropores, a higher aggregate percentage (WSA and MWD) and an increase in faunal activity and residual litter that enhanced the organic carbon content under NT [83,84]. The increased K_s in the ZT system might be due to improved pore continuity, aggregation and a decreased tortuosity. According to Shipitalo et al. [85], ZT retains soil aggregations and macropores formed by decaying roots, whereas CT destroys the continuity of these macropores.

3.6. Soil Moisture Content

As seen in Figure 3 for the sandy loam soil, the soil moisture content fluctuated significantly under various tillage and residue management options. The residue retained treatment (T2) had higher moisture content at a depth of 0–15 cm than the straw-removed treatment. The soil moisture retention was highest in the T2 treatment, followed by the T4 treatment. In comparison to residue removal or burning, Kushwaha et al. [86] and Bhagat et al. [87] showed a significant increase in the soil water content after straw incorporation. Due to the depletion of residue-derived organic materials, a deterioration in the soil structure, and high losses by evaporation, the conventional tillage after removing the rice straw (T1) at a depth of 0–15 cm from 0.1 to 15 bar matric potential showed the least significant soil moisture content [40].

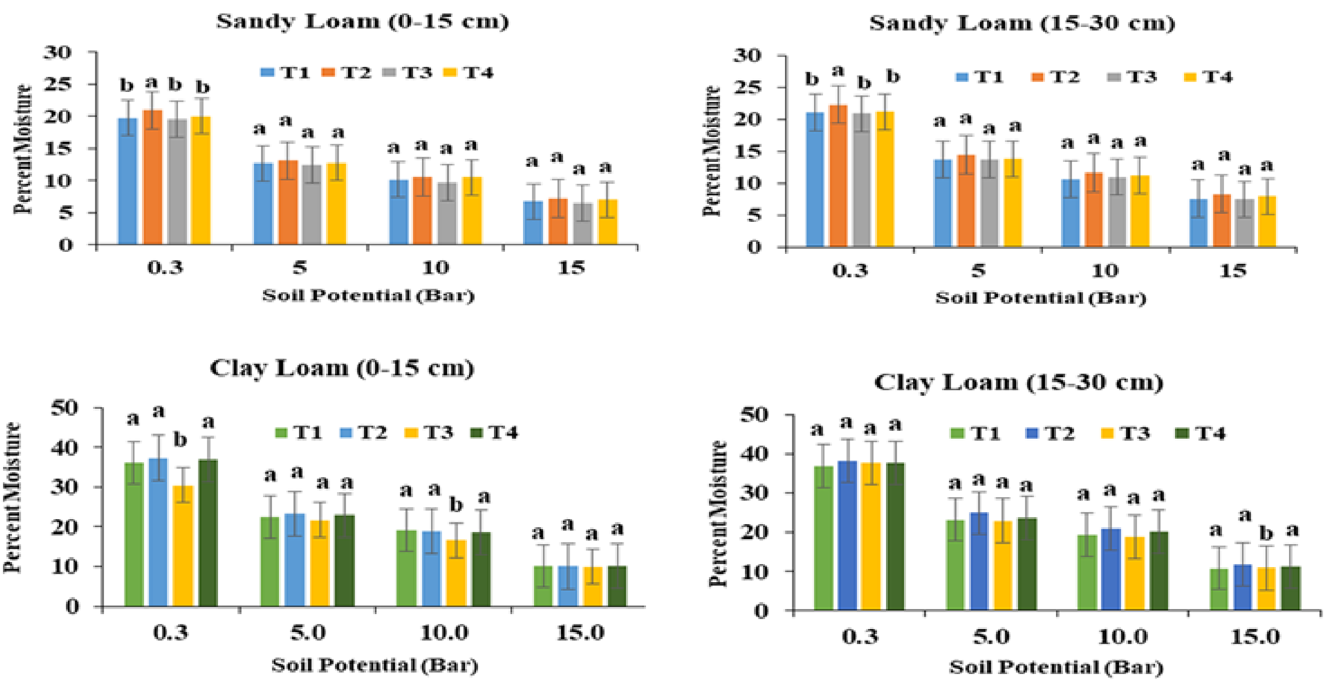

Figure 3. Effect of various tillage practices depth-wise on the volumetric water content in sandy loam and clay loam soils. (Using Duncan's Multiple Range Test (DMRT), mean values within a graph are distinguished by a different letter when the difference is significant at $p < 0.05$).

Similar patterns emerged in the 15–30 cm of sandy and clay loam soil depth (Figure 3), possibly due to better soil aggregates. The T2 treatment was comparable with the T4 treatment in increasing the volumetric water content, where the rice residue was incorporated with the super seeder treatment. Straw mulching has been reported to increase soil water storage [88], apparently due to reduced soil water evaporation. The minimum volumetric water content was noticed in the T3 treatment at all the soil depths, which was at par with the T1 treatment.

4. Conclusions

Zero tillage with residue retention substantially impacts the soil's mechanical properties, hydrological parameters, and structural characteristics in the Indo-Gangetic Plains of South Asia. In our study, compared to CT (−RS), ZT (+RS) exhibited a greater water transmission and lower mechanical impedance. Crop residue retention improves the structural qualities of soil, such as the infiltration capacity, saturation hydraulic conductivity, reduced bulk density and minimum soil penetration resistance in ZT (+RS) compared to CT (−RS). The soil's MWD and WSA are improved by adding crop residue and better organic matter decomposition under ZT. Due to the formation of macroaggregates, higher water content, and crop residue retention/incorporation under zero tillage, the soil structure and moisture conservation improved. Conventional tillage was unable to produce a stable structure because of soil compaction. The findings showed that, regardless of the soil type, zero tillage with rice residue retention considerably changed the hydrological and mechanical properties of the soil for a more sustainable agriculture.

Author Contributions: Conceptualization, methodology, investigation, resources, data curation, writing—original draft preparation, V.S., R.K.G., M.S.K. and N.A.-A.; project administration, formal analysis, writing—review and editing, A.S.T., K.B.S., N.A.-A. and M.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: Researchers Supporting Project number (RSPD2023R958), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Researchers Supporting Project number (RSPD2023R958), King Saud University, Riyadh, Saudi Arabia.

Conflicts of Interest: The authors declare no conflict of interest.

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