



Article

Improvement of Soil Health through Residue Management and Conservation Tillage in Rice-Wheat Cropping System of Punjab, Pakistan

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Abstract: In South Asia, soil health degradation is affecting the sustainability of the rice-wheat cropping system (RWCS). Indeed, for the sustainability of the soil quality, new adaptive technologies, i.e., conservation tillage and straw management resource conservation, are promising options. This investigation was focused on the interaction of tillage and straw management practices and their effects on Aridisols, Yermosols soil quality, and nutrients dynamics with different soil profiles within RWCS. The long-term field experiment was started in 2014 with the scenarios (i) conventional tillage (SC₁), (ii) residue incorporation (SC₂), (iii) straw management practices (SC₃ and SC₄) and conservation tillage (SC₅). Conservation tillage practice (SC₅) showed significant impact on properties of soil and availability of nutrients in comparison with that of conventional farmers practice (SC₁) at the studied soil depths. The SC₅ showed significant results of gravitational water contents (25.34%), moderate pH (7.4), soil organic-matter (7.6 g kg⁻¹), total nitrogen (0.38 g kg⁻¹), available phosphate (7.4 mg kg⁻¹), available potassium (208 mg kg⁻¹) compared to SC₁ treatment at 0 to 15 cm soil depth. Whereas, DTPA-extractable-Cu, Mn, and Zn concentration were significantly higher, i.e., 1.12 mg kg⁻¹, 2.14 mg kg⁻¹, and 4.35 mg kg⁻¹, respectively under SC₅ than conventional farmer's practices, while DTPA (diethylene triamine pentaacetic acid) extractable Fe (6.15 mg kg⁻¹) was more in straw management practices (SC₄) than conventional and conservation tillage. Therefore, conservation tillage (SC₅) can surge the sustainability of the region by improving soil assets and nutrients accessibility and has the potential to minimize inorganic fertilizers input in the long run.

Keywords: conservation tillage; micronutrients; nutrients accessibility; Aridisols; Yermosols; soil degradation; straw management practices; soil organic matter

1. Introduction

The RWCS is an important cropping pattern of the Indo-Gangetic Plains (IGP) of the South Asia region. Cereals is the major source of living for the farming community of this region and it is cultivated in areas even more than 13.5 million hectare (Mha) in India, Bangladesh, Pakistan, and Nepal [1]. In Pakistan, RWCS covers an area of more than 2.2 Mha, out of which Punjab province covers nearly 75% [2–4]. In the last few years, RWCS productivity has been declining due to conventional tillage, superfluous application of chemical fertilizers, and mono-cropping [5,6]. Kumar et al. [7] reported that poor soil health, shortage of water, improper application of nutrients, and reduction of soil organic matter (SOM) are the main reasons for yield reduction. These all could be due to intensive use of

conventional practices in IGP. In an investigation, Ramos et al. and Khan et al. [8,9] concluded that traditional soil management practices effect the nutrients volume in soil and availability to plant for better production. RWCS in IGP produces around 10 to 12 Mg-ha residues [10,11] which were taken off or burned before sowing of the next crop. Burning or the removal of residues are adversely affecting the soil physio-chemical properties, especially nutrients such as macro and micronutrients [12]. Additionally, conventionally rice grown in standing water conditions requires a higher volume of energy and labor [13] on one hand, and on the other hand, 7–11 mm per day per hectare of water is evapotranspired through rice fields in which evaporation contributes around 30–40% of virtual water loss [14,15]. There is no direct relationship of energy and water with soil physical and chemical properties but it affects the financial conditions of the farmers and utilization of water that results depletion. The water scarcity resulted in the deterioration of soil physical and chemical properties as reported by Ramos et al. [8]. Overall, 2500–5000 L of water is required for producing one kg of rice [16]. Both of these factors affect soil properties (both physical and chemical) and crop yield which ultimately influenced the productivity and economy of the country under changing climate [16,17].

To address all the above issues, there is an essential need to adopt best management practices to conserve soil health, improve ecosystem service, and protect the environment. Conservation agriculture seems to be the best alternative conventional practice through preserving energy, labor, time, and environment quality that could ultimately help to sustain the crop-productivity [18,19]. Efficient, soil health improvement was noted under conservation agriculture by slowing down the activities of physical and biotic processes [20,21] and it also helps in the reduction of production cost. Soil physio-chemical and biological properties are significantly affected by conservation or reduced tillage [22–24]. Conservation tillage encourages more residues on the surface which enhances soil organic matter accretion and biological processes [25–27].

RWCS sustainability is based on the information about the soil physio-chemical properties and availability of nutrients under different practices [28,29]. Salahin et al. and Nandan et al. [30,31] concluded that carbon and nutrient concentration increase would help in the improvement of soil-health parameters under conservation tillage at surface soil. Hence, by adding the crop residues or incorporation of residue in soil improve the soil nutrient status in RWCS, as reported earlier [12,32]. Very few studies have been conducted on the variations in the availability of nutrients and soil physio-chemical properties under different conservation agriculture-based strategies in RWCS. The current study is based on the hypothesis that tillage, which left more amounts of residues on the surface and causes less soil disturbance, could improve soil quality and reduce soil degradation compared with the tillage that leaves less residues and more soil disturbance under RWCS. The objectives of the present study were: to study the impact of tillage and straw management practices on soil physical and chemical properties; to determine dynamics of soil nutrient availability under different soil profiles after six years of RWCS in Punjab, Pakistan. To fulfil the objectives after six years of experiment, total 135 soil samples were collected from the studied scenarios to determine soil physio-chemical properties and nutrients at three different depths through standard protocols and procedures as detailed in the methodology section.

2. Materials and Methods

2.1. Site Selection, Climatic Conditions, and Soil Descriptions

The experimental site was located at the Rice Research Institute (31°72' N, 74°28' E, slope 1.8%), Kala Shah Kaku (RRI, KSK), Shiekhupura, Punjab, Pakistan (Figure 1), and has sub-humid, subtropical climate. The average annual precipitation for the study period (2014–2018) was 585 mm, and 70–80% (409–468 mm) of the precipitation was recorded during summer (June–August) while winter received gentle rainfall of around 35–40 mm. The annual mean maximum temperature ranged from 36 to 42 °C with extremes of 48 °C during summers and a minimum of 4–6 °C during winter for the same period. From May to September, the relative humidity ranged 35–70%, whereas from January to May, the

annual light period varied from 5.1 to 10.4 h. The reference evapotranspiration (ET^0) was higher (6.4 mm) in May and minimum (1.1 mm) in December. Soil in the area is classified as Bahalike series loam (a village in central Punjab). However, according to the Food and Agriculture Organization (FAO) classification system, it is classified as Haplic Yermosols (FAO, 2014) [33] and in the United States Department of Agriculture (USDA) classification system it is classified as hyperthermic Ustalfic Haplargid [34]. Wheat and rice are the important cereals of the area. Generally, wheat is rotated with summer rice. The wheat crop is cultivated in between 24–28 November and harvested at the end of April (25 April to 10 May), while rice was transplanted at the end of July (25–30 July) and harvested in mid-November (15–20 November) during all the experimental year.

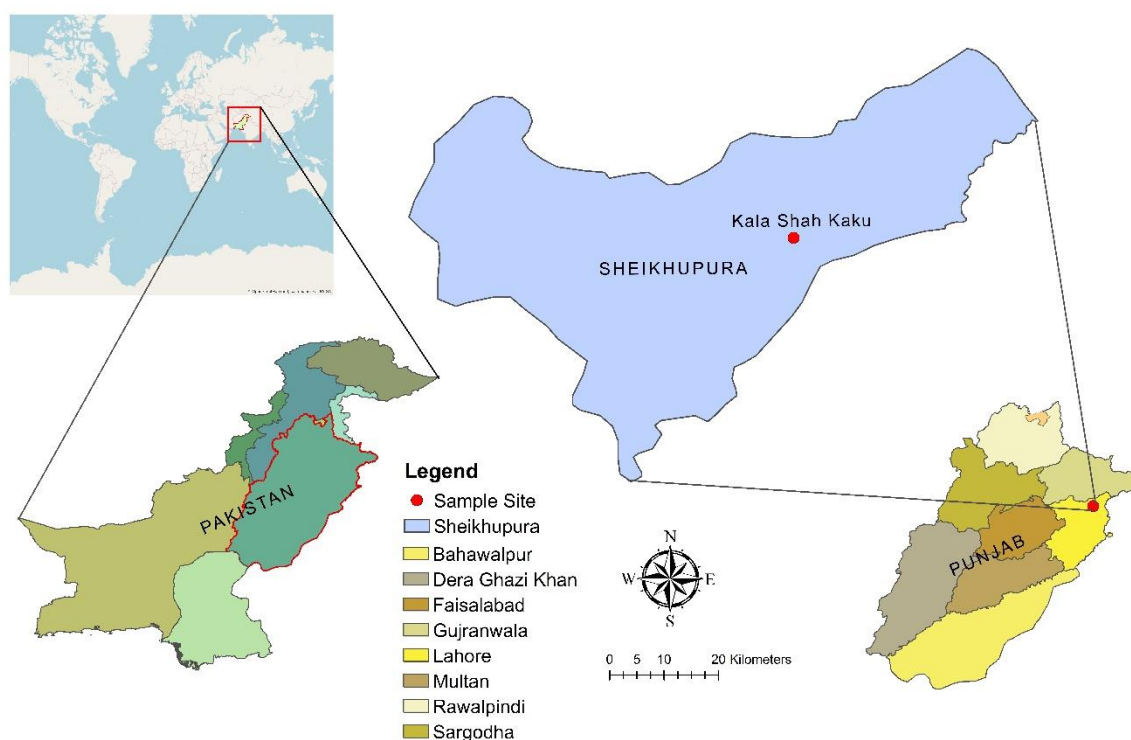


Figure 1. Geographical location of the experimental area.

2.2. Treatments and Experimental Design

A long-term crop residue management experiment was carried out in a fall wheat-summer rice rotation. Total 9 composite soil samples with three replication at 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm depths were collected to perform soil physical and chemical analyses in the started year (21 October 2014) of the long-term field-experiment (Table 1). The investigation comprised of five scenarios that combined tillage and crop-straw management practices into 15 plots of equal size (10×20 m) in randomized complete block design (Table 2 and Graphic Abstract). Wheat/rice crops were seeded with the following scenarios: (i) Rice/wheat residue was burned and removed, ploughing of field 3–4 times (18 to 20 cm depth), and planked (SC_1); (ii) Rice/wheat residues were chopped with straw chopper incorporated by disc plow, ploughing of field 2–3 times (18–20 cm depth), and planked (A wooden or iron rod used to level the land for proper sowing and uniform irrigation) (SC_2); (iii) Rice residues were retained and wheat was planted with zero till (ZT) at 3–5 cm depth, whereas wheat residues were removed for non-puddled direct seeded rice sowing (SC_3); (iv) Rice residue was retained and wheat was planted with ZT at 3–5 cm depth, while wheat residues were removed for transplanting puddled rice sowing (SC_4); (v) Rice/wheat residues were retained and wheat/rice were planted with ZT drill at 3 to 5 cm depth (SC_5). Soil disturbance was determined based on tillage implements depth application. In conventional tillage, plough the soil around 50 cm. Whereas, in conservation tillage,

zero drill times is disturbed to only 5–7 cm deep for sowing purpose. The detailed information and residue management practices are given in Table 2.

Table 1. Basic soil physio-chemical properties of the experimental site (9 composite soil samples with 3 replicates).

Soil Properties	Soil Depth		
	0–15 cm	15–30 cm	30–45 cm
Texture	Clay loam	Clay loam	Clay loam
pH	8.1–8.5	8.3–8.7	8.3–8.7
EC (mS-cm)	1.4–2.2	1.3–1.8	1.3–1.8
Organic matter (%)	0.52–0.69	0.48–0.56	0.40–0.51
Bulk density (g cm ⁻³)	1.18	1.18	1.17
Saturation (%)	58–62	56–60	50–55
Available P (mg kg ⁻¹)	4–6.5	3.5–5.8	3.5–5.8
Available K (mg kg ⁻¹)	135–160	128–148	128–148

Table 2. Description of tillage practices, sowing methods, and residue management under five scenarios.

Scenarios	SC ₁	SC ₂	SC ₃	SC ₄	SC ₅
Crop rotation	Rice-Wheat	Rice-Wheat	Rice-Wheat	Rice—Wheat	Rice—Wheat
Tillage	Rice-puddled Wheat-CT	Rice-puddled Wheat-CT	Rice-DSR Wheat-ZT	Rice-puddled Wheat-ZT	Rice-ZT Wheat-ZT
Soil disturbance (%)	Rice:100% Wheat:100%	Rice:100% Wheat:100%	Rice:90% Wheat:2%	Rice:90% Wheat:2%	Rice:2% Wheat:2%
Sowing Method	Rice-transplanting Wheat-broadcast	Rice-transplanting Wheat-broadcast	Rice-broadcast Wheat-ZT (drill)	Rice-transplanting Wheat-ZT (drill)	Rice-ZT (drill) Wheat-ZT (drill)
Residue management	Removed + burn	Incorporated	Rice-retained Wheat-removed	Rice-retained Wheat-removed	Rice-retained Wheat-retained
Left residue % age	Rice:2% Wheat:2%	Rice:65% Wheat:65%	Rice:10% Wheat:65%	Rice:10% Wheat:65%	Rice:65% Wheat:65%

SC₁: conventional transplanting puddled rice–conventional till wheat; SC₂: conventional transplanting puddled rice–conventional till wheat and residue incorporated; SC₃: conventional tilled non-puddled rice while wheat residue removed–zero till wheat with residue; SC₄ = conventional till puddled rice transplanted while wheat residue removed–zero till wheat with residue; SC₅: non-puddled zero till direct seeded rice with residue–zero till wheat with residue.

2.3. Wheat Management

Wheat crop variety (Faisalabad-2008, PBW65/2*Pastor, CGSS974000367-099 TOP-067Y-099M-099Y-099B-16Y-0B, whealtas.org) was sown by means of zero till seeder in SC₃, SC₄, and SC₅ scenarios on the rice residue with 22 cm of row spacing, whereas for scenarios SC₁ and SC₂, wheat seeds were manually broadcasted. The macronutrients were applied through inorganic fertilizers i.e., urea (46% of nitrogen), di-ammonium phosphate (18% nitrogen), and murate of potash (MOP). The fertilizers were applied with ratio 120:85:62 of N: P₂O₅: K₂O Kg ha⁻¹. In conventional and ZT wheat, half and complete amount of nitrogen (N), phosphorus (P), and potassium (K) were applied manually and by zero-drill simultaneously. At booting stage (10–15 March), the remaining amount of N for all scenarios was applied. Atlantis @ 150 g ha⁻¹ (mesosulfuron-methyl and iodosulfuron-methyl-sodium) was sprayed as a post emergence herbicide at first irrigation in saturated soil condition for weed management. During the study period, (2014–2018) wheat was harvested at the end of April. Scenarios (SC₁, SC₂, SC₃, and SC₄) were harvested and threshed manually, while zero tillage scenario (SC₅) was harvested and threshed with combine harvester.

2.4. Rice Management

In non-puddled rice scenarios (SC₃ and SC₅), rice super basmati variety was sown @ 30 kg ha⁻¹ seed rate with 20 cm of row spacing using zero till drill during mid of June. The nursery was raised by using the same rice variety on the same day with 40 g ha⁻¹ seed rate. Around four-weeks-old

rice seedlings were transplanted in SC₁, SC₂, and SC₄ scenarios with a row spacing of 20 and 10 cm hill-to-hill space. The dose of N: P₂O₅: K₂O: zinc sulfate (ZnSO₄) was applied to puddle and non-puddled rice crop was 133:82:62:12.5 kg ha⁻¹. In puddled and non-puddled rice at the sowing, half (N) and other chemical fertilizers were applied, whereas remaining (N) was broadcasted at the booting stage. Two sprays (22 and 40 days after sowing (DAS)) of clover herbicide (bispiribac sodium @ 300 g ha⁻¹) were used to eradicate the weed in SC₃ and SC₅ scenarios. In puddled rice crop weeds, biotypes were managed by proper flooding. At the end of November, physiologically mature rice crop was harvested throughout the entire experiment. The combined harvester was used for the scenarios SC₃, SC₄, and SC₅, while the other two scenarios SC₁ and SC₂ were harvested manually.

2.5. Soil Sampling and Processing

Random 9 soil samples per plot per 3 replicates were collected within each scenario at depths of 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm keeping in view the root profile of the crops by using soil auger from each plot at the first week of April after five days of wheat harvesting on 8th April 2018. Composite samples of each scenario were dried at 40 °C, cleaned of all visible above- and belowground plant residues, and ground to pass via a 2 mm sieve.

2.6. Soil Parameters Measurement

Moisture content was determined through the gravimetric method by finding soil dry mass in each core [35]. Electrical conductivity (EC) and pH were determined in 1:2.5 soil water moisture using Thermo Scientific Orion 4-star meter (Thermo Fisher Scientific Inc., Beverly, MA, USA). Total nitrogen (TN), available phosphorous (P), and extractable-potassium (K) were determined by using methods described by Bremner et al. [36], Olson et al. [37], and Richards [38] methods. The Walkley and Black [39] method was used to determine total soil organic carbon (SOC). Soil micronutrients such as available DTPA-extractable Fe, Mn, Cu, and Zn were measured by the Lindsay et al. [40] method.

2.7. Statistical Analysis

A two-way factorial design was used to investigate the effect of the tillage practices on soil properties using Statistix 8.1 tool (Analytical software, Statistix; Tallahassee, FL, USA, 1985–2003). Significance of scenarios was noted through least significance difference test performance (LSD) at $\alpha = 0.05$ [41]. Studied soil properties and nutrients were compared by constructing Pearson's correlation matrices.

3. Results

3.1. Soil Physio-Chemical Properties under Tillage and Residue Management

SC₅ significantly influenced gravitational water content as compared to the conventional tillage in all soil depths (Table 3). The highest gravitational water content, i.e., 41.85% was found at 30–45 cm depth in SC₅, while conventional tillage held the lowest water content 18.08%. The water content increased with soil depths in all tillage practices. The gravitational water content at significance level 0.05% was increased by 1.52%, 3.77%, and 7.92% under SC₂, 4.7%, 7.02%, and 13.06% under SC₃, 2.99%, 6.34%, and 12.73% under SC₄, and 7.26%, 14.67%, and 18.16% under SC₅ than SC₁ at 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm depths, respectively.

SC₅ scenario showed statistically ($p = 0.05$) lower 01 units of soil pH than SC₁, while SC₅ had no significant difference with straw management practices at 0–15 cm soil depth (Table 3). Lower pH values were observed under all tillage practices, but the differences were not significant at depths of 15 to 30 cm and 30 to 45 cm layers. Increase in soil-depth caused in the surge of soil pH in all the experimental scenarios used during the course of the study. All the studied soil depths resulted in low EC values than that of harmful condition of 4 dS m⁻¹ in all the scenarios which reduces risks of toxic effects of salts on the plants on this soil (Table 3).

The significant ($p = 0.05$) effect produced by conservation tillage (SC_5) on accumulation of organic matter at all studied soil profile (Table 3). Highest organic matter was observed under SC_5 at 7.6 g kg^{-1} , which was followed by SC_2 (6.5 g kg^{-1}) and SC_1 (6.5 g kg^{-1} at 0 to 15 cm depth), while lowest organic matter was observed SC_4 (6.2 g kg^{-1}). Significantly higher organic matter (6.6 g kg^{-1}) and (5.75 g kg^{-1}) was observed under SC_5 at subsoil (15 to 45 cm) compared to other scenarios. Total N contents under different scenarios showed similar tendency of organic matter (Table 4). Significantly, more organic matter was observed under SC_5 at 0.38 g kg^{-1} , 0.33 g kg^{-1} , and 0.29 g kg^{-1} at surface (0 to 15 cm) subsurface (15 to 45 cm), respectively in comparison to other scenarios. The results of other scenarios were shown significant throughout the studied soil profile.

Olsen available P is significantly ($p = 0.05$) higher 7.4 mg kg^{-1} , 6.3 mg kg^{-1} , and 6.0 mg kg^{-1} under SC_5 , SC_4 , and SC_3 compared to conventional scenario (SC_1) 4.5 mg kg^{-1} (Table 4). The available P concentration in all scenarios declined with lower soil depth. In the 15 to 30 cm and 30 to 45 cm soil profile, the same trend was observed as in the surface layer (0 to 15 cm). The results among straw management practices were insignificant in all soil depths (Table 4). It may be attributed to high retention of residues on surface and sub-surface, which was moderate to temperature and soil moisture linked to crop growth. Like available P, soil under SC_5 , SC_4 , and SC_3 had significantly higher available K concentration compared to SC_1 (Table 4). Conservation tillage practice (SC_5) had significantly higher concentration 208 mg per kg , 185 mg kg^{-1} , and 144 mg kg^{-1} , whereas lower concentration was observed under available K 127 mg kg^{-1} , 110 mg kg^{-1} , and 105 mg kg^{-1} at 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm, respectively.

The SC_5 resulted maximum extractable Cu (1.12 mg kg^{-1}) significantly higher than other experimental scenarios viz. SC_1 (0.93 mg kg^{-1}), SC_2 (0.72 mg kg^{-1}), SC_3 (0.68 mg kg^{-1}), and SC_4 (0.67 mg kg^{-1}). Insignificant differences in Cu concentration were observed between SC_2 (0.72 mg kg^{-1}) and SC_4 at the top soil depth 0 to 15 cm (Figure 2). At the soil depth 15 to 30 cm, conservation tillage (SC_5) had significantly more Cu concentration (0.60 mg kg^{-1}) than conventional tillage and straw management practices scenarios, while there was no significance difference among SC_1 , SC_2 , and SC_3 on Cu-concentration at this depth (Figure 2). Extractable Cu under SC_4 declined significantly with the decline in soil depth, while in all other scenarios, non-significant results were noted (Figure 2).

Tillage practices and soil depth interaction significantly affected the concentration of DTPA extractable Mn ($p < 0.001$). Conservation tillage practice (SC_5) had significantly greater extractable Mn in all studied depths in comparison with that of all other scenarios i.e., 2.14 , 1.23 , and 0.99 mg kg^{-1} in the 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm, respectively (Figure 2). Irrespective of SC_5 scenario, the straw management practices (SC_4 and SC_3) showed highest extractable Mn concentration than under conventional tillage (SC_1) (0.89 mg kg^{-1} vs. 0.53 mg kg^{-1}) in the 0 to 15 cm and (0.76 mg kg^{-1} vs. 0.46 mg kg^{-1}) in the 15 to 30 cm soil depth (Figure 2). The extractable Mn concentration decreased within the subsoils in all the studied scenarios.

Table 3. Influence of tillage and straw management practices to gravimetric water content (%), electrical conductivity (dS m⁻¹), pH and organic matter (g kg⁻¹) under different soil profiles after harvesting of wheat, 2018 (9 soil samples per plot per 3 replicates for 5 scenarios at three depth; 9 × 3 × 5 = 135).

Scenarios	Gravimetric Water Content (GWC, %)			Electrical Conductivity (dS m ⁻¹)			pH			Organic Matter (g kg ⁻¹)		
	Soil Depths (cm)											
	0–15 cm	15–30 cm	30–45 cm	0–15 cm	15–30 cm	30–45 cm	0–15 cm	15–30 cm	30–45 cm	0–15 cm	15–30 cm	30–45 cm
SC ₁	18.08 h	21.00 fgh	23.69 ef	1.4 d	1.8 c	1.3 de	8.4 abc	8.6 ab	8.8 a	6.5 bc	5.5 def	4.4 g
SC ₂	19.60 gh	24.77 de	31.61 c	1.4 d	2.1 b	2.9 a	8.1 abcd	8.4 abc	8.6ab	6.5 bc	5 efg	4.71 fg
SC ₃	22.78 efg	28.02 d	36.75 b	1.00 g	1.4 d	1.4 d	7.6 cd	7.9 abcd	8.3 abcd	6.3 bcd	5.6 de	5.21 efg
SC ₄	21.07 fgh	27.34 d	36.42 b	1.3 de	1.30 de	1.1 fg	7.81 bcd	8 abcd	8.2 abcd	6.2 bcd	5.5 def	5 efg
SC ₅	25.34 de	35.67 b	41.85 a	1.3 de	1.2 ef	1.1 fg	7.4 d	7.7 bcd	8.21 abcd	7.6 a	6.6 b	5.75 cde

Same alphabetical letters showed non-significant difference at $p = 0.05\%$ at least significant difference test.

Table 4. Influence of tillage and straw management practices to nitrogen (g kg⁻¹), available phosphorus (mg kg⁻¹), and available potassium (mg kg⁻¹) under different soil profile after harvesting of wheat, 2018 (9 soil samples per plot per 3 replicates for 5 scenarios at three depth; 9 × 3 × 5 = 135).

Scenarios	Total Nitrogen (g kg ⁻¹)			Available Phosphorus (mg kg ⁻¹)			Available Potassium (mg kg ⁻¹)					
	Soil Depths (cm)											
	0–15 cm	15–30 cm	30–45 cm	0–15 cm	15–30 cm	30–45 cm	0–15 cm	15–30 cm	30–45 cm			
SC ₁	0.33 b	0.28 ef	0.22 h	4.5 efg	4.1 fgh	3.9 gh	127 efg	110 gh	105 h			
SC ₂	0.33 b	0.25 fgh	0.235 gh	4.7 ef	4.2 fgh	3.8 h	141 de	130 efg	111.13 gh			
SC ₃	0.32 bc	0.28 def	0.26 efg	6 bc	5.5 cd	4.9 de	154 cd	128 efg	116.14 fgh			
SC ₄	0.31 bcd	0.28 def	0.25 fgh	6.3 b	5.7 bc	4.1 fgh	171 bc	154 cd	135 def			
SC ₅	0.38 a	0.33 b	0.29 cde	7.4 a	6.2 b	4.51 efg	208 a	185 b	144.00 de			

Same alphabetical letters showed non-significant difference at $p = 0.05\%$ at least significant difference test.

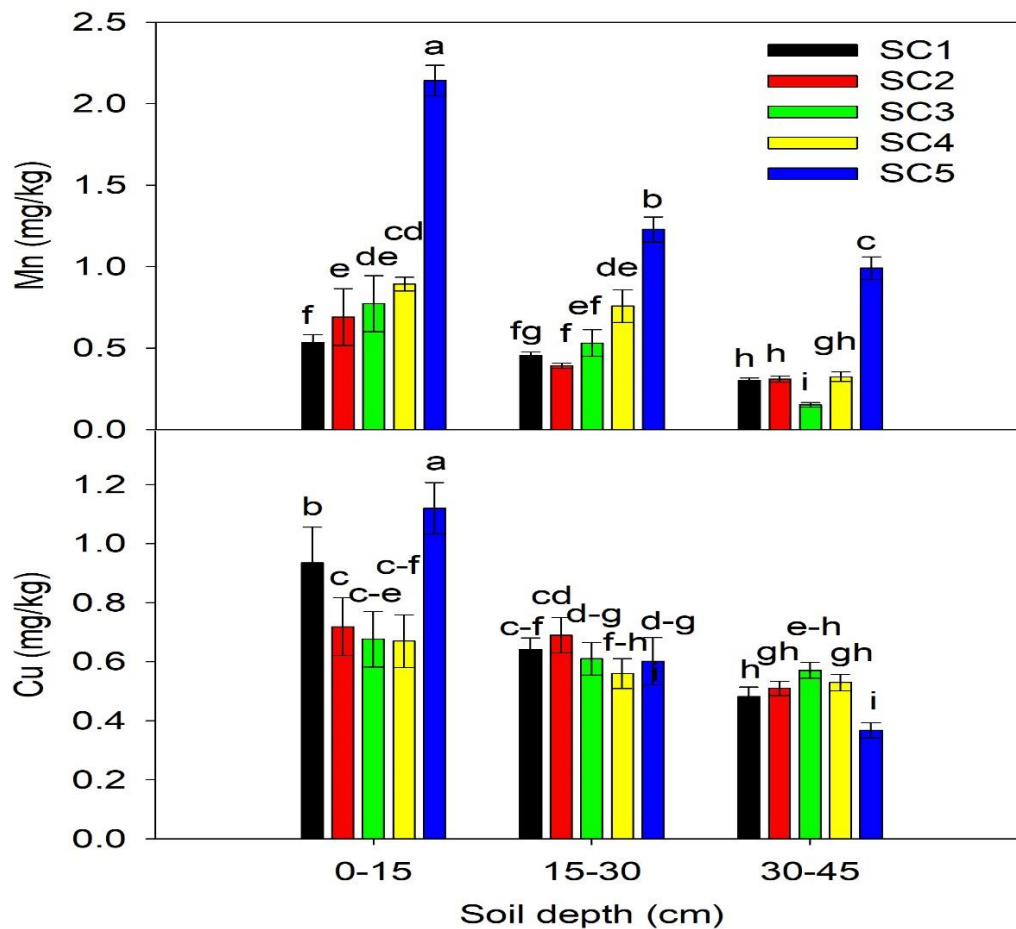


Figure 2. Influence of tillage and straw management practices on DTPA extractable Cu and Mn concentration in different soil depths after six years of rice-wheat cropping rotation. Same letters bars are not significant at 5% probability level (9 soil samples per plot per 3 replicates for 5 scenarios at three depth; $9 \times 3 \times 5 = 135$).

3.2. DTPA-Extractable Micronutrients under Tillage and Residue Management Practices

DTPA extractable Zn-concentration ranged from 4.35 to 1.45 mg kg⁻¹ at 0 to 15 cm, 2.82 to 1.05 mg kg⁻¹ at 15 to 30 cm, and 2.06 to 0.97 mg kg⁻¹ across all scenarios after six years of continuous experiment (Figure 3). Extractable Zn concentration was found to be significantly higher in all soil depths under the SC₅ (4.35 to 2.06 mg kg⁻¹) scenario than the rest of the experimental scenarios used during the research study (Figure 3). SC₅ resulted in statistically significant differences with those of SC₁, SC₃, and SC₂, while no significant differences were found with SC₄ at the 15–30 cm soil profile. In the depth of 30 to 45 cm, conventional tillage showed higher concentration of extractable Zn (1.55 mg kg⁻¹) in comparison with that of SC₂ (0.99 mg kg⁻¹) and SC₄ (0.97 mg kg⁻¹) straw management practices (Figure 3).

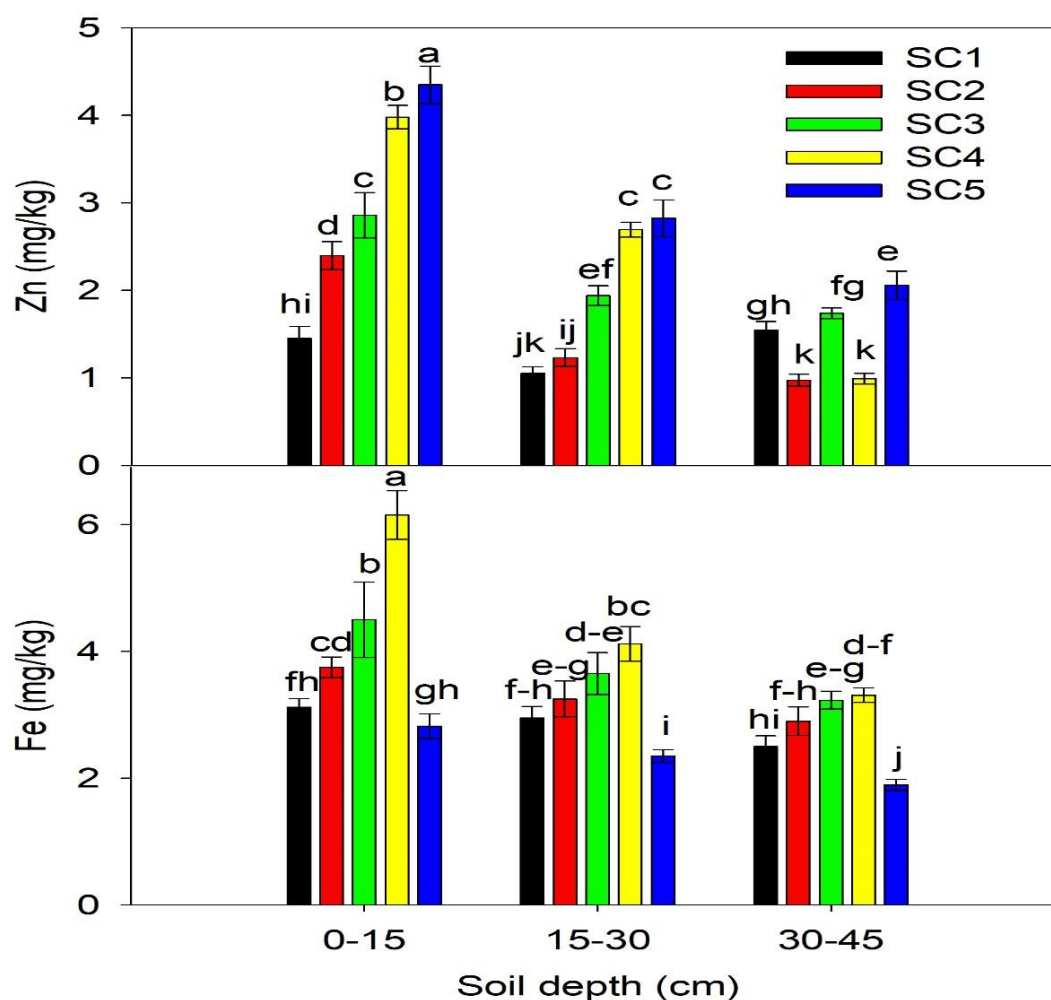


Figure 3. Influence of tillage practices and straw management practices on DTPA extractable Zn and Fe concentrations in different soil depths after six years of rice-wheat cropping rotation. Same letters bars are not significant at 5% probability level (9 soil samples per plot per 3 replicates for 5 scenarios at three depth; $9 \times 3 \times 5 = 135$).

Tillage methods influenced the concentration of extractable Fe, which is comparable among all the scenarios within each soil profile (Figure 3). The Fe concentration was higher on the uppermost soil surface and decreased with the soil depth (15 to 30 cm and 30 to 45 cm) (Figure 3). The Fe concentration (6.15 mg kg^{-1} at 0 to 15 cm, 2.35 mg kg^{-1} at 15 to 30 cm, and 3.31 mg kg^{-1} at 30 to 45 cm) was significantly higher under SC₄ than SC₃, SC₂, SC₁, and SC₅. The lowest concentrations, i.e., 2.82 mg kg^{-1} , 2.35 mg kg^{-1} , and 1.89 mg kg^{-1} were found in the SC₅ (Conservation tillage) scenario in all studied soil profiles i.e., 0 to 15 cm, 15 to 30 cm, and 30 to 45 cm, respectively (Figure 3).

3.3. Correlation Matrix

Most of the soil properties showed significant correlations at proximity level ($p \leq 0.01$ and $p \leq 0.05$), regardless of soil depth and tillage scenarios. Electrical conductivity showed negative significant correlation with all the soil properties (Table 5). Significantly, positive relationship of SOM was recorded with other soil physio-chemical properties except for gravimetric water content (Table 5). Macro and micronutrient correlation was positively significant, except Mn and Fe correlation.

Table 5. Correlation of soil properties and soil nutrients regardless of soil depth and tillage scenarios.

	pH	EC	Av P	Av K	SOM	TN	GWC	Zn	Mn	Fe	Cu
pH	1										
EC	0.339	1									
Av P	-0.546 **	-0.424 **	1								
Av K	-0.592 **	-0.385 **	0.836 **	1							
SOM	-0.515 **	-0.352 *	0.716 **	0.836 **	1						
TN	-0.462 **	-0.327 *	0.708 **	0.743 **	0.879 **	1					
GWC	-0.033	-0.039	-0.074	0.053	-0.196	-0.142	1				
Zn	-0.501 **	-0.452 **	0.879 **	0.810 **	0.661 **	0.696 **	-0.168	1			
Mn	-0.446 **	-0.335 *	0.784 **	0.838 **	0.727 **	0.750 **	-0.022	0.809 **	1		
Fe	-0.206	-0.119	0.405 **	0.211	0.168	0.151	-0.441 **	0.415 **	-0.042	1	
Cu	-0.326	-0.052	0.513 **	0.533 **	0.742 **	0.667 **	-0.512 **	0.442 **	0.538 **	0.162	1

** Significant at the 0.01 level; * significant at the 0.05 level. EC: electrical conductivity; GWC: gravimetric water content; SOM: Soil organic matter; TN: total nitrogen; Av P: available phosphorus; Av K: available potassium; Zn: DTPA-Zn; Cu: DTPA-Cu; Mn: DTPA-Mn; Fe: DTPA-Fe.

4. Discussions

4.1. Soil Physio-Chemical Properties under Tillage-Residue Management Practices

Higher gravimetric water contents at studied soil depths under conservation tillage as compared to farmer's traditional tillage practice (Table 3) could be due to low soil disturbance and residue cover [42]. Higher accumulation of crop residues under conservation tillage resulted in reduction in evaporation, runoff, and improvement in soil infiltration [43]. Another reason for high water content under conservation tillage is to have high volume of medium size pores than conventional tillage [44,45]. In this study, conservation tillage had more gravitational moisture content (7.26%, 14.67%, and 18.16%) at three studied soil depths than conventional tillage practice, which is similar to the results of Wahbi et al., Jat et al., and Kumar et al. [46–48]. They reported that soil moisture content is 7%, 10%, and 20–30% more in conservation tillage than conventional tillage in long-term field trials and increased with increasing soil depth. Similarly, Bachchan et al. and Chimsah et al. [49,50] reported more water storage efficiency 24.5% under ZT than conventional tillage (21.9%).

It is well reported that surface soil acidity increases under conservation agriculture (CA) practices [51–53] due to increase in electrolytes and pH reduction [54,55]. Soil pH is lower at the top of the surface 0–15 cm under SC₅ practice than SC₁, which was reported in earlier studies [47,52,56]. They suggested that CA-based scenarios observed lower pH values on the surface layer due to more organic residues that further releases the organic acid upon decomposition and changes soil pH with increasing soil depth. Contrastingly, soil surface pH reduced with increasing tillage disturbance as reported by Cookson et al. [57], which might differ due to climatic conditions, soil type, and management factors. In this study, EC values declined in conservation tillage than farmer's practice traditional tillage after six years of long term residue management, which are in agreement with Jat et al. [47] who found lower EC with decreasing soil depth. Similarly, Botha [58] reported that no-tillage resulted to be useful in terms of salinity effect on plant growth and had the lowest EC, showing that salts leach out of the profile.

Our results showed that the concentration of soil organic carbon and soil total nitrogen was significantly higher (Table 4) under SC₅ than other scenarios, which results from the mineralization-immobilization processes of incorporated or retained residues in the soil as reported by Das et al. [58]. Under conservation tillage, residues accumulated on the surface and subsurface and slow decomposition of these due to reduced soil disturbance resulted in higher organic C and total N. Earlier work reported that SOC and N concentration increased by 7.7 g kg⁻¹ and 197 kg-ha respectively, at 0 to 15 cm soil after continuous 4 years of rice-wheat rotation in north-west India [18,44,59]. Similarly, Małecka et al. [60] found maximum SOC and total N 10,200 mg kg⁻¹ and 1120 mg kg⁻¹ at top (0 to 5 cm) soil of 7 years continuous no-till in Poland. Whereas, more organic carbon and nitrogen in wet tillage with crop residues incorporation of the rice scenario in comparison with that of other in the deeper soil profile (15 to 30 cm soil depth) was reported earlier [47,61]. Generally, intensive tillage destroyed

the soil structure that can lead to decline in SOC and total N contents in agriculture system [61,62]. Adopting no-till practices will help to reduce the risk of SOC and total N depletion and ultimately produces more SOC and TN in comparison to traditional tillage [63].

Conservation tillage had significantly higher concentrations of P and K in soil compared to conventional tillage (Table 4) and was associated with residue incorporation and their decomposition, which causes recycling of nutrients present in the residues [64,65] and improves nutrient status of N, P, and K in the soil [66,67]. The results of available P (Table 4) showed the higher concentration of nutrients on the surface which agrees with the study of Jat et al. [47] who reported that Olsen P concentration was 38% and 25% higher under straw management practices and conservation tillage compared to conventional farmer's practices at top soil surface [47]. Similarly, Das et al. [21] found 7% more phosphorus under conservation tillage than conventional tillage after three years of the rice-rapeseed rotation system in subtropical eastern Himalayas. Our results suggest that SC₅ practice has shown declining trend of available P along the soil depths. It has been reported in earlier work that conservation tillage had less nutrient concentration under the subsoil profile than the top surface due to reduction of surface runoff and infiltration which allow more nutrients to accumulate on the surface (0–20 cm) [61,68]. Significantly, higher available K was found under SC₅ than other tillage and residue management practices (Table 4). This could be due to the reason that under acidic soils in which K⁺ ions compete with H⁺ ions and hydroxyl-aluminum ions for interchange or interaction with adsorption sites. Thus, it resulted in more K⁺ in the solution phase and decreases the chances of fixation due to organic matter addition [69,70]. While, incorporated rice residues constitutes 2.25% of K among which 65% of K is rapidly available in water soluble form in the soil [71] which may be the reason for higher K concentration under SC₅ tillage practice. Earlier studies reported that available K is higher under conservation tillage due to higher availability of residues for decomposition in comparison to conventional tillage [21,47].

4.2. Soil DTPA-Extractable Micronutrients under Tillage-Residue Management

The data presented in Figures 2 and 3 indicated that DTPA-extractable Cu, Mn, and Zn concentration remained significantly higher under SC₅ than SC₁ at 0 to 15 cm soil depth. The higher Cu, Mn, and Fe concentration might be attributed due to more accumulation of organic matter on the upper surface [47]. The interaction of Cu, Mn, and Zn with soil organic matter resulted in poor soil mixing under low pH, which decreased the Cu, Mn, and Zn availability in the subsoil [72,73]. Similarly, de Santiago et al. [74] reported more Cu, Mn, and Zn concentration under conservation tillage, which is associated with higher SOM and higher microbial activity under less soil disturbance than that of conventional tillage at 0 to 5 cm soil-depth after 21 years of the long term experiment. In the present study, more residues were left in the SC₅ scenario with least soil disturbance resulting from higher Cu, Mn, and Zn availability on the top surface and it decreased with an increase in soil depth, which restricts the movement in the soil due to complexation of Cu, Mn, and Zn with the chelated agents [75]. The Fe (Figure 3) was significantly higher in residue returning practices (SC₄) than other scenarios while conservation tillage showed minimum concentration of Fe (Figure 3), probably due to conditions that favor more available Fe²⁺ than Fe³⁺ fractions [47]. Whereas, some earlier work found no significant changes under long term conservation tillage practices [73,74].

Significant correlation with studied parameters was presented in Table 5. These correlation results (Table 5) corroborated with the finding of earlier work [47,76]. Nnabude et al. and Reardon et al. [77,78] reported correlation at the 0.01 probability level between total nitrogen and organic matter which was strongly significant in tropical agro-ecosystems. Available sulfur, total nitrogen, and organic carbon correlation was positively correlated as reported earlier [79]. Under conservation tillage practices, soil physical and chemical properties were improved due to more organic matter which can be further seen by the significant positive correlation between organic matter and other soil properties [21]. Nandan et al. and Yadav et al. [31,80] also suggested that conservation tillage-based crop establishment practices combined with residue retention have significant impact on soil nutrients and soil carbon that leads to

improved sustainability of the rice-based systems in the region. Positive accumulation of soil nutrients such as nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), copper (Cu), and manganese (Mn), were observed in the present work under conservation tillage in the rice-wheat system of Punjab, Pakistan. Nadan et al. [81] documented the potential of conservation agriculture in their work. They concluded that conservation tillage could increase straw per stover and grain yields of crops. Furthermore, it resulted in higher output energy, net energy, energy ratio, and energy productivity. Similarly, residue retention resulted in reduced net energy, energy ratio, and energy productivity as compared to residue removal. Thus, zero tillage-based crop establishment helps to conserve non-renewable energy, reduce water demand, and increase crop productivity. Similarly, it can also solve the problem of burning of crop residues, which resulted in air pollution in the region. The results confirmed that conservation tillage has great potential to manage resources on a sustainable basis under a changing climate [82–90].

5. Conclusions

Farmers' illiteracy, lack of knowledge, unavailability of the implementation of conservation technology, and limited research on conservation tillage are the major obstacles to adoption of conservation agriculture in this region. The current adoption rate of conservation agriculture is very low due to the above obstacles. However, researchers in close association with farmers can improve soil health by developing and refining conservation agriculture (CA)-based crop management practices for the RWCS in South Asia. This study on tillage, crop establishment, and crop residues (key elements of CA) in the RWCS provides systematic information on the effect of CA-based crop management. The results of the long-term impact of conservation tillage and residue management practices suggest that soil properties and availability of nutrients (viz. N, P, K, Cu, Mn, and Zn) are improved in the surface soil layer in comparison with that of conventional farmers' practice. Significant and positive correlation of organic matter with soil properties and nutrients suggested that higher organic matter has a strong relationship with soil health. Conservation agriculture works on three principles i.e., minimum or no soil disturbance, maintaining soil cover, and promoting biodiversity. Thus, for sustainable crop production in future, it is recommended that conservation agriculture should be considered as a compulsory component of the cropping system. Based on our work, it can be clearly seen that conservation tillage increases carbon sequestration in soil. However, shifting from the traditional tillage system to conservation tillage needs intervention at the national level, which is only possible through a joint venture between farmers and researchers working in universities, research organizations, and extension departments. Since, adoption of new technology needs significant change in behavior, thus training facilities should be provided to the farming communities so that they can see real benefits of conservation tillage at the ground scale. Furthermore, adoption of new technology also follows an 'S' curve with a relatively slow start initially, but afterwards, it moves to an exponential rate if farmers are given opportunities to become leader by having trials on their fields. However, this system can only be cost effective and attractive to farmers if priority is given to the constraints of the farmers (e.g., socio-economic and education) and production objectives. Institutional support is of the utmost importance for the adoption of conservation agriculture at farmers' fields. The agriculturally induced soil degradation can be reversed by adopting conservation tillage as it can ensure the long-term sustainability of agroecosystems. Thus, it is investment with long-term advantage for all i.e., environments, soil, farmers, and society.

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