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RESOURCE CONSERVATION TECHNOLOGIES SHAPING RICE YIELD, AVAILABLE NITROGEN, AND CARBON DYNAMICS IN THE TERAI RICE–WHEAT CROPPING SYSTEM

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ABSTRACT

Conservation agriculture practices that reduce tillage and retain crop residues can improve soil health and sustainability in rice–wheat systems, but effects on yield and nutrient distribution vary with management and bio-fertilizer use. We evaluated the effects of two tillage practices (zero tillage, ZT; conventional tillage, CT), residue management (residue retained, R1; residue removed, R0) and seed bio-inoculation (B1, B0) in a factorial randomized block design established on a long-term experiment at Uttar Banga Krishi Viswavidyalaya, Cooch Behar, West Bengal, during the 2023 rice season. Rice (variety MTU-1153) yield, yield components, and soil properties like pH, soil organic carbon (SOC), available nitrogen were measured at 0-5, 5-10 and 10-20 cm depths. CT produced higher grain and straw yields than ZT (maximum grain yield 4.63 t ha^{-1} in CT+B1+R1 while, minimum 3.04 t ha^{-1} in ZT+B0+R0), while ZT with residue retention increased surface SOC and available N stratification. SOC was higher in residue-retained plots and in bio-fertilizer treatments, whereas available N accumulated near the surface under ZT and in deeper layers under CT. Interaction effects showed ZT+R1 increased surface available nitrogen, and CT+R1 increased subsurface nitrogen availability. The results indicate that residue retention and bio-fertilizers enhance SOC and N availability, but site-specific water and weed management are critical to realize yield benefits under ZT in this agro-ecological context.
***Keywords* :** SOC, bio-fertilizer, tillage practices, residue management, available nitrogen.

Introduction

While addressing the constraints presented by rice-wheat cropping systems, conservation agriculture techniques seek to increase the overall sustainability of the agricultural production system by reducing excessive use of water and soil resources and improving environmental quality. Changing from "intensive tillage" to "no or reduced tillage" is one potential solution. The physical, chemical, and biological properties of soil are greatly impacted by reduced tillage (RT) or zero tillage (ZT) because these practices improve aggregation and increase the amount of organic matter in the soil, which in turn affects crop production and sustainability (Kumar *et al*., 2020, 2021). Because it leaves more leftovers in the soil, reduced soil tillage has various benefits over conventional soil tillage with a plough, including limiting soil erosion, decreasing water loss, and cutting crop cultivation costs. The addition of organic matter from leftovers under no-till situations improves soil aggregation and raises the soil's potential to hold onto more carbon, as suggested by Saurabh *et al*. (2021). Preserving this organic carbon is crucial for addressing global climate change, as the reduction of organic carbon is closely linked to the rise in atmospheric carbon dioxide (CO_2) levels (Sinha *et al*., 2023). The production of rice and wheat straw has recently increased in tandem with the continuous growth in rice and wheat production. Crop straw, once widely used as animal feed and household fuel, is increasingly treated as agricultural waste because of changing socioeconomic conditions. Consequently, farmers often burn crop residues to reduce labour and facilitate field preparation, leading to environmental pollution, loss of valuable biomass, degradation of soil health, and adverse impacts on human well-being (Fang *et al*., 2018)). Rice (*Oryza sativa* L.), the staple food for more than half of the world's population, plays a pivotal role in global food security (Yadav, Adhikari, *et al*., 2023; Yadav, Mehata, *et al*., 2023). Sustaining rice productivity requires improved soil fertility through enhanced nutrient availability, reproductive development, and soil quality (Ma *et al*., 2023). Along with appropriate cultivation practices, biofertilizers offer an effective and sustainable approach to achieve these objectives (Eginarta *et al*., 2021; Lestari *et al*., 2021). Besides increasing crop yield, biofertilizers also contribute to maintaining soil fertility and improving overall soil health in rice-based production systems. Incorporating crop residues and bio-fertilizers while focussing on zero and intensive tillage is thus essential. Many problems with soil health may be resolved by proper tillage, which can alter the physical, chemical, and biological characteristics of soil. Considering all these aspects, the present study has been conducted to identify the effects of tillage practice, crop residues and bio-fertilizers on the yield and nutrient uptake characteristics of rice under rice-wheat cropping system.

Materials and Methods

Description of the study area

Tests have been conducted in an unaltered long-term study area that was established in 2006 as a part of the Uttar Banga Krishi Viswavidyalaya research farm in the Cooch Behar District of West Bengal. In 2023, field trials were conducted as experiments with identical treatment designs and field layouts. Located 43 meters above mean sea level and being subtropical and perhumid, the experimental site (26°19' N, 89°23' E) belongs to the Terai agro-climatic region. During the experiment, as clearly seen from figure 1, the temperature varied between a maximum of 32.86 °C to minimum of 31.45 °C with relative humidity varying from 69% to as high as 92.90%. The mean rainfall received during this period is around 20.73 cm, the majority of which is received in June month. The soils in the area are classified as Typic Fluvaquent. The texture of a soil can be loamy sand to sandy loam, its pH can be strong to slightly acidic, its organic carbon content can be medium to high. The soils are poor in terms of available nitrogen and potassium content, although high status in available phosphorus content (Sinha *et al*., 2025). In 0-15 cm soil depth, the initial status of the soil suggests that the available nitrogen content has been found 80.92 kg/ha, the available phosphorus content was found 32.48 kg ha^{-1} and the available potassium content was 59.75 kg ha^{-1}.

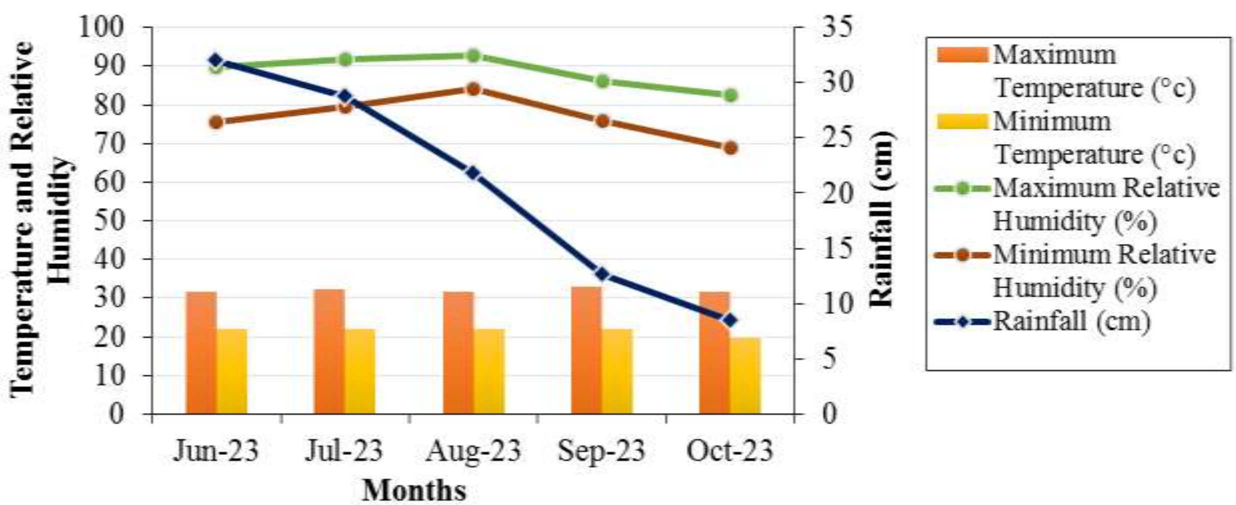

Fig. 1: Meteorological observations during the field experiment

Experimental design:

The field experiment was conducted following factorial randomized block design (RBD) with three factors (tillage practice, crop residue and bio-fertilizer), each of two levels. T1, T2, and up to T8 corresponding to eight treatment combinations. The rice variety used in this experiment was MTU-1153. The recommended dose of straight fertilizer (RDF) has been administered to each treatment. Table 1 provides information on the treatments and combinations of treatments used to the rice and wheat crops (RDF- 100:60:80 $N:P_2O_5:K_2O$ kg ha^{-1}).

Table 1: Treatment description of the experiment

Treatments	Combinations	Description
T1	$ZTB_1 R_0$	Zero tillage + bio-inoculation + residue removed
T2	$ZTB_0 R_0$	Zero tillage + no bio-inoculation + residue removed
T3	$ZTB_1 R_1$	Zero tillage + bio-inoculation + residue added
T4	$ZTB_0 R_1$	Zero tillage + no bio-inoculation + residue added
T5	$CTB_1 R_0$	Conventional Tillage + bio-inoculation + residue removed
T6	$CTB_0 R_0$	Conventional Tillage + no bio-inoculation + residue removed
T7	$CTB_1 R_1$	Conventional Tillage + bio-inoculation + residue added
T8	$CTB_0 R_1$	Conventional Tillage + no bio-inoculation + residue added

ZT= Zero tillage, CT= Conventional tillage, B1= Bio-fertilizer applied, B0= Bio-fertilizer not applied, R1= Residue retained, R0= Residue removed

Plant characteristics record

Yield attributes of Rice were recorded from $1m^2$ area in each treatment plot. Plant height, panicle length, number of tillers per plant, test weight were measured at harvest maturity of the crop. Grain and straw yield of rice were measured and sun-drying and subsequent oven dry weight basis.

Collection of the soil and plant samples

Soil samples have been collected before rice cultivation (post wheat soil) and after rice harvest (post rice soil). Soil samples have been collected from three different depths from each of the plots (0-5 cm, 5-10 cm, and 10-20 cm). A composite soil sample for a treatment plot was created by combining sub-samples taken from four to five uniform places at the specified depth. The collected samples were air-dried, passed through 2 mm sieve and kept in plastic containers for analysis. Samples of grain and straw were taken from three distinct locations, each with a size of one square metre. Seven days before the crop harvest, these samples were collected from every treatment plot.

Analysis of the soil samples

The pH and electrical conductivity (EC) of the soil samples were measured by the soil-water suspension method by Jackson (1973). The organic carbon content in the soil samples (SOC) were measured by wet oxidation method (Walkley & Black, 1934). The soil samples were also analysed for the determination of available nitrogen (Av-N) by steam distillation method (Subbiah & Asija, 1956).

Statistical analysis

The experimental design was according to the factorial Randomized Block Design with three factors each having 2 level. The main effects and interaction effects of the treatments and their significance ($p \leq 0.05$) was measured by R studio (version 4.3.2) and some mean separations of the treatment combinations were done using SPSS statistical software (version 2024.12.1+563). Significance differences between different treatments have been calculated according to Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$.

Results and Discussions

Effect of Tillage, Residue and Bio-fertilizers on Rice yield and growth attributes under Rice-Wheat cropping system

The effects of tillage, residue, and biofertilizers on rice growth and yield are presented in Table 2. Plant height was highest in T7 (127.4 cm) and lowest in T2 (98.75 cm). No significant differences were observed between T3 and T4 or between T5 and T6; however, T3 and T4 recorded significantly greater plant height ($p \leq 0.05$) than T5 and T6. Overall, conventional tillage produced taller plants than zero tillage, likely due to improved soil physical conditions, better crop establishment, and enhanced availability of moisture and nutrients during the early growth stage.

Rice grain yield was higher under conventional tillage (CT) than zero tillage (ZT). The highest grain yield was recorded in T7 (4.63 t ha^{-1}), while the lowest was observed in T2 (3.04 t ha^{-1}). Among the ZT treatments, T3 produced the highest yield (3.86 t ha^{-1}), which was significantly higher ($p \leq 0.05$) than T1, T2, and T4. The lower yields under ZT were likely due to greater weed infestation and poor water retention caused by higher infiltration rates, making weed management more difficult (SETH *et al*., 2020). Straw yield was highest in T8 (5.81 t ha^{-1}) and lowest in T4 (3.62 t ha^{-1}). Overall, CT treatments consistently outperformed ZT treatments in both grain and straw yield.

Status and distribution of soil pH, Available Nitrogen (Av-N) and Organic Carbon in initial soil (post wheat) under Rice-Wheat cropping system.

The pH of the initial (post-wheat) soil differs among the different treatments and among different soil depths. The pH has been found to vary between 5.41-6.15 in 0-5 cm soil depth, 5.11-6.56 in 5-10 cm soil depth and 5.9-6.86 in 10-20 cm soil depth (Table 3). The soil organic carbon (SOC), which is one of the most important factors responsible for the improvement of soil health was found to vary from 1.15% (T6) to 1.53% (T3) at 0-5 cm. At the depth of 5-10 cm, the highest SOC has been found in T3 (1.2%) and the lowest amount of SOC was found in T6 (0.91%). In the lower layer (10-20 cm), the range of SOC has been found from 0.45% (T6) to 0.85% (T3). The SOC concentration was significantly ($p \leq 0.05$) higher in ZT than the CT indicating better carbon sequestration. Under ZT system the residue application has resulted in improvement of SOC. Similarly, SOC increase was also observed in CT where residues were applied (T-7 & T-8). The result finds it's similarity with the findings of the research conducted by Ghimire *et al*. (2012). The maximum amount of Av-N has been found in T1 (200.7 kg ha^{-1}) while the minimum amount of Av-N was found in T5 (147.39 kg ha-1) at 0-5 cm depth. The sequence of the status of Av-N at 0-5 cm is T1>T3=T4>T2>T6=T8>T7>T5. At 5-10 cm, the range of Av-N was found from 150.22 kg ha-1 (T4) to 178.75 kg ha-1 (T5). Critical inspection of the Table 3 further reveals that in 5-10 and 10-20 cm soil depths the average concentration of the nitrogen was more in conventional tillage (CT) due to tilling and mixing of fertilizers in soil. Under zero tillage (ZT) the fertilizers under rice are added on the surface and therefore results in nutrient stratification.

Table 2: Rice yield, growth and yield attributing characteristics under Rice- Wheat Cropping System

Treatments	Plant Height (cm)	No. of Tillers/plant	Panicle length (cm)	Test weight (g)	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})
T1	102.44^{b}	11.5^{bc}	24.49^{ab}	24^{c}	3.11^{a}	3.84^{c}
T2	98.75^{a}	11.4^{b}	22.92^{a}	23.5^{b}	3.04^{a}	3.72^{d}
T3	107.12^{c}	11.4^{b}	25.99^{bcd}	25^{d}	3.86^{d}	4.40^{bc}
T4	105.80^{c}	11.8^{bc}	25.07^{abc}	25^{d}	3.14^{a}	3.62^{bc}
T5	118.18^{d}	11.9^{c}	27.63^{bcd}	21.5^{a}	3.38^{b}	4.64^{ab}
T6	117.78^{d}	10.9^{a}	26.38^{bcd}	23.75^{bc}	3.06^{a}	5.43^{bc}
T7	127.40^{e}	15.2^{e}	27.89^{d}	25^{d}	4.63^{e}	5.37^{a}
T8	121.36^{f}	13.4^{d}	26.64^{bcd}	26.5^{e}	3.59^{c}	5.81^{bc}
S.Em. (±)	1.31	0.23	0.51	0.39	0.06	0.08
C.D. ($p \leq 0.05$)	3.98	0.71	1.54	1.09	0.18	0.23

Means with same letter are not significantly different according to DMRT test at $p \leq 0.05$
CD – Critical difference

Table 3: Status of pH, SOC and Av-N content in initial soil (post wheat) under Rice-Wheat cropping system

Treatments	pH			SOC (%)			AV-N (kg ha^{-1})		
	0-5 cm	**5-10 cm**	**10-20 cm**	**0-5 cm**	**5-10 cm**	**10-20 cm**	**0-5 cm**	**5-10 cm**	**10-20 cm**
T1	5.56	5.11	6.12	1.45	1.02	0.64	200.70	163.07	109.76
T2	6.15	5.75	6.29	1.29	0.93	0.55	166.20	156.80	97.21
T3	5.87	6.56	6.86	1.53	1.20	0.85	172.48	153.66	87.80
T4	5.92	5.98	6.31	1.48	1.19	0.72	172.48	150.52	106.62
T5	5.68	5.31	5.9	1.32	0.93	0.55	147.39	178.75	103.48
T6	5.44	6.1	6.72	1.15	0.91	0.45	163.07	156.80	87.80
T7	5.41	5.34	6.2	1.40	1.15	0.64	153.66	166.20	131.71
T8	5.49	5.17	6.08	1.34	1.00	0.60	163.07	166.20	156.80
Max	6.15	6.56	6.86	1.53	1.2	0.85	200.7	178.75	156.8
Min	5.41	5.11	5.9	1.15	0.91	0.45	147.39	150.52	87.8
CD ($p \leq 0.05$)	**0.005**	**0.01**	**0.01**	**0.002**	**0.003**	**0.003**	**0.30**	**0.16**	**0.39**

Effect of Tillage, Residue and Bio-fertilizer on some important soil properties in post rice.

At the 0–5 cm soil depth, soil pH ranged from 4.85 (T5) to 6.20 (T3) (Figure 2). Soil pH increased with increasing depth, consistent with the findings of Rakesh *et al*. (2020) and Padbhushan *et al*. (2023). In the surface layer, zero-tillage treatments recorded a significantly higher ($p < 0.05$) mean soil pH (5.94) than conventional tillage (5.04). In contrast, treatments with crop residue incorporation showed a significantly lower ($p < 0.05$) mean soil pH (5.36) than those where residue was removed (5.62).

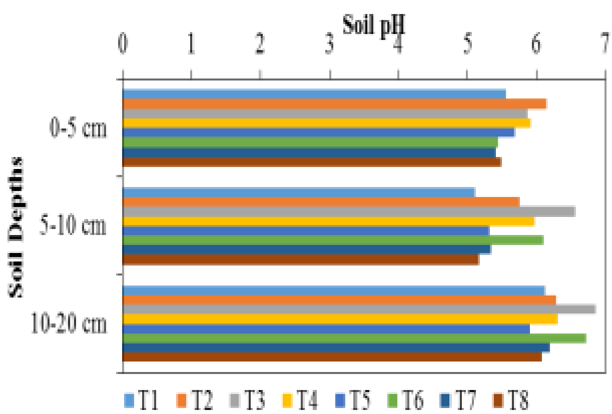

Fig. 2: Changes of pH in post-harvest rice soils under long term Rice-wheat system

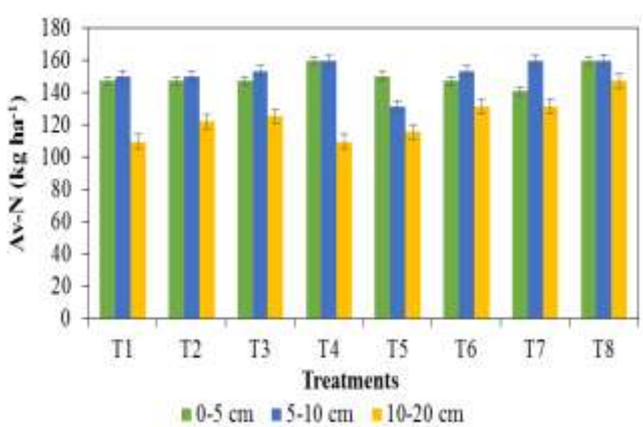

Fig. 3 : Status and distribution of Av-N in post-harvest rice soils under long term Rice-wheat system.

At the 0-5 cm soil depth, the highest SOC content was recorded in T3 and T7 (1.34%), while the lowest was observed in T6 (1.04%) (Figure 4). At the 5–10 cm depth, SOC followed the order T5 > T7 > T6 > T8 > T3 > T4 > T2 > T1. In the 10-20 cm soil depth, the highest SOC was recorded in T5 (0.68%) and the lowest in T2 (0.57%). Overall, SOC decreased with increasing soil depth, primarily because plant residues, the major source of soil organic carbon, accumulate mainly in the surface soil (Lei *et al*., 2019). The effect of tillage, residues and Bio fertilizers on Av-N and SOC are variable. The impact of addition of residues and seed inoculation of Bio-fertilizers in two tillage regimes were more or same. However, the individual effect of the factors presented in Table 4 reveal that at 0-5 cm, Av-N is significantly ($p \leq 0.05$) higher in ZT treatment as compared to CT treatment. The treatment receiving crop residue has significantly ($p \leq 0.05$) higher (152.09 kg ha^{-1}) than the treatments with no residue applied (148.17 kg ha-1). And the treatments where Bio-fertilizers were applied has significant ($p \leq 0.05$) difference (7.06 kg ha^{-1}) with the treatments having no Bio-fertilizer applied.

The post-rice soil's Av-N distribution and status at various depths were found to be greatest in T4 and T8, with 159.93 kg ha-1 at 0–5 cm depth. The amounts of accessible nitrogen at 0–5 cm (147.39 kg ha^{-1}) are identical for T1, T2, T3, and T6. At 5-10 cm, the higher amount of available nitrogen is found in T4, T7 and T8 treatments. The least amount was found in T5 which is 131.71 kg ha^{-1} (Table 4). In the lower layer (10-20 cm), the amount of available nitrogen was found to decrease as compare to the upper layers in each treatment (Figure 3).

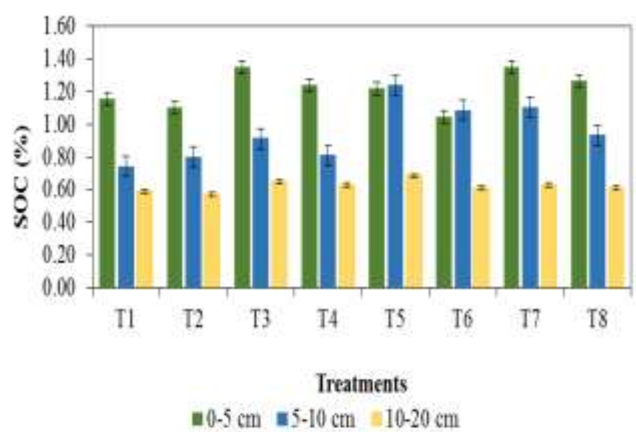

Fig. 4 : Status and distribution of SOC in post-harvest rice soils under long term Rice-wheat system.

Surface residue retention under zero tillage (ZT) increased available nitrogen (Av-N) in the topsoil, whereas under conventional tillage (CT), residue incorporation enhanced Av-N in the 10-20 cm soil layer. Similar findings were reported by Xue *et al.* (2015), who observed greater total nitrogen accumulation in surface soils under no-till but not in subsurface layers. At the 5-10 cm depth, ZT treatments recorded higher available nitrogen than CT treatments. Residue-applied treatments also had greater available nitrogen (158.36 kg ha^{-1}) than treatments without residue (146.60 kg ha^{-1}), while biofertilizer application resulted in significantly lower available nitrogen (Table 4). Soil organic carbon (SOC) at the 0-20 cm depth was significantly lower ($p \leq 0.05$) under ZT than CT. Residue incorporation significantly increased SOC compared with residue removal. Likewise, biofertilizer-inoculated treatments recorded a significantly higher SOC content (0.99%) than non-inoculated treatments (0.90%) (Table 4).

Table 4: Effect of tillage, Residue and Bio-fertilizer on Available Nitrogen and Soil organic carbon in post rice soil in a Rice - Wheat cropping system.

Treatments		Av-N (kg ha^{-1})			SOC (%)		
		0-5 cm	5-10 Cm	10-20 cm	0-5 cm	5-10 Cm	10-20 cm
Tillage	ZT	150.52^a	153.66^a	116.81^b	1.20^b	0.81^b	0.60^b
	CT	149.74^b	151.31^b	131.71^a	1.21^a	1.08^a	0.63^a
CD (*p≤ 0.05*), Tillage		0.05	0.07	0.1	0.0007	0.001	0.0003
Residue	R1	152.09^a	158.36^a	128.57^a	1.29^a	0.93^b	0.62^a
	R0	148.17^b	146.60^b	119.95^b	1.12^b	0.96^a	0.61^b
CD (*p≤ 0.05*), Residue		0.05	0.07	0.1	0.0007	0.001	0.0003
Bio- fertilizer	B1	146.60^b	148.96^b	120.73^b	1.26^a	0.99^a	0.63^a
	B0	153.66^a	156.01^a	127.79^a	1.16^b	0.90^b	0.60^b
CD (*p≤ 0.05*), Bio-fertilizer		0.05	0.07	0.1	0.0007	0.001	0.0003

Means with same letter are not significantly different according to DMRT test at p ≤ 0.05 CD – Critical difference

The interaction effect between Tillage and Residue is explained in Table 5. ZTR1 has the maximum amount of available nitrogen (153.66 kg ha^{-1}) at 0–5 cm, whereas ZTR0 exhibits the lowest amount (147.39 kg ha^{-1}). The CTR1 displays the higher values of available nitrogen (159.93 kg ha^{-1}) at a depth of 5-10 cm, whereas the CTR0 treatment represents the least amount (1425.68 kg ha^{-1}). Additionally, CTR1 has the most available nitrogen in 10–20 cm (139.55 kg ha^{-1}). Under ZT and CT, residue had a significant effect on Av-N. In case of SOC, the interaction of the ZT with residue increased the content of the SOC in 0-20 cm soil (Table 5) layer further corroborating the advantage of the combined effect of both ZT and residues. Residue decomposition is poor under anaerobic rice system.

Table 5: Significant Interaction effect of Tillage X Residue interaction on Available Nitrogen and Soil organic carbon in post rice soils.

Treatment	Av-N (kg ha^{-1})			SOC (%)		
	0-5cm	**5-10cm**	**10-20cm**	**0-5cm**	**5-10cm**	**10-20cm**
CTR1	150.52^b	159.93^a	139.55^a	1.30^a	1.01^b	0.61^c
CTR0	148.96^c	142.68^d	123.87^b	1.13^c	1.15^a	0.64^a
ZTR1	153.66^a	156.80^b	117.60^c	1.29^b	0.85^c	0.63^b
ZTR0	147.39^d	150.52^c	116.03^d	1.12^d	0.76^d	0.57^d

Means with same letter are not significantly different according to DMRT test at p<0.05

Conclusion

Residue, tillage and bio-fertilizer have positive correlation to the yield and other growth attributes of rice. Although many studies suggested a better response in zero tillage as compared to the conventional tillage, the present study has resulted in poor crop yield in zero tillage owing to lower water retention and high weed infestation. Strong impact has been found between the SOC content and the interaction effect of tillage and residue. The impact of tillage practice has significant impact on the availability of nitrogen in the soil as at the depth of 0-10 cm, under available nitrogen has been found in ZT than in CT conditions. Also, the positive interaction has been found between residue retention and the soil available nitrogen content. At 5-10 cm depth the residue retained treatments have shown higher available nitrogen (158.36 kg ha^{-1}) as compared to the residue removed treatments (146.60 kg ha^{-1}). Residue and Bio-fertilizers application increases the quantity and rate of nitrogen mineralization in soil and thus it is found that significantly higher ($p \leq 0.05$) values when bio-fertilizer is applied with residues at 5-20 cm soil depth.

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Author Contribution: The work has been carried out with the contributions of all authors. Author SB has carried out the field work and laboratory analysis. Author SS wrote the original draft, did statistical analysis and generated figures. Author AKS has conceptualized the work, wrote the protocol and did data curation. Author NR did the statistical analysis. Author PS collected literatures and did formatting of the manuscript. Authors JDS and SP did laboratory analysis. Author MS generated the figures and collected literatures. All authors have read and approved the final manuscript.

Competing Interests: The authors declare that there is no conflict of interests.

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