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Different Tillage and Residue Management Practices Affect Soil Biological Activities and Microbial Culturable Diversity in Rice-Wheat Cropping System Under Reclaimed Sodic Soils

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ABSTRACT

Agricultural management practices alter soil characteristics and influence soil biological properties. Hence, a field trial was carried out to assess the 14-year long-term impact of tillage and residue management practices on soil biological activities and microbial population in a rice-wheat cropping system in two depths viz., 0–15 and 15–30 cm. Soil organic carbon levels differed significantly ($p > 0.05$) across various treatments. Microbial biomass carbon, microbial quotient, and soil enzymatic activities were significantly greater (10–82%) in crop residue incorporation/retention treatments. Zero tillage with residue retention (ZT+R) had the greatest bacterial, actinomycetes, and fungi population, followed by reduced tillage with residue incorporation (RT+R). The ZT+R treatment had the greatest value of K-strategist and r-strategist, and was equivalent to RT+R across both soil depths. When compared to conventional tillage (CT), zero tillage (ZT) increased wheat yield by 9%. However, compared to CT, rice and rice-wheat systems had lower grain yields, whereas crop residue increased wheat and rice-wheat system yields by 10% and 6%, respectively. The findings of this long-term study show that residue management and tillage practices can enhance soil biological attributes while also supporting microbial diversity.

Keywords: microbial population, diversity indices, residue incorporation, conventional tillage, zero tillage.

INTRODUCTION

The degradation of land triggered by salt accumulation in soil poses an imminent risk to sustainable agriculture and its productivity. In India, approximately 6.73 million ha of the soil are pretentious by excessive salt are considered as salt affected areas, accounting for 2.1% of the country's geographical area [Rai et al., 2021a]. Out of which 2.8 million ha of these are sodic, occurring predominately in the alluvial soils of India's Indo-Gangetic plains (IGP). Sodic soils are characterized by presence of excessive soluble salts with exchangeable sodium of more than 15%. Gypsum ($CaSO_4{\cdot}2H_2O$) is most commonly used for soil reclamation for remedial soil sodification because it provides structural stability (more favorable aeration of the soil as well as movement of water) by replacing sodium ions to flocculating calcium ions. However, subsurface sodicity remains a problem in reclaimed sodic soils [Basak et al. 2020]. The rice-wheat cropping system (RWCS), one of the most important cereal-based approaches in western IGP, provides sustenance, nutrition, and economic prosperity to the region. It exists in approximately 10.3 million ha, accounting for roughly half of India's grain output and providing food security along with living to millions of individuals Dhanda et al., 2022. However, productiveness of the RWCS under conventional practice is stagnant or shrinking in the IGP for a variety of reasons, including conventional tillage and excessive resource exploitation [Kumar et al., 2018]. The region of IGP due to over-exploitation is facing several problems like degrading soil health, environmental pollution, lower factor productivity, and decreasing farm profitability [Chauhan et al., 2012]. Conservation agriculture (CA) practices that emphasize minimizing disturbance to the soil, maintaining soil cover by crop residues (CR), as well as diversifying crops are becoming more popular among farmers because they restore soil biodiversity and natural biological processes, increase nutrient use efficiency, and endure crop production. CA practices also address the environmentally hazardous issue of residue burning. Conservation tillage with residue management may be an option for addressing several of the aforementioned issues, as conventional practices of repeated tillage consume a large amount of water and degrade soil health [Chauhan et al., 2012]. Crop quality and yield are strongly linked to the soil's attributes [Sainju et al., 2022; Fagodiya et al. 2023]. The characteristics of the soil encompass available nutrients content, microbial population and its biomass [Paz-Ferreiro and Fu 2016]. The availability or presence of nutrients influences soil microbial population and its biomass [Chandra et al., 2022a]. Microorganism's inhabitant in soil serves a significant function in the soil contributing to its wellness [Rai et al., 2021b]. Soil microbes aid in nutrient transformation and cycling, all of which have an impact on sustainability. The activities of soil enzymes (SM) are associated with soil biological health, which responds quickly with management practices modification and the external environment [Chandra et al., 2022c, 2023]. Tillage and proportion of crop residue incorporation also affect the soil nutrient dynamics, which indirectly or directly impact soil microbes and microbial processes. The carbon to nitrogen ratio (C:N) and decomposable organic C content of soil are directly linked to residue incorporation which influences and promotes soil microorganism's swift multiplication. This process leads to increased microbial biomass and their population, ultimately influencing soil microbial enzymatic processes. As the SM have been strongly related to the pace of microbial facilitated processes, they serve as remarkable indicator of biological health of soil [Yang et al., 2020]. Hence, crops residue incorporation into soil supply organic matter (OM) and C as well as influencing soil biological characteristics [Lehman et al., 2015]. Several studies have been carried out on the evaluation of tillage (TILL) and residue management practices (RMP) on crop yield [Jat et al., 2014; Pandey and Kandel 2020], soil attributes [Singh et al., 2023], and economic profitability [Nawaz et al., 2017] in RWCS. As there is still scarcity of meticulous data which illustrate the influence of TILL and RMP on soil biological properties as well as on microbial diversity in RWCS under reclaimed sodic soils. However, there are some reports on short-term effects of such practices [Jat et al., 2014; Nawaz et al., 2017; Magar et al., 2022] whereas the long-term effect of TILL and RMP on these attributes in RWCS is not studied comprehensively under such types of soil. So, the current investigation was carried out with the hypothesis that TILL and RMP might be linked to improved soil biological properties, variation in diversity along with higher grain yield. The study has the objective to assess the effect of TILL and RMP on soil biological properties, agronomic productivity and relationship between these two in RW system under reclaimed sodic soils.

MATERIALS AND METHODS

Treatment details and experimental setup

An experiment was started since 2006 at the research farm of ICAR – Central Soil Salinity Research Institute, Karnal, Haryana, India and

Table 1. The physicochemical properties of the soil types used in the study; ± standard deviation

Properties	Value
Sand (%)	40.6 ± 2.2
Silt (%)	34.3 ± 1.7
Clay (%)	22.6 ± 1.23
Soil $pH_{1:2}$ (1:2; soil:water)	8.28 ± 0.05
Electrical conductivity EC_e ($dS\ m^{-1}$)	0.90 ± 0.03
Organic carbon (%)	0.7 ± 0.02
$KMnO_4$ oxidizable nitrogen ($kg \cdot ha^{-1}$)	123.0 ± 9.12
Olsen–P ($kg \cdot ha^{-1}$)	26.4 ± 1.7
NH_4OAc–K ($kg \cdot ha^{-1}$)	242.0 ± 10.4
Soil texture	sandy-clay loam
USDA classification	typic natrustalf
Location	28.717° N, 73.967° E, 244 m above MSL

long term viz. fourteen-year period effect was evaluated on soil biological properties. The soil of experimental field represents well-drained reclaimed alkali soil and its soil attributes are mentioned in Table 1. The experimental site has semi-arid type climate and precipitation of 700 mm are received annually, 70% of which falls during the Kharif season (July–September). Treatments were in randomized block design and each treatment was replicated four times. The size of the individual plot was (20 × 15 m) and it remained the same over the years of experimentation. Rice crop was sown as conventional transplanted rice (TPR) in CT and as direct seeded rice (DSR) in RT and ZT. However, wheat was sown as conventional wheat sowing (CWS) in CT, reduced tillage wheat (RTW) in RT, and zero tillage wheat (ZTW) in ZT. The particulars of the treatments are illustrated in Table 2. The soil samples were collected after harvesting of wheat (2019–2020) as described earlier (Singh et al., 2022).

Soil microbial properties

The wet oxidation method [Walkley and Black 1934] and the chloroform fumigation-extraction method [Vance et al., 1987] was followed

Table 2. Crop management practices in different tillage and residue management practices for rice-wheat system

Management practice	CT–R (Farmers' practice)	CT+R	RT–R	RT+R	ZT–R	ZT+R
Field Preparation	Rice: Two passes of disc harrow and puddle harrow each followed by planking Wheat: Two passes of disc harrow and cultivator each followed by one planking	Same as in CT–R	Rice: One pass each of disc harrow and cultivator followed by one planking Wheat: One pass each of disc harrow and cultivator followed by one planking	Same as in RT–R	No tillage	Same as in ZT–R
Residue management	100% crop residues removed	1/3rd crop residue incorporated	Same as in CT–R	Same as in CT+R	Same as in CT–R	1/3rd crop residue retained
Seed rate	Rice: 12.5 kg ha^{-1} for nursery raising Wheat: 100 kg ha^{-1}	Same as in CT–R	DSR: 25 kg ha^{-1} Wheat: 100 kg ha^{-1}	Same as in RT–R	Same as in RT–R	Same as in RT–R
Fertilizer dose (N:P:K)	Rice: 150:60:60 kg ha^{-1} Wheat: 150:60:60 kg ha^{-1}	Same as in CT–R	Rice: 150:60:60 kg ha^{-1}+ 25 kg $ZnSO_4$ ha^{-1} + 7 kg $FeSO_4$ ha^{-1} Wheat: 150:60:60 kg ha^{-1}	Same as in RT–R	Same as in RT–R	Same as in RT–R
Water management	Rice: Continuous flooding for initial 30 days and then irrigation 2 days after disappearance of ponded water Wheat: Irrigation at critical growth stages	Same as in CT–R	Rice: Field was kept moist for initial 15 days and then irrigation based on appearance of small cracks Wheat: Irrigation at critical growth stages	Same as in RT–R	Same as in RT–R	Same as in RT–R
Weed management	Rice: Pretilachlor (Rifit Plus 37% EW) at 1.0 kg ha^{-1} PRE* Wheat: Pendimethalin (Stomp 30% EC) 1.5 kg ha^{-1} PRE followed by pinoxaden (Axial 5.1% EC) 0.05 kg ha^{-1} POST**	Same as in CT–R	Rice- Pendimethalin (Stomp 30% EC) 1.25 kg ha^{-1} PRE followed by bispyribac-sodium (Nominee Gold 10% SC) 0.025 kg ha^{-1} POST Wheat- Pendimethalin (Stomp 30% EC) at 1.5 kg ha^{-1} PRE followed by pinoxaden (Axial 5.1% EC) 0.05 kg ha^{-1} POST	Same as in RT–R	Same as in RT–R	Same as in RT–R

Note: *PRE – pre-emergence (within 2 days after sowing, DAS/transplanting in rice and wheat); **POST – post-emergence (20–25 DAS in DSR and 30 DAS in wheat); CT-R – conventional practice without residue; CT+R – conventional practice with residue; RT-R – reduced tillage without residue; RT+R – reduced tillage with residue; ZT-R – zero tillage without residue; ZT+R– zero tillage with residue for the estimation of oxidizable soil organic carbon (SOC) and microbial biomass carbon (MBC), respectively. Microbial quotient (MQ), is the ratio of MBC to SOC values. Soil alkaline phosphatase activity (AIP) [Tabatabai and Bremner 1969] and dehydrogenase activity (DHA) [Casida et al., 1964] was determined by standard protocol. Culturable microbial population [Chandra et al., 2020] including bacteria (BA), actinomycetes (AC), fungi (FN) and r/K bacterial strategists [Rai et al., 2021b] in the rhizosphere soils were evaluated by serial dilution method. Microbial diversity indices (Simpson's dominance index (SDI), Simpson's index of diversity (SPD), Simpson's reciprocal index (SRI), Shannon-Weiner diversity index (SWD) and Pielou's index of evenness (EV)) were calculated using different equations as described earlier [Suchiang et al., 2020].

Crop yield

At physiological maturity stage rice and wheat were manually harvested in each plot in two random quadrates (3 × 3 m). After air drying the grains to 14% moisture content, the final yield was converted to a per-ha basis and was expressed in $t \cdot ha^{-1}$. The grains from each treatment were manually separated from the straw, and the RWCS productivity was determined as described earlier [Singh et al., 2022].

Statistical analysis

The 'analysis of variance (ANOVA)' technique for the Randomized Block Design (RBD) using the GLM procedure in SAS®9.3 (Cary, NC, SAS Institute Inc., 2012) was applied for data analysis [SAS, 2015]. Tukey's test was used to determine the statistically significant differences between the treatment means at the 5%. Contrast analysis was used for comparison between the means of tillage (conventional, reduced, and zero tillage) and residue (with residue and without residue) practices.

RESULTS

Soil organic carbon, MBC and MQ

SOC differed significantly ($p < 0.05$) within treatments and soil depths (Table 3). In the upper layer, SOC ranged from 0.58% (in CT-R) to 0.84% (in ZT+R). The highest SOC (0.84%) was found in ZT+R. Regardless of the treatments used, SOC values in the lower soil depth were lower than those in the upper soil depth, ranging from 0.46% (ZT-R) to 0.61% (CT+R). Among the three TILL practices, CR addition resulted in significantly ($p < 0.01$) higher SOC values in both depths (Table 7, Figure 1a). Similarly, enhanced SOC was observed in ZT (0.79%) and RT (0.76%) than in CT (0.68%). These variations, nevertheless, didn't seem significant when RT and ZT were used. SOC was significantly greater ($p < 0.01$) in CT (0.57%) versus RT (0.53%) and ZT (0.52%) in lower soil depth (Table 7, Figure 1a).

The values of MBC varied between 130.3 to 288.8 $mg \cdot kg^{-1}$ (0–15 cm) and 107.9 to 235.3 $mg \cdot kg^{-1}$ (15–30 cm) (Table 3). MBC levels were considerably greater in CR incorporation treatments versus all other TILL practices. The MBC was 82, 10 and 14% higher in 0–15 cm depth and 82, 8 and 14% higher in 15–30 cm depth under CT+R, RT+R, and ZT+R treatments, respectively, as respective to non-residue addition treatments.

The contrast analysis of MBC suggested that TILL and RMP impacted it significantly ($p < 0.01$) (Table 7). In both soil layers, residue addition increased MBC by 26 and 25%, respectively, when compared to no residue addition. In both soil depths, MBC was 48 and 45% higher ZT in comparison to CT practice within the RMP (Figure 1b). The MQ varied significantly across treatments (Table 3). The RT-R had the greatest MQ value, and was similar to the RT+R, ZT-R, and ZT+R (Table 3), and the CT-R treatment had the least MQ value in upper soil layer. The ZT-R treatment had the highest MQ in lower soil depth, which was similar to RT-R and significantly higher than the other treatments. TILL and RMP had a substantial impact on MQ (Table 7). MQ was found to be higher with residue incorporation than without residue incorporation in both depths (Figure 1c). ZT and RT, on the other hand, had 30 and 32% higher MQ in the upper layer, respectively, and 61 and 55% higher MQ in the lower layer.

Microbial enzymes

TILL and CR management had an impact on enzymatic activities (AIP and DHA) at both depths (Table 3). In comparison to CT-R, AIP activity was 78% higher in ZT with residue. The highest AIP was found in ZT+R in the

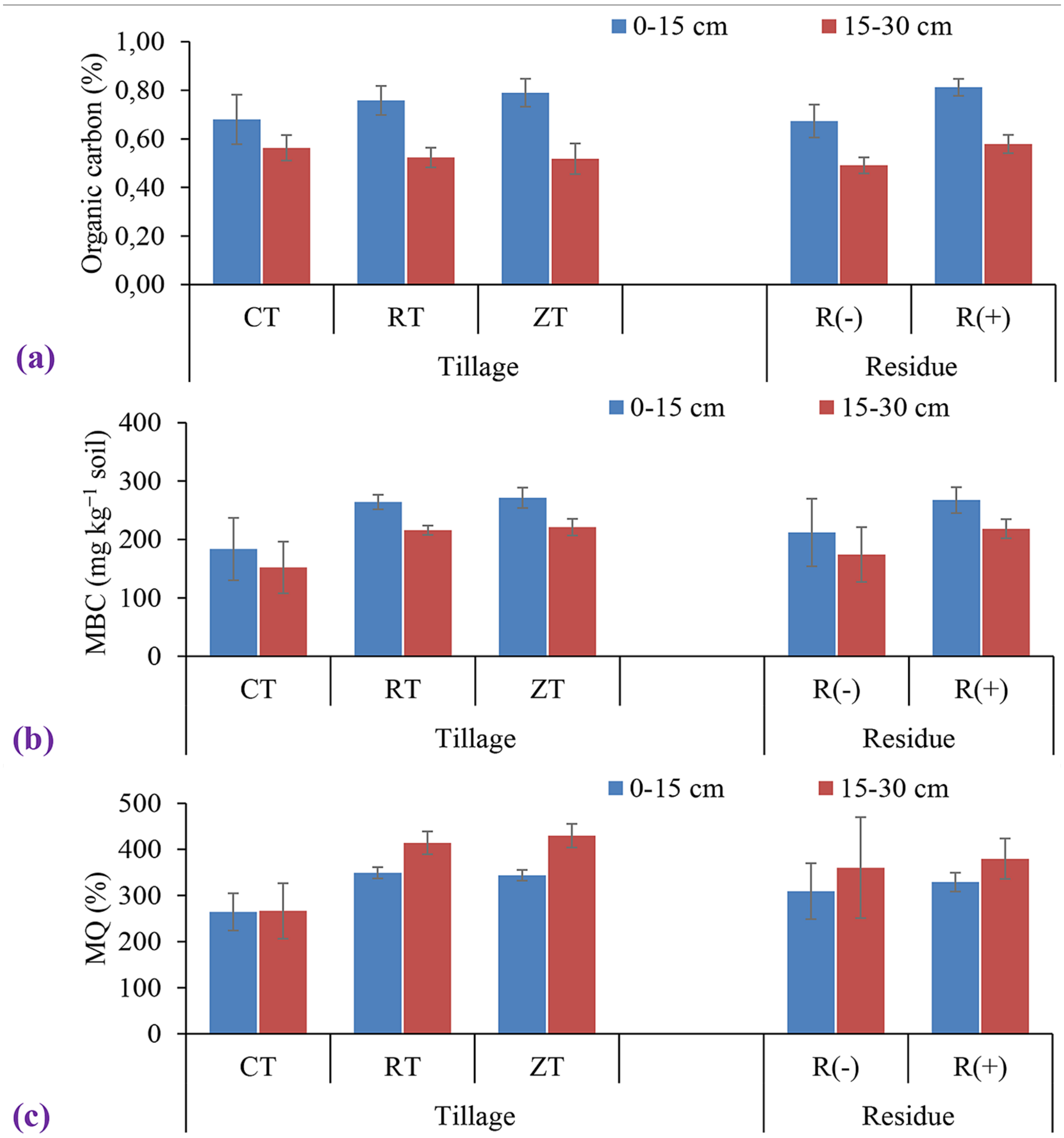

Figure 1. Effect of long-term tillage and residue management practices on (a) organic carbon, (b) microbial biomass carbon, and (c) microbial quotient

upper layer and a similar trend of AlP was observed at lower layer also. At upper soil depth, 65% higher DHA activity was observed in ZT+R as compared to CT-R. A similar trend for DHA was discovered in soil depths of 15–30 cm. The results of the contrast analysis indicated that both TILL and RMP had a significant ($p < 0.05$) impact on enzymatic (AlP and DHA) activities in both soil depths (Table 7). AlP and DHA activity raised by 30 and 22%, respectively, alongside residue addition in 0–15 cm soil depth regardless of TILL management practices. Similarly, in the 0–15 cm soil depth, ZT had 36 and 35% higher AlP and DHA activity than CT. A comparable pattern was observed in the 15–30 cm soil layer also.

Microbial population

Different TILL and RMP molded the population of microbes in soil significantly ($p < 0.01$) across both soil depths (Table 4). ZT+R had the greatest population of BA, AC, and FN, followed by RT+R, however CT-R had the lowest. At upper soil depth, the population of BA, AC, and FN was 82, 87, and 152% more prevalent in ZT+R than in CT-R. A comparable trend of soil microbial population was observed in lower soil layer. The contrast analysis revealed that ZT has a 33, 31 and 84% higher microbial population than CT in upper soil depth. Similarly, CR incorporation enhances the population of BA, AC, and FN by 47, 38,

Table 3. Microbial biomass carbon, microbial quotient and enzymatic activities influenced by long-term tillage and residue management practices

Soil depth	Treatments		OC (%)	MBC (mg·kg^{-1} soil)	MQ (10^{-2} hr^{-1})	AlP (µmol p-nitrophenol g^{-1}·h^{-1})	DHA (µg TPF g^{-1} 24 h^{-1})
0-15 cm	T1	CT-R	0.58^{D}	130.25^{E}	225.12^{C}	113.10^{C}	80.61^{E}
	T2	CT+R	0.78^{AB}	237.00^{D}	303.86^{B}	150.38^{B}	91.06^{BC}
	T3	RT-R	0.70^{C}	251.75^{C}	359.73^{A}	144.37^{B}	89.47^{D}
	T4	RT+R	0.82^{A}	276.50^{B}	338.89^{A}	187.48^{A}	103.60^{B}
	T5	ZT-R	0.74^{BC}	254.00^{C}	343.35^{A}	158.30^{B}	99.29^{C}
	T6	ZT+R	0.84^{A}	288.75^{A}	344.43^{A}	200.82^{A}	133.13^{A}
15-30 cm	T1	CT-R	0.52^{BC}	107.90^{E}	208.03^{D}	97.19^{C}	65.70^{E}
	T2	CT+R	0.61^{A}	196.40^{D}	324.89^{C}	122.76^{B}	83.18^{BC}
	T3	RT-R	0.50^{CD}	207.93^{C}	419.79^{AB}	119.70^{B}	79.54^{D}
	T4	RT+R	0.55^{ABC}	223.74^{B}	408.72^{B}	150.82^{A}	86.88^{B}
	T5	ZT-R	0.46^{D}	206.91^{C}	453.62^{A}	129.02^{B}	82.93^{C}
	T6	ZT+R	0.58^{AB}	235.31^{A}	406.00^{B}	160.68^{A}	106.87^{A}

Note: CT-R: conventional practice without residue; CT+R: conventional practice with 1/3rd residue incorporation; RT-R: reduced tillage without residue; RT+R: reduced tillage with 1/3rd residue incorporation; ZT-R: zero tillage without residue; ZT+R: zero tillage with 1/3rd residue retained/anchored

OC = organic carbon; MBC – microbial biomass carbon; MQ – microbial quotient; AlP – alkaline phosphatase; DHA = dehydrogenase activity. Means with at least one letter common are not statistically significant at $p < 0.05$ using Tukey's

and 41%, respectively at upper soil layer. The K-strategist and r-strategist also diverged substantially across treatments (Table 4) in 0–15 cm depth. In both soil depths, the ZT+R treatment had the most significant value for both K-strategist and r-strategist. According to the contrast analysis, K-strategist and r-strategist varied significantly ($p < 0.01$) across TILL and RMP (Table 7). With residue incorporation, K-strategist and r-strategist increased by 41% across tillage practices. Similarly, among RMP, ZT had a 30% higher population of K- and r-strategists than CT.

Microbial diversity indices

Microbial diversity was influenced significantly ($p < 0.05$) by different TILL and CR management practices (Table 5). In upper soil depth, the SDI, SPD, SRI, SWD, and EV ranges are 0.47–0.50, 0.50–0.53, 1.99–2.14, 0.85–0.93, and 0.61–0.67, respectively. For 15–30 cm, the corresponding ranges were 0.48–50, 0.50–0.53, 1.99–2.09, 0.85–0.93, and 0.61–0.66, respectively. In both soil depths, the ZT+R treatment had the most significant SPD (0.53), SRI (2.14), SWD (0.93), and EV (0.67) values, while CT-R had the lowest. However, a reversal of the trend was observed for SDI, which was substantially ($p < 0.05$) better in CT-R as compared to ZT+R at both depths. The contrast analysis indicated a significant variance ($p < 0.01$) in microbial diversity indices among various TILL and CR management methods (Table 7). In both soil depths, the SDI was better in CT (3%) than ZT. Similarly, it was 2.7 and 1.4% higher in the soil layer without CR treatments, respectively. However, at upper depth, ZT had 2.0–5.6% higher SPD, SRI, SWD, and EV than CT. Similarly, these diversity indices were 4.0–7.0% higher in 15–30 cm ZT than CT. Similarly, CR incorporation resulted in 3.3–3.8 and 1.0–2.1% high diversity in both soil depths.

Crop yield

Rice (4.98–6.84 t·ha^{-1}), wheat (5.52–6.64 t·ha^{-1}), and RWCS (11.41–12.88 t·ha^{-1}) grain yields varied significantly across treatments (Table 6). The grain yield in CT+R (6.84 t·ha^{-1}) treatment had the highest, however it was least in ZT+R treatment (4.98 t·ha^{-1}). Wheat grain yield was highest in RT+R (6.64 tha^{-1}) treatments, which was statistically equal to yield in ZT+R

Table 4. Effect of long-term tillage and residue incorporation on the soil microbial population

Soil depth	Treatments		K-strategist (CFU $g^{-1}\times10^5$)	r-strategist (CFU $g^{-1}\times10^5$)	Bacteria (CFU $g^{-1}\times10^5$)	Actinomycetes (CFU $g^{-1}\times10^4$)	Fungi (CFU $g^{-1}\times10^3$)
0–15 cm	T1	CT-R	4.15^{C}	9.69^{C}	13.85^{C}	12.18^{E}	10.40^{F}
	T2	CT+R	5.25^{B}	12.24^{B}	17.49^{B}	17.50^{BC}	14.90^{D}
	T3	RT-R	4.66^{BC}	10.87^{BC}	14.53^{BC}	14.30^{D}	13.57^{E}
	T4	RT+R	6.96^{A}	16.23^{A}	23.19^{A}	18.81^{B}	21.50^{B}
	T5	ZT-R	4.95^{B}	11.55^{B}	16.50^{B}	16.20^{CD}	20.40^{C}
	T6	ZT+R	7.25^{A}	16.91^{A}	25.15^{A}	22.72^{A}	26.20^{A}
15–30 cm	T1	CT-R	3.39^{C}	7.90^{C}	11.19^{C}	9.92^{E}	8.48^{F}
	T2	CT+R	4.28^{B}	9.98^{B}	14.25^{B}	14.16^{BC}	12.56^{D}
	T3	RT-R	3.80^{BC}	8.86^{BC}	11.66^{BC}	12.65^{D}	12.06^{E}
	T4	RT+R	5.67^{A}	13.23^{A}	20.90^{A}	14.33^{B}	17.34^{B}
	T5	ZT-R	4.03^{B}	9.41^{B}	14.45^{B}	13.10^{CD}	15.63^{C}
	T6	ZT+R	5.91^{A}	13.78^{A}	21.69^{A}	17.52^{A}	21.54^{A}

Note: CT-R: conventional practice without residue; CT+R: conventional practice with 1/3rd residue incorporation; RT-R: reduced tillage without residue; RT+R: reduced tillage with 1/3rd residue incorporation; ZT-R: zero tillage without residue; ZT+R: zero tillage with 1/3rd residue retained/anchored. Means with atleast one letter common are not statistically significant at $p < 0.05$ using Tukey's

Table 5. Effect of long-term tillage and residue management on the microbial diversity indexes

Soil depth	Treatments		Simpson's dominance index	Simpson's index of diversity	Simpson's reciprocal index	Shannon-Weiner diversity index	Pielou's index of evenness
0-15 cm	T1	CT-R	0.50^{A}	0.50^{D}	1.99^{E}	0.85^{E}	0.61^{D}
	T2	CT+R	0.49^{B}	0.52^{B}	2.05^{C}	0.89^{C}	0.64^{C}
	T3	RT-R	0.49^{A}	0.51^{CD}	2.02^{D}	0.87^{D}	0.63^{C}
	T4	RT+R	0.48^{C}	0.52^{AB}	2.08^{B}	0.90^{B}	0.65^{B}
	T5	ZT-R	0.49^{B}	0.51^{BC}	2.04^{CD}	0.90^{B}	0.65^{B}
	T6	ZT+R	0.47^{D}	0.53^{A}	2.14^{A}	0.93^{A}	0.67^{A}
15-30 cm	T1	CT-R	0.50^{A}	0.50^{D}	1.99^{C}	0.85^{E}	0.61^{D}
	T2	CT+R	0.49^{AB}	0.51^{CD}	2.03^{BC}	0.87^{D}	0.63^{CD}
	T3	RT-R	0.49^{BC}	0.51^{BC}	2.06^{AB}	0.89^{C}	0.64^{BC}
	T4	RT+R	0.48^{C}	0.52^{AB}	2.08^{A}	0.90^{BC}	0.65^{AB}
	T5	ZT-R	0.48^{C}	0.52^{AB}	2.09^{A}	0.91^{B}	0.65^{AB}
	T6	ZT+R	0.48^{C}	0.53^{A}	2.09^{A}	0.93^{A}	0.66^{A}

Note: CT-R: conventional practice without residue; CT+R: conventional practice with 1/3rd residue incorporation; RT-R: reduced tillage without residue; RT+R: reduced tillage with 1/3rd residue incorporation; ZT-R: zero tillage without residue; ZT+R: zero tillage with 1/3rd residue retained/anchored. Means with atleast one letter common are not statistically significant at $p < 0.05$ using Tukey'

treatments. The CT+R treatment produced the highest RWCS yield (12.88 $t \cdot ha^{-1}$). Wheat yield contrast analysis revealed that grain yield was 9% higher in ZT than in CT. However, when compared to CT, ZT practice reduced rice and RWCS yield by 23 and 8%, respectively. In comparison to no residue addition, CR boosts wheat and RWCS yield by 10% and 6%, respectively.

DISCUSSION

Incorporation/retention of CR improves SOC in both the soil layers, with the upper layer benefiting the most. The maximum SOC content was reported in ZT+R (0.84%), followed by RT+R (0.82%), which used ZT and RT practices having 1/3 of CR incorporation or retention. It was

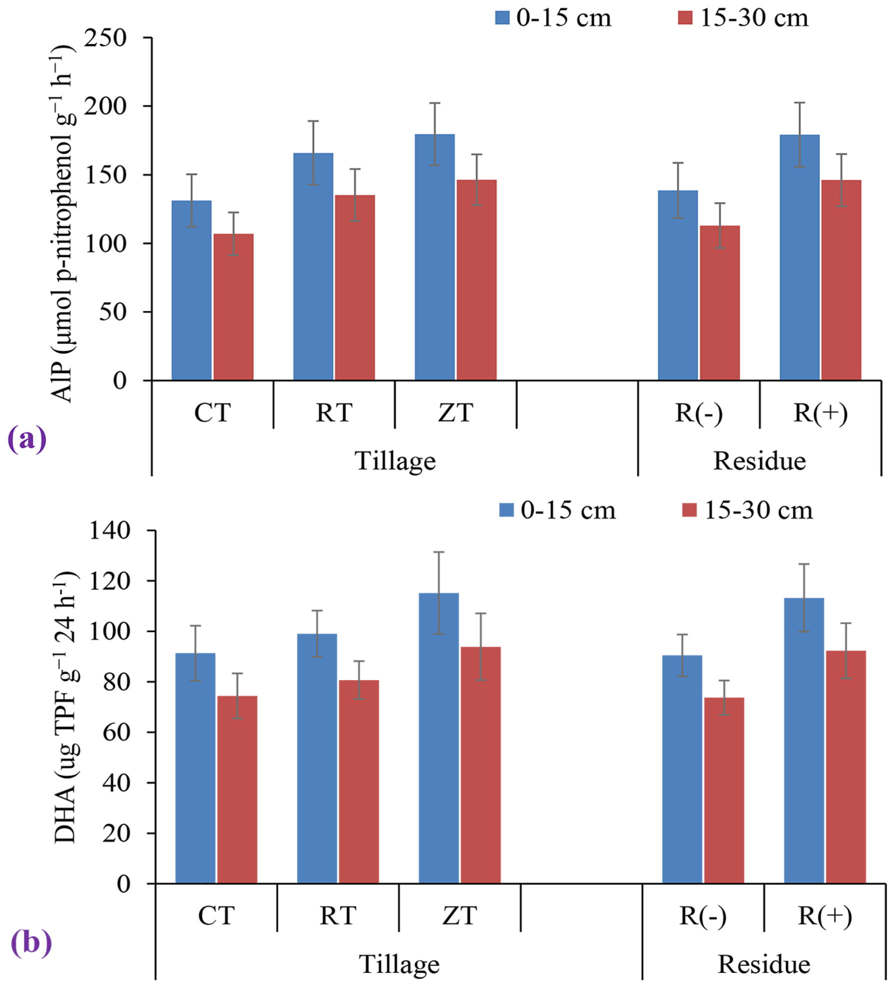

Figure 2. Effect of long-term tillage and residue management practices on enzymes (a) alkaline phosphate (b) dehydrogenase

primarily due to the inclusion of a substantial quantity of CR [Zhang et al., 2020] in ZT practices [Chandra et al., 2023]. Residue incorporation in ZT improves soil structural stability, promotes macroaggregate formation, and reduces aggregate breakdown, resulting in less SOC decomposition [Bhattacharyya et al., 2013; Dutta et al., 2022]. The CT-R (conventional farmers practice) had the lowest SOC. The intensive TILL practices exposed the soils, increasing the rate of SOC decomposition [Ghimire et al., 2017]. It is well established that intensive TILL exposes the soil macro-aggregates associated SOC for microbial decay and causing loss from the soils [Busari et al., 2015; Haddaway et al., 2017]. Microbial biomass carbon is considered as most reliable and important parameter of soil biological health as it directly linked to soil carbon and N cycle which is an important parameters of the nutrient dynamics [Singh and Sharma, 2020]. In all TILL practices, treatments with CR incorporation/retention had significantly higher MBC and MQ than treatments without residue. Similarly, MBC and MQ values were higher in upper soil layer as compared to the 15–30 cm layer which is mainly because of higher availability of CR in upper layer [Behera et al., 2007; Bera et al., 2018]. Incorporation/retention of the CR enhanced the SOC and had positive impacts on soil biological health which enhances the MBC and MQ. Soil enzymes (AlP and DHA) incorporation/retention was significantly higher in RT and ZT practices in comparison to CT practices (Figure 2). In the current study, higher soil enzymatic activities were observed in the upper soil layers than in the deeper depth (Figure 2). This could be because CR incorporation/retention increased microbial biomass C (Table 3) and microbial population (Table 4), which contributed OM and utilized as substrate of SM [Samal et al., 2017]. SM has positive relationship with OM

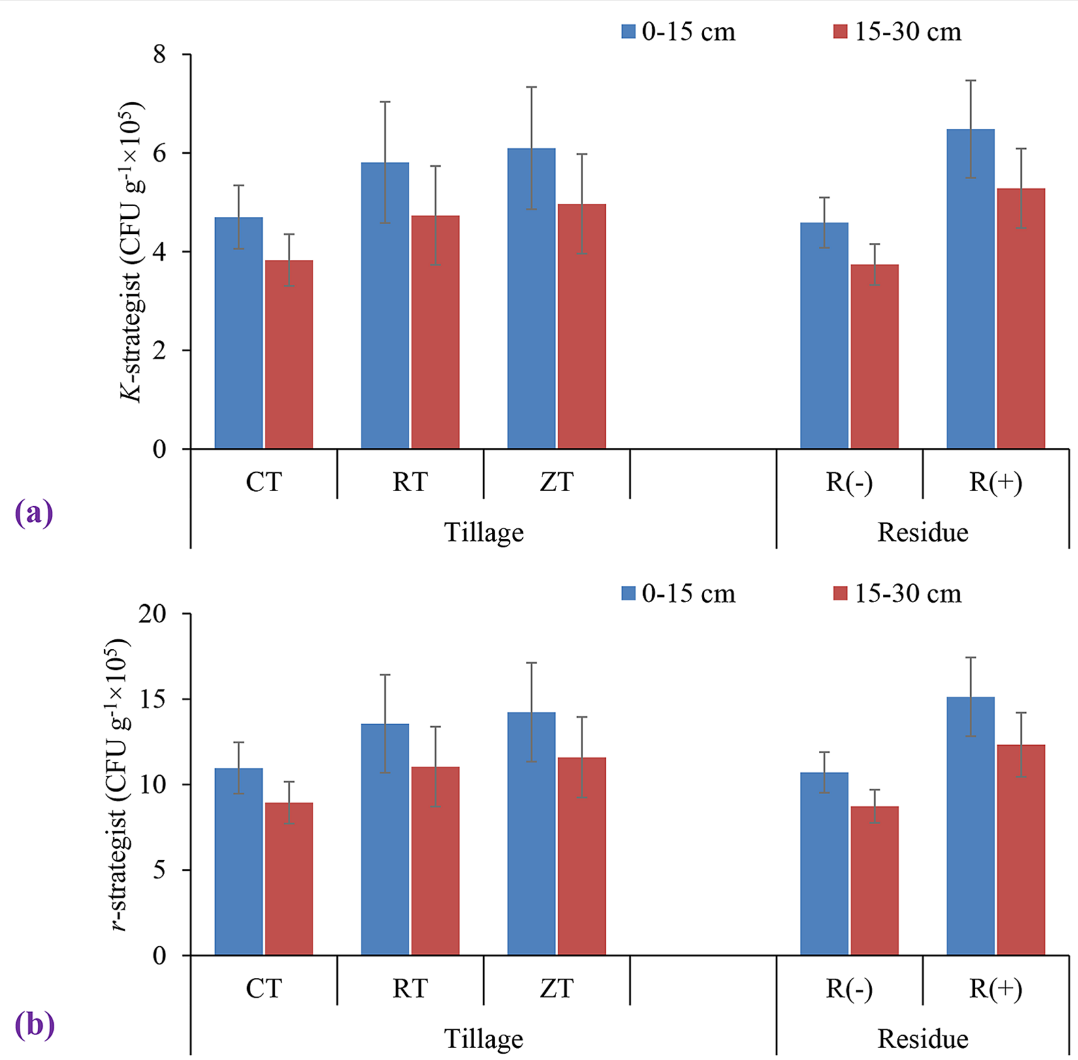

Figure 3. Effect of long-term tillage and residue management practices on (a) K-strategist and (b) r-strategist

Table 6. Effect of long-term tillage and residue management on crop productivity

Treatments		Rice yield-2019 (t ha^{-1})	Wheat yield-2019-20 (t ha^{-1})	Rice-wheat system yield (t ha^{-1})
T1	CT-R	6.53^{AB}	5.52^{B}	12.05^{AB}
T2	CT+R	6.84^{A}	6.04^{AB}	12.88^{A}
T3	RT-R	5.58^{BC}	5.89^{AB}	11.47^{B}
T4	RT+R	5.84^{ABC}	6.64^{A}	12.48^{AB}
T5	ZT-R	5.33^{C}	6.08^{AB}	11.41^{B}
T6	ZT+R	4.98^{C}	6.56^{A}	11.54^{B}

Note: CT-R – conventional practice without residue; CT+R – conventional practice with 1/3rd residue incorporation; RT-R – reduced tillage without residue; RT+R – reduced tillage with 1/3rd residue incorporation; ZT-R – zero tillage without residue; ZT+R – zero tillage with 1/3rd residue retained/anchored. Means with atleast one letter common are not statistically significant at $p < 0.05$ using Tukey's test.

content [Mooshammer et al., 2022], which was higher in these treatments (Figure 1a).

Carbon addition through straw incorporation increased SOC and thus soil biological fertility. Moreover, crop straw contains adequate OM to support microorganism growth [Han et al., 2017]. In the upper layer of soil, surface mulching with straw mulch increases SM activity due to the surface activation effect [Duanyuan et al., 2023]. The study highlighted the significance of crops grown in conjunction with direct seeding systems. The enzyme activity of the phosphatases

Table 7. Analysis of variance for various soil properties influenced by different residue and tillage-based crop establishment treatments at 0–15 and 15–30 cm soil layer

Soil depth (cm)	Contrast	Parameters				
		Soil organic carbon and microbial enzymes				
		OC (%)	MBC (mg·kg^{-1} soil)	MQ (%)	AlP (µmol p-nitrophenol g^{-1} h^{-1})	DHA (ug TPF g^{-1} 24 h^{-1})
0–15	NR vs RR	**	***	**	***	***
	CT vs RT	**	***	***	***	**
	CT vs ZT	**	***	***	***	***
	RT vs ZT	NS	***	NS	**	***
15–30	NR vs RR	**	***	*	***	***
	CT vs RT	**	***	***	***	***
	CT vs ZT	**	***	***	***	***
	RT vs ZT	NS	***	NS	**	***
		Microbial population				
		K-strategist (CFU g^{-1}×10^{5})	r-strategist (CFU g^{-1}×10^{5})	Bacteria (CFU g^{-1}×10^{5})	Actinomycetes (CFU g^{-1}×10^{4})	Fungi (CFU g^{-1}×10^{3})
0–15	NR vs RR	***	***	***	***	***
	CT vs RT	***	***	***	**	***
	CT vs ZT	***	***	***	***	***
	RT vs ZT	NS	NS	NS	***	***
15–30	NR vs RR	***	***	***	***	***
	CT vs RT	***	***	***	**	***
	CT vs ZT	***	***	***	***	***
	RT vs ZT	NS	NS	NS	***	***
		Microbial diversity indices				
		Simpson's dominance index	Simpson's index of diversity	Simpson's reciprocal index	Shannon-Weiner diversity index	Pielou's index of evenness
0–15	NR vs RR	**	**	**	**	**
	CT vs RT	**	NS	**	**	**
	CT vs ZT	**	**	**	**	**
	RT vs ZT	**	**	**	**	**
15–30	NR vs RR	NS	**	NS	**	NS
	CT vs RT	**	**	**	**	**
	CT vs ZT	**	**	**	**	**
	RT vs ZT	NS	**	NS	**	**

		Crop yield (t ha^{-1})		
		Rice (2019)	Wheat 2018–19	Rice-wheat system
	NR vs RR	NS	**	NS
	CT vs RT	**	NS	NS
	CT vs ZT	**	**	**
	RT vs ZT	NS	NS	NS

Note: *NS: non-significant; *: p≤0.05; **: p≤0.01; ***: p≤0.001CT-R: conventional practice; CT+R: conventional practice; RT-R: reduced tillage without residue; RT+R: reduced tillage with residue; ZT-R: zero tillage without residue; ZT+R: zero tillage with residue.

was increased due the existence of OM [Nugroho et al., 2023]. The present research found that the quantity of straw mulching (treatment levels) boosted the activity of SM. Straw mulching also boost the number of soil microorganisms and the levels of soil nitrogen and carbon, while simultaneously offering energy and an ideal environment for soil microbial growth [Wei et al., 2015]. The RMP in the treatments benefited soil by increasing SOC as well as the availability of water hence

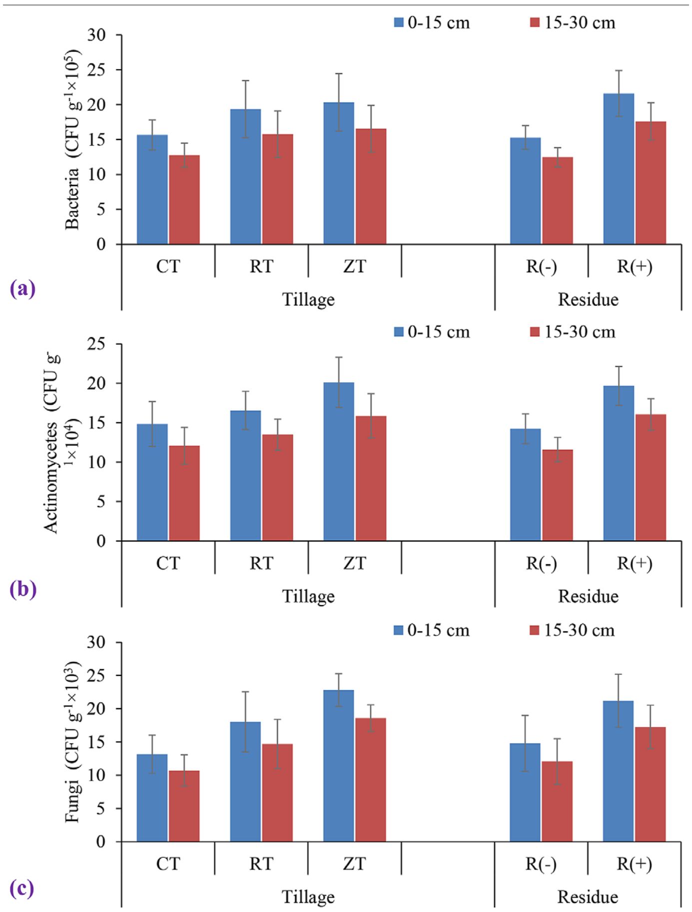

Figure 4. Effect of long-term tillage and residue management practices on soil microbial population (a) bacteria (b) actinomycetes and (c) fungi

improving soil microbial factors. In the current study, the 0–15 cm depth had a greater overall microbial population than the lower depth, presumably attributed to the rhizodeposition process, which is accountable for "nutritional rich topsoil" and determines plant-soil-microbial associations. Root exudates, are a crucial component of the rhizodeposition processes and are composed of organic compounds. They are released from plant roots close to the apical meristem of tap and lateral roots. The abundance of vital nutrients and organic compounds draws microbes around the root proximity, which improve nutrient availability and transport soil OM transformations. This vicinity referred to "rhizosphere" of plants [Chandra et al., 2022b]. Similarly, CR incorporation also leads to improved microbial population which is mainly due to supply of essential nutrients provided by CR in the soil [Chandra et al., 2022a]. CR improves soil SOC significantly when used in conjunction with CA [Bobųská et al., 2015]. r/K strategist was found to be most effective when combined with CR in ZT/RT tillage practices, as r/K strategist is conceptually based on their natural selection for nutrients as a growth limiting factor. Population dynamics change their "either-or" options in rapid rate for acquiring nutrition or a strong preference for nutrients, and they function as "specialists" or "generalists." R strategist population is superior to K strategist population because higher soil C may contribute to greater microbial biomass. This can result in r-strategists that rapidly metabolize available substrates, outcompeting slow-growing K-strategists [Blagodatskaya et al., 2010].

Highest BA, AC and FN population was in ZT/RT tillage practices because physical stress leads active vegetative cells to convert into spores. CR left on the surface or incorporated act as a substrate which triggers growth of microorganisms [Ghimire et al., 2017]. When compared to residue removal under ZT and CT, RT resulted in higher total BA, and AC population [Govaerts et al., 2007]. The high FN population in residue incorporation treatments was primarily due to their critical role in CR breakdown [Frąc

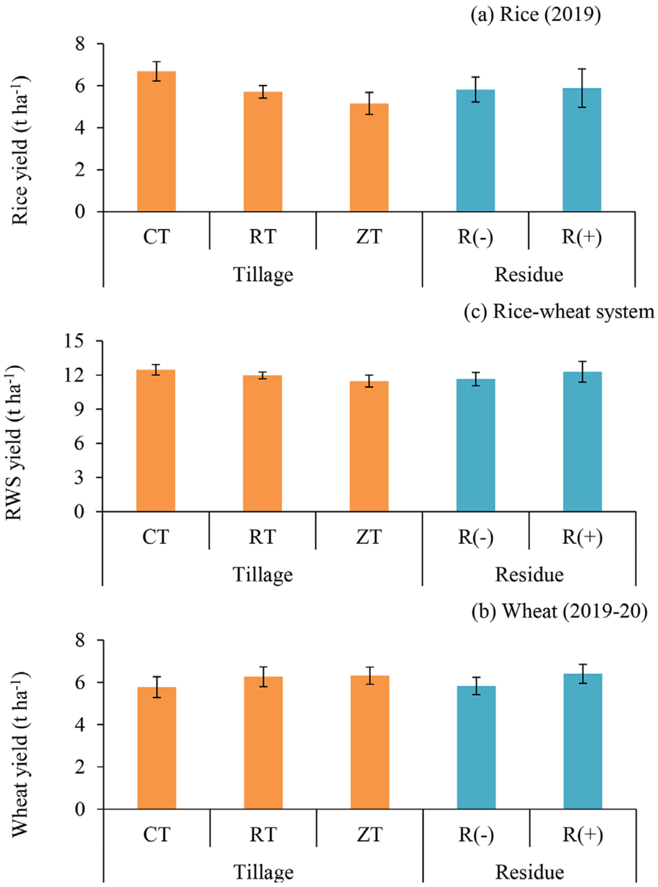

Figure 5. Effect of long-term tillage and residue management practices on (a) rice productivity, (b) wheat productivity, and (c) rice-wheat system productivity

et al., 2018]. Because an array of microbes is required to perform different ecological processes including nutrient cycling mineralization and decomposition, the diversity index regarded as the richness of microbial populations and their functionality along with evenness [Chandra et al., 2020]. As ZT+R have residue incorporation and undisturbed tillage which supports higher nutrient's mineralization, cycling and decomposition led to higher diversity indices and evenness. The results indicated presence of such functional microbes participating in such soil ecological processes including nutrient cycling. SDI represents the dominance of the customary microbial genus of the community. Highest SDI in CT-R and RT-R indicated presence/dominance of very specific soil microbial communities which were preferentially proliferated in these treatments and on the contrary exhibiting reduced diversity [Chandra et al., 2020]. Better yield of wheat was obtained in the ZT and RT as well as in residue incorporation /retention treatments (Table 6, Figure 5) which was in consonance with earlier studies [Jat et al., 2014; Mahanta et al., 2017] carried out in IGP of India due to existence of carbon which is the primary component that influences the fertility of the soil by facilitating the dissolution of various plant-attainable nutrients in soil, thereby determining crop yield. Improvements in fertility of soil and it characteristics have been credited to the advantageous impact of residue incorporation on wheat yield [Thomsen and Christensen 2004; Mitran et al., 2016; Rai et al., 2022]. Under CA practices, residue incorporation significantly improves soil SOC status [Yan et al. 2020]. In an earlier study 18.8% enhancement of rice grain yield was perceived however, such sort of results was not observed in the present study (Table 7) while rice yield was significantly higher in CT as compared to RT and ZT. It has been found that puddling offers an optimal microenvironment, which includes anaerobic atmosphere, less weed competition, and reduced percolation, leading to increased crop yield [Bera et al., 2018].

CONCLUSIONS

Overall, it is concluded that RT and ZT practices increased the soil biological properties comparison to conventional tillage. Further, residue incorporation in RT and retention in ZT improves SOC, MBC and MQ in reclaimed sodic soils. Long term TILL and RMP support the improvement of biological soil attributes. ZT accompanied by residue retention are also associated with the higher microbial diversity index and evenness indicating presence of diverse group of microorganisms while CT supports SDI which means presence of similar types of dominant groups. However, ZT practices reduced the rice yield, CR addition supports yield enhancement. The outcome of the current investigation demonstrates that long-term CR retention improves soil biological status in reclaimed sodic soils.

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