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Influence of Tillage, Residue, and Nutrient Management Practices on Physico-chemical and Biological Properties of Soil under Salt-affected Conditions in Wheat (*Triticum aestivum* L.) Crop

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Sustainable soil management practices such as conservation tillage, residue retention, and integrated nutrient management are important for improving soil health and crop productivity under salt-affected conditions. The field experiment was conducted during the rabi season of 2022-23 at the Research Farm, School of Agriculture, Galgotias University, Greater Noida, Gautam Buddh Nagar, Uttar Pradesh, India. The experiment was laid out in a split-plot design with three replications. The main plot treatments consisted of two tillage systems, viz., zero tillage and conventional tillage. The sub-plot treatments comprised five residue and nutrient management practices: 100% rice residue (RN_1), no residue + 100% recommended dose of fertilizers (RDF) (RN_2), 100% rice residue + 75% RDF (RN_3), 100% rice residue + 100% RDF (RN_4), and 100% rice residue + 125% RDF (RN_5). The results revealed that tillage and residue–nutrient management practices had a non-significant effect on soil pH, organic carbon, and electrical conductivity. However, relatively higher values of organic carbon were observed under zero tillage and RN_5 (100% rice residue + 125% RDF), followed by RN_1 (100% rice residue). In contrast, available nitrogen (N), phosphorus (P), and potassium (K) were significantly influenced by the treatments, with values increasing over the initial soil status. Zero tillage in combination with residue and nutrient management practices significantly enhanced the availability of N, P, and K in the soil after crop harvest. The highest available N, P, and K were recorded under RN_5 (100% rice residue + 125% RDF). Furthermore, soil biological properties were markedly influenced by the treatments. The maximum microbial population of bacteria (39.06×10^6 CFU g^{-1}), fungi (14.13×10^3 CFU g^{-1}), and actinomycetes (21.63×10^4 CFU g^{-1}) was recorded under zero tillage. Among residue and nutrient management practices, the highest microbial population of bacteria (39.79×10^6 CFU g^{-1}), fungi (14.88×10^3 CFU g^{-1}), and actinomycetes (22.12×10^4 CFU g^{-1}) was observed with RN_5 (100% rice residue + 125% RDF).

Keywords: Tillage, crop residue management; nutrient management; physico-chemical properties; microbial population and wheat productivity.

1. Introduction

The Indo-Gangetic Plains (IGP) constitute approximately 15% of India's total land area and have played a pivotal role in the success of the Green Revolution (Koshal 2014). This region contributes nearly half of the country's total food grain production, supporting about 40% of the population. Characterized by deep, fertile alluvial soils, the IGP is highly suitable for intensive cropping systems, including double and triple cropping (Gangwar et al., 2006; Pal et al., 2009). The rice–wheat cropping system, covering about 9.2 million hectares in India, is a cornerstone of national food security (Jat et al., 2020).

Globally, wheat is cultivated over an area of approximately 215 million hectares, with a total production of around 785 million tonnes. China has the highest wheat production (136.6 million tonnes), followed by India (112.01 million tonnes). During 2021–22, India recorded a wheat cultivation area of 30.47 million hectares, with a production of 106.84 million tonnes and an average productivity of 3507 kg ha^{-1} (Statista, 2023). Soil salinity is known to be a significant threat to food security for the increasing population, which is further aggravated under the climate change scenario. Indo-Gangetic plain (IGP) is one of the most productive in the world and is most affected by salinity (Jaiswal et al., 2022).

Tillage is the process of physically disturbing the soil with tools and instruments to make it easier for crops to grow. Zero tillage, sometimes called no-till or direct planting, means planting crops in soil that hasn't been prepared or disturbed by normal tillage processes. The goal of this approach is to keep the soil healthy and stable while causing as little disruption as possible. On the other side, reduced or minimum tillage is all about cutting down on the number of times you have to till the soil to plant a certain crop. Conventional tillage is a labour-intensive way to get the field ready for planting that requires several passes of tillage machinery. This technique modifies soil structure by adjusting soil bulk density and moisture content, facilitating the disruption of the plough pan, enhancing infiltration, and integrating organic and chemical additives in light-textured soils (Bartaula et al., 2020). A cutting-edge kind of sustainable agriculture, conservation agriculture (CA) involves reducing tillage, maintaining constant soil cover, using a variety of cropping techniques, and effectively utilizing the resources at hand (Gulaiya et al., 2025). Regular and continual tillage has a big effect on the soil's physical, chemical, and biological qualities. So, it's very important to use tillage methods that don't affect the soil structure, keep agricultural yields high, and keep ecosystems stable. These practices, which include methods such as no till, strip till, mulch till, and ridge till, aim to minimize soil disturbance, thereby promoting a range of environmental, economic, and agronomic benefits (Bezboruah et al., 2024). This strategy strives to improve ecological integrity and reconstruct rural livelihoods in addition to raising farm productivity and profitability (Gulaiya et al., 2024).

Soil salinity increased during the winter season (crops grown during October to February) hence decreased microbial biomass, soil respiration, and enzyme activities as compared to monsoon (the crop sown at the beginning of the summer rains during June to September (Mitran et al., 2021).

Crop residue management (CRM) is a cultural practice that keeps more of the leftovers from the last crop and requires fewer and/or less intensive tillage operations. Its goal is to help protect soil and water resources and provide other environmental benefits (Gulaiya et al., 2023). Crop residue is the parts of plants that are left in the fields after they have been harvested or grazed. Putting these leftovers in the ground or preserving them on the surface with conservation farming methods is excellent for the soil in a number of ways. These strategies, which include physical, chemical, and biological elements, make the soil structure better. This lowers the soil's bulk density and makes it easier for water to flow through it. Keeping crop waste on the surface cuts down on runoff and makes it simpler for water to soak in. This saves both soil and water resources and leads to higher yields in the next crops. The way crops are grown and the way they are left over both have an effect on soil conditions, either directly or indirectly. Using the right methods for managing agricultural residue makes the soil better, boosts productivity, and has less of an impact on the environment. Burning food scraps hurts the earth and pollutes the air. Burning the rest of the material eliminates microbes and makes the soil unfit for growing plants. Soil residue burning also makes it easy for macro and micronutrients to evaporate (Gulaiya et al., 2023). Bajpai et al., (2006) say that Integrated Nutrient Management (INM) is a good way to keep soil healthy and increase crop yields. There are many parts of the soil that affect how plants can get micronutrients. These include water-soluble, exchangeable, available, reducible, soluble, and residual fractions. Furthermore, soil characteristics such as pH, electrical conductivity (EC), organic matter content, presence of free lime, soil moisture levels, ratios of clay and silt fractions, types of clay minerals present, and concentrations of interacting ions also influence the availability of micronutrients in the soil, as noted by Munawery et al., (2011). Nevertheless, 75% RDF + FYM at 5 tonnes ha^{-1} + Zinc Sulphate at 12.5 kg ha^{-1} demonstrated superior values across all assessed properties, with organic carbon exhibiting a significantly higher level compared to NM1 (RDF: 120: 60: 40), NM2 (RDF + Zinc Sulphate at 25 kg ha^{-1}), and NM3 (RDF + FYM at 5 tonnes ha^{-1}); however, it was statistically comparable to NM4 (75% RDF + FYM at 10 tonnes ha^{-1}) (Yadav et al., 2026).

2. Material and Methods

A field experiment was undertaken during the rabi season of 2022–23 at the Research Farm, School of Agriculture, Galgotias University, Greater Noida, Gautam Buddh Nagar, Uttar Pradesh, India. The experiment took place at a location with a latitude of 28.368867° N and a longitude of 77.540302° E, and the site was 228 m above sea level. The climate in this area is semi-arid and subtropical. The mean minimum temperature fell to 3.79°C in the second week of January, and the mean maximum temperature rose to 38°C in April. In the rabi season of 2022–23, there was a total of 356 mm of rainfall. The soil in the test field was sandy clay loam.

The soil of the experimental field was sandy clay loam in texture. Prior to the initiation of the experiment, representative soil samples were collected and analyzed to determine the initial physico-chemical properties of the soil. The initial soil pH was 8.35, indicating slightly alkaline conditions, while the electrical conductivity (EC) was 5.78 dS m^{-1}. The soil was medium in organic carbon content (0.41%). The available macronutrient status showed that the soil was medium in available nitrogen (185.9 kg ha^{-1}) and phosphorus (9.8 kg ha^{-1}), and low in available potassium (130.3 kg ha^{-1}).

The experiment consisted of ten treatment combinations arranged in a split-plot design. The main plot treatments included two tillage systems, viz., zero tillage and conventional tillage. The sub-plot treatments comprised five residue and nutrient management practices: 100% rice residue (RN$_1$), no residue + 100% recommended dose of fertilizers (RDF) (RN$_2$), 100% rice residue + 75% RDF (RN$_3$), 100% rice residue + 100% RDF (RN$_4$), and 100% rice residue + 125% RDF (RN$_5$). For the analysis of soil physical, mechanical, and chemical properties, soil samples were collected from multiple locations within the experimental field at a depth of 0–15 cm before the application of fertilizers. The collected samples were thoroughly mixed to form a representative composite sample. These composite samples were then processed and analyzed using standard laboratory procedures to determine the physico-chemical characteristics of the soil.

The total number of actinomycetes, bacteria, and fungus in the soil sample was found using the procedures of serial dilution-agar plating. To make a microbiological suspension, a substance with a known weight of 10 grams was mixed or suspended in a known volume of sterile water (90 milliliters, to bring the total volume to 100 milliliters).

No. of cells ml^{-1} or g = No. of colonies (average of 3 replication) × Dilution factor Dilution factor = Reciprocal of the dilution (e.g. $10^{-9} = 10$).

Table 1. Status of soil before the start of experiment.

Texture	Sandy clay loam (sand: 53.21%, silt: 16.42%, and clay: 30.37%).
Soil pH	8.35
Electrical Conductivity (dSm^{-1})	5.78
Organic Carbon (%)	0.41
Available Nitrogen (kg ha^{-1})	185.9
Available Phosphorus (kg ha^{-1})	9.8
Available Potassium (kg ha^{-1})	130.3

3. Results and Discussion

3.1 Effect of Tillage, Residue and Nutrient Management Practices on Soil Physico-chemical Properties of Soil

The data presented in Table 2 and Fig. 1 revealed that different tillage methods exerted a non-significant effect on soil pH. Nevertheless, comparatively lower soil pH (8.23) was recorded under zero tillage, whereas conventional tillage exhibited a slightly higher pH value (8.27). Likewise, residue and nutrient management practices did not significantly influence soil pH. Among the treatments, the minimum pH (8.19) was observed under the application of 100% rice residue along with 125% RDF, while the maximum pH (8.32) was recorded with the application of 100% rice residue alone. The non-significant variation in soil pH across treatments may be attributed to the buffering capacity of the soil, which resists abrupt changes in soil reaction over a short experimental period.

Table 2. Effect of tillage, residue and nutrient management practices on soil physico-chemical properties of soil

Treatment	pH	Organic carbon (%)	Electrical conductivity (dSm^{-1})
Factor A: Tillage			
ZT-Zero tillage	8.23	0.51	5.68
CT-Conventional tillage	8.27	0.48	5.74
SEm (±)	0.13	0.01	0.10
CD (P=0.05)	NS	NS	NS
Factor B: Residue and nutrient management practices			
RN_1-100% rice residue	8.32	0.46	5.79
RN_2-No residue + 100% RDF	8.29	0.48	5.76
RN_3-100 % rice residue + 75 % RDF	8.25	0.49	5.73
RN_4-100% rice residue + 100% RDF	8.21	0.52	5.66
RN_5-100% rice residue + 125% RDF	8.19	0.53	5.61
SEm (±)	0.24	0.02	0.24
CD (P=0.05)	NS	0.05	NS
Interaction Factor A × B			
SEm (±)	0.34	0.02	0.33
CD (P=0.05)	NS	NS	NS

Similarly, soil electrical conductivity (EC) was not significantly affected by different tillage methods, as indicated in Table 2 and Fig. 1. However, relatively lower EC (5.68 dS m⁻¹) was recorded under zero tillage, whereas conventional tillage resulted in a slightly higher EC value (5.74 dS m⁻¹). Different residue and nutrient management practices also failed to exert a significant influence on soil EC. Among the treatments, the lowest EC (5.61 dS m⁻¹) was observed with the application of 100% rice residue + 125% RDF, whereas the highest EC (5.79 dS m⁻¹) was recorded under 100% rice residue application alone. The non-significant differences in EC may be attributed to the short duration of the study and the inherent buffering capacity of the soil, which minimizes rapid fluctuations in soluble salt concentration.

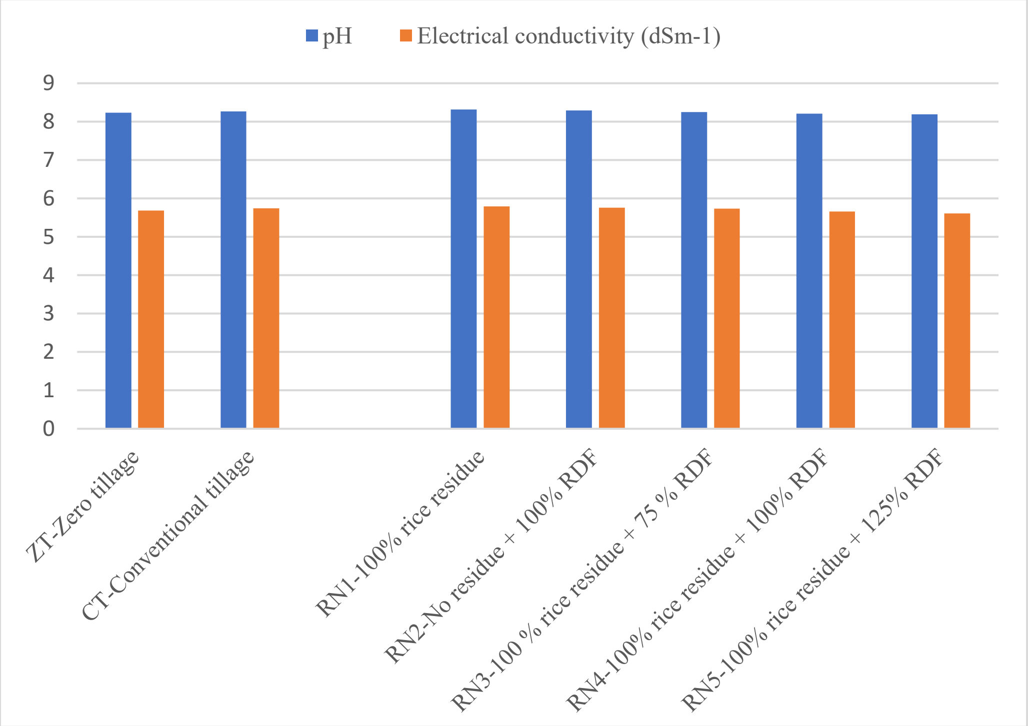

Fig. 1. Graph showing Effect of tillage, residue and nutrient management practices on pH and Electrical Conductivity

The soil organic carbon content was also non-significantly influenced by different tillage practices during the experimental period, as presented in Table 2 and Fig. 2. However, comparatively higher organic carbon content (0.51%) was recorded under zero tillage compared to conventional tillage (0.48%). The relatively higher organic carbon under zero tillage may be attributed to reduced soil disturbance and greater retention of crop residues on the soil surface, which favour carbon accumulation and reduced oxidation losses.

Similarly, residue and nutrient management practices did not exert a statistically significant effect on soil organic carbon content. Nevertheless, the maximum organic carbon content (0.53%) was observed with the application of 100% rice residue along with 125% RDF, whereas the minimum value (0.46%) was recorded under the application of 100% rice residue alone. The improvement in soil organic carbon under integrated residue and nutrient management treatments may be attributed to the combined effect of residue addition and enhanced microbial activity, which facilitates greater biomass production and stabilization of carbon in the soil system.

The results revealed that soil pH, electrical conductivity (EC), and organic carbon content were non-significantly influenced by different tillage and residue–nutrient management practices. Nevertheless, slight variations among the treatments were observed. Zero tillage recorded comparatively lower soil pH and EC, along with relatively higher organic carbon content, as compared to conventional tillage. The higher organic carbon content under zero tillage may be attributed to reduced soil disturbance and greater retention of crop residues on the soil surface, which favour improved soil aggregation and accumulation of organic matter.

Similar findings were reported by Rhoton et al., (1993) who observed enhanced soil organic carbon and only marginal changes in soil chemical properties under conservation tillage systems.

Among the residue and nutrient management practices, treatment RN_5 (100% rice residue + 125% RDF) resulted in comparatively lower soil pH and EC, along with higher organic carbon content, whereas RN_1 (100% rice residue) recorded relatively higher pH and EC with lower organic carbon content. The slight reduction in soil pH under higher residue and nutrient application may be attributed to the formation of organic acids during residue decomposition and increased microbial activity in the soil. Similarly, the marginal decline in EC might be associated with improved nutrient uptake and redistribution within the soil system. Although the differences among treatments were statistically non-significant, the observed trends suggest that integrated residue and nutrient management practices, particularly when combined with zero tillage, may contribute to gradual improvement in soil health. These conservation-based practices enhance soil organic matter dynamics, stimulate microbial processes, and help maintain favourable soil physico-chemical properties over time. Therefore, the long-term adoption of such management strategies may play a significant role in improving soil quality and sustaining crop productivity.

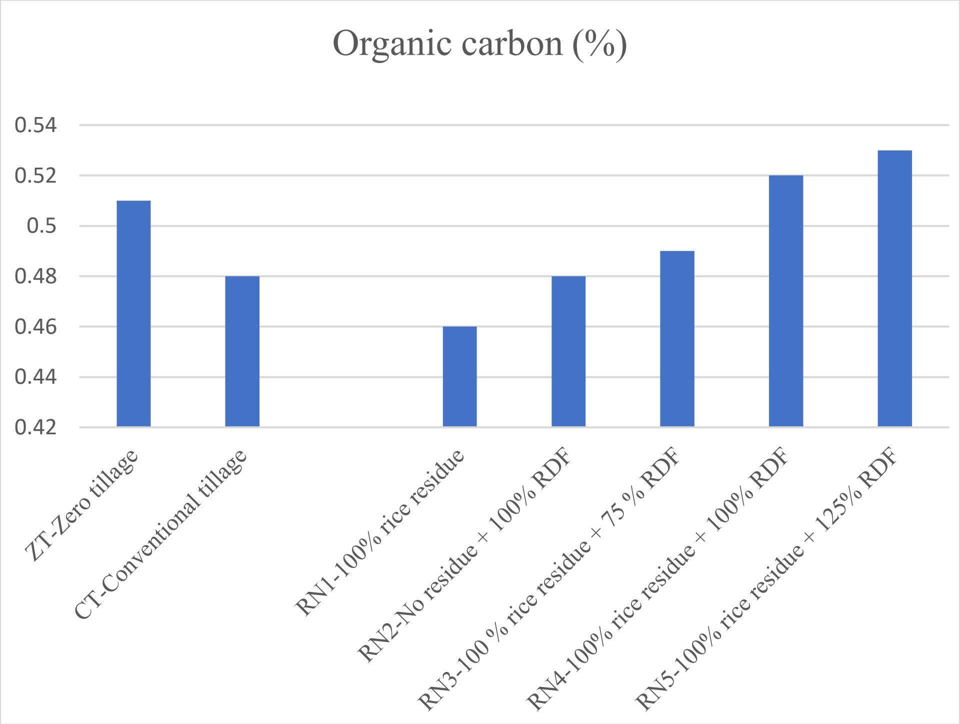

Fig. 2. Graph showing Effect of tillage, residue and nutrient management practices on Organic Carbon (%)

3.2 Effect of Tillage, Residue and Nutrient Management Practices on Status of Nutrient in Soil

The data presented in Table 3 and Fig. 3 revealed that different tillage methods significantly influenced the availability of nitrogen (N) in the soil after crop harvest. Among the tillage treatments, zero tillage recorded significantly higher available nitrogen (218.29 kg ha^{-1}), whereas the lowest value (204.42 kg ha^{-1}) was observed under conventional tillage. The higher nitrogen availability under zero tillage may be attributed to reduced soil disturbance, greater retention of crop residues, and enhanced mineralization processes, which collectively improve nutrient conservation and nitrogen cycling within the soil system.

Residue and nutrient management practices also exerted a significant effect on available nitrogen content in the soil. The maximum available nitrogen (226.80 kg ha^{-1}) was recorded under treatment RN_5 (100% rice residue + 125% RDF), which remained statistically at par with RN_4 (100% rice residue + 100% RDF; 220.59 kg ha^{-1}). In contrast, the minimum nitrogen availability (193.48 kg ha^{-1}) was observed under RN_1 (100% rice residue). The increase in available nitrogen under integrated residue and nutrient management treatments may be attributed to the combined effect of fertilizer application and decomposition of crop residues, which enhance nitrogen mineralization and improve nutrient availability in the soil.

Available phosphorus (P) content in the soil was also significantly influenced by tillage practices, as presented in Table 3 and Fig. 3. Zero tillage recorded the highest available phosphorus content (20.03 kg ha^{-1}), whereas conventional tillage exhibited the lowest value (16.48 kg ha^{-1}). The improvement in phosphorus availability under zero tillage may be attributed to reduced phosphorus fixation, increased microbial activity, and improved soil biological processes that facilitate phosphorus solubilization and availability.

Table 3. Effect of tillage, residue and nutrient management practices on status of nutrient in soil

Treatment	Available nitrogen (kg ha^{-1})	Available phosphorus (kg ha^{-1})	Available potassium (kg ha^{-1})
Factor A: Tillage			
ZT-Zero tillage	218.29	20.03	148.87
CT-Conventional tillage	204.42	16.48	143.79
SEm (±)	0.79	0.27	0.64
CD (P=0.05)	5.19	1.75	4.16
Factor B: Residue and nutrient management practices			
RN$_1$-100% rice residue	193.48	12.79	138.68
RN$_2$-No residue + 100% RDF	204.80	16.43	143.61
RN$_3$-100 % rice residue + 75 % RDF	211.11	17.90	146.14
RN$_4$-100% rice residue + 100% RDF	220.59	20.99	150.33
RN$_5$-100% rice residue + 125% RDF	226.80	23.18	152.91
SEm (±)	2.26	0.89	1.66
CD (P=0.05)	6.84	2.69	5.02
Interaction Factor A × B			
SEm (±)	3.20	1.26	2.35
CD (P=0.05)	NS	NS	NS

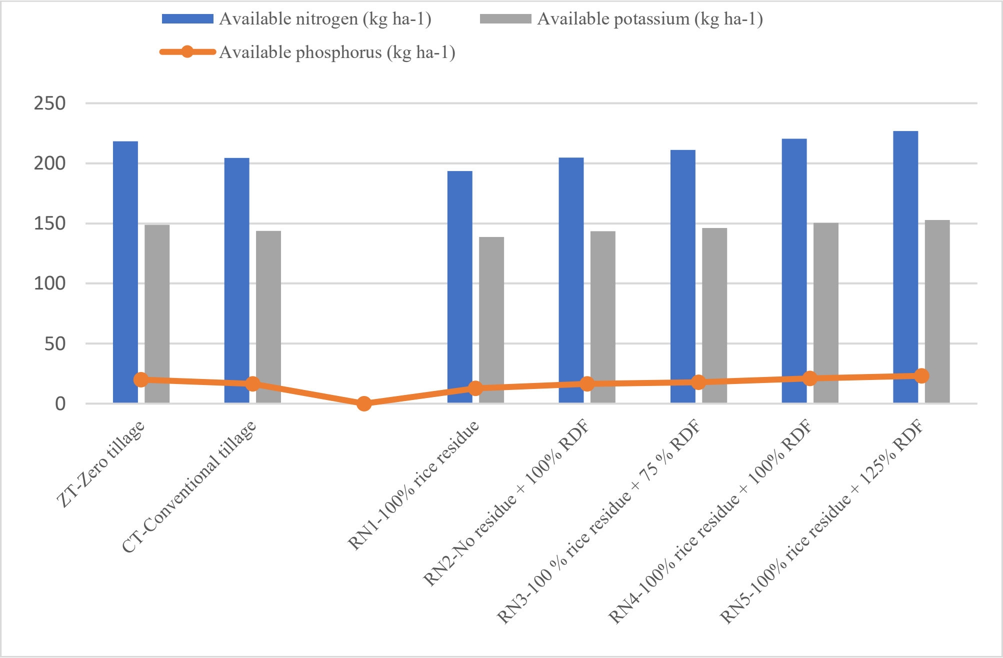

Fig. 3. Graph showing effect of tillage, residue and nutrient management practices on status of Available Nitrogen, Phosphorus and Potassium of soil

Similarly, residue and nutrient management practices significantly affected the available phosphorus content in the soil after harvest. The highest available phosphorus (23.18 kg ha^{-1}) was observed under treatment RN_5 (100% rice residue + 125% RDF), which was statistically at par with RN_4 (100% rice residue + 100% RDF; 20.99 kg ha^{-1}). The lowest phosphorus availability (12.79 kg ha^{-1}) was recorded under RN_1 (100% rice residue). The enhanced phosphorus availability under integrated treatments may be due to the combined application of fertilizers and crop residues, which improve phosphorus cycling, reduce fixation losses, and enhance microbial-mediated nutrient transformation in the soil.

Available potassium (K) content was significantly influenced by both tillage and residue–nutrient management practices (Table 3). Among the tillage treatments, zero tillage recorded significantly higher available potassium (148.87 kg ha^{-1}), whereas conventional tillage recorded the lowest potassium content (143.79 kg ha^{-1}). The higher potassium availability under zero tillage may be attributed to reduced nutrient losses through leaching and enhanced recycling of potassium through retained crop residues.

Among the residue and nutrient management practices, treatment RN_5 (100% rice residue + 125% RDF) recorded the highest available potassium content (152.91 kg ha^{-1}), which was statistically at par with RN_4 (100% rice residue + 100% RDF; 150.33 kg ha^{-1}). In contrast, the lowest potassium availability (138.68 kg ha^{-1}) was observed under RN_1 (100% rice residue). The increased potassium availability under integrated residue and nutrient management treatments may be attributed to residue mineralization and fertilizer addition, which collectively improve soil nutrient reserves and nutrient recycling processes. The results indicated that conservation-based management practices, particularly zero tillage combined with integrated residue and nutrient management, improved the availability of major nutrients in the soil. Enhanced nutrient availability under these treatments may be associated with improved residue retention, reduced nutrient losses, greater microbial activity, and better nutrient cycling within the soil system. These findings suggest that long-term adoption of zero tillage along with integrated residue and nutrient management practices can play a vital role in sustaining soil fertility, improving soil health, and enhancing the productivity of cropping systems.

Available nitrogen (N), phosphorus (P), and potassium (K) contents in the soil were significantly influenced by both tillage and residue–nutrient management practices. Among the tillage treatments, zero tillage recorded comparatively higher available N, P, and K contents than conventional tillage. This improvement may be attributed to reduced soil disturbance, enhanced crop residue retention, and improved soil structure under zero tillage, which collectively favour nutrient conservation and minimize losses through leaching and volatilization. Furthermore, the accumulation of organic matter under zero tillage promotes microbial activity, thereby enhancing nutrient mineralization and increasing the availability of essential nutrients in the soil.

Among the residue and nutrient management treatments, RN_5 (100% rice residue + 125% RDF) consistently recorded the highest available N, P, and K contents, followed by RN_4 (100% rice residue + 100% RDF). These findings clearly indicate the beneficial effect of integrated residue retention along with higher nutrient application on soil fertility status. The enhanced nutrient availability under these treatments may be attributed to the combined effect of gradual nutrient release through residue decomposition and the direct supply of nutrients through fertilizer application. In addition, decomposition of organic residues enhances soil microbial activity, which plays a vital role in nutrient cycling and transformation processes within the soil system.

The increased availability of phosphorus under integrated treatments may be associated with reduced phosphorus fixation and enhanced solubilization mediated by microbial activity, whereas the higher potassium availability could be attributed to the release of non-exchangeable potassium from soil minerals along with efficient recycling through crop residues. Similar findings were also reported by Fang et al. (2018) and Andrews et al. (2021) who observed improved nutrient availability under conservation tillage and integrated nutrient management practices.

3.3 Biological Properties of Soil as Influenced by Tillage, Residue and Nutrient Management Practices

The microbial population comprising bacteria, fungi, and actinomycetes in the soil after crop harvest was non-significantly influenced by tillage practices during the experimental period, as presented in Table 4 and Fig. 4. However, comparatively higher microbial populations were recorded under zero tillage (ZT) than conventional tillage (CT). Under zero tillage, the populations of bacteria, fungi, and actinomycetes were 39.06 × 10^6 CFU g^{-1}, 14.13 × 10^3 CFU g^{-1}, and 21.63 × 10^4 CFU g^{-1}, respectively, whereas the corresponding values under conventional tillage were 38.29 × 10^6 CFU g^{-1}, 13.26 × 10^3 CFU g^{-1}, and 20.99 × 10^4 CFU g^{-1}, respectively. The relatively higher microbial population under zero tillage may be attributed to minimal soil disturbance, improved soil moisture retention, and enhanced availability of organic substrates due to residue retention, which collectively create a favourable environment for microbial proliferation and activity.

Table 4. Biological properties of soil as influenced by tillage, residue and different nutrient management practices

Treatment	**Bacteria** (× 10^6 CFUg^{-1})	**Fungi** (× 10^3 CFUg^{-1})	**Actinomycetes** (× 10^4 CFUg^{-1})
Factor A: Tillage			
ZT-Zero tillage	39.06	14.13	21.63
CT-Conventional tillage	38.29	13.26	20.99
SEm (±)	0.75	0.21	0.38
CD (P=0.05)	NS	NS	NS
Factor B: Residue and nutrient management practices			
RN_1-100% rice residue	37.77	12.53	20.51
RN_2-No residue + 100% RDF	38.11	13.10	20.86
RN_3-100 % rice residue + 75 % RDF	38.48	13.62	21.30
RN_4-100% rice residue + 100% RDF	39.22	14.35	21.78
RN_5-100% rice residue + 125% RDF	39.79	14.88	22.12
SEm (±)	1.14	0.62	0.62
CD (P=0.05)	NS	NS	NS
Interaction Factor A × B			
SEm (±)	1.61	0.88	0.87
CD (P=0.05)	NS	NS	NS

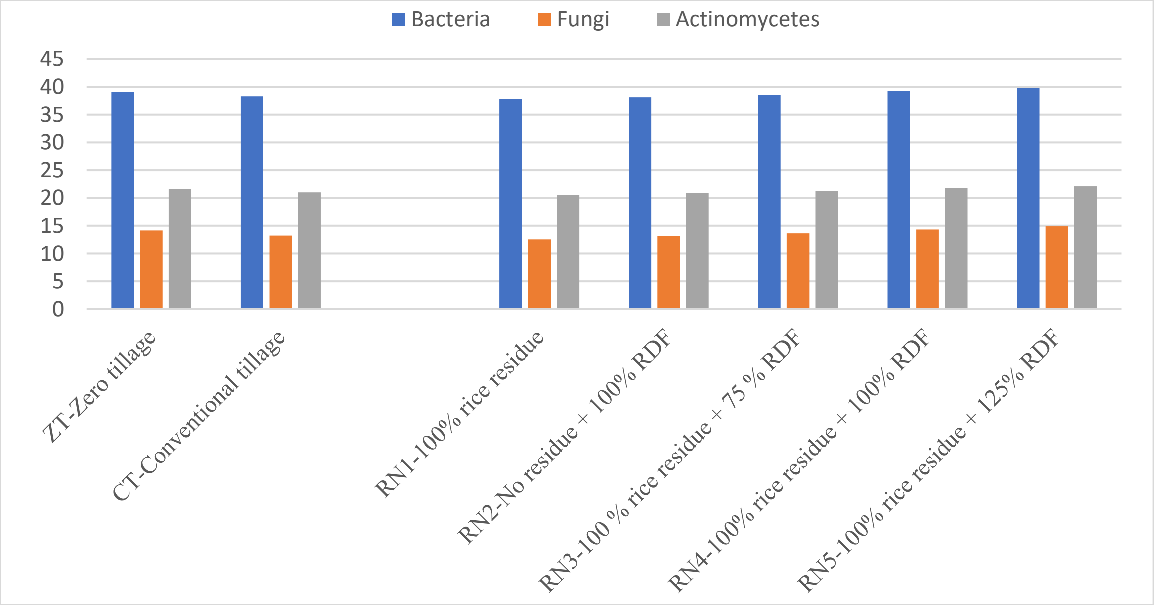

Fig. 4. Graph showing biological properties of soil as influenced by tillage, residue and different nutrient management practices

Similarly, residue and nutrient management practices exerted a non-significant effect on the microbial population; however, noticeable variations among treatments were observed (Table 4 and illustrated in Fig. 4). The highest populations of bacteria (39.79 × 10^6 CFU g^{-1}), fungi (14.88 × 10^3 CFU g^{-1}), and actinomycetes (22.12 × 10^4 CFU g^{-1}) were recorded under treatment RN_5 (100% rice residue + 125% RDF). In contrast, the lowest microbial counts were observed under RN_1 (100% rice residue), with bacterial, fungal, and actinomycetes populations of 37.77 × 10^6 CFU g^{-1}, 12.53 × 10^3 CFU g^{-1}, and 20.51 × 10^4 CFU g^{-1}, respectively. The comparatively higher microbial population under integrated residue and nutrient management treatments may be attributed to the combined effect of organic residue addition and adequate nutrient supply, which stimulate microbial growth, activity, and diversity in the soil. Decomposition of crop residues provides a continuous source of carbon and energy for soil microorganisms, while fertilizer application supports microbial metabolism and biological processes. Although the differences among treatments were statistically non-significant, the observed trends suggest that conservation-based management practices, particularly zero tillage coupled with higher residue retention and nutrient application, may enhance soil biological activity and contribute to the improvement of overall soil health over time.

The present study revealed non-significant differences in microbial populations, including bacteria, fungi, and actinomycetes, under different tillage and residue–nutrient management practices. However, comparatively higher microbial populations were consistently observed under zero tillage and treatment RN_5 (100% rice residue + 125% RDF). These findings suggest that conservation-based management practices, particularly zero tillage combined with higher residue retention and nutrient application, may provide a more favourable environment for microbial growth and activity. The enhanced microbial activity observed under these treatments may be attributed to improved availability of soil organic matter, better soil moisture retention, and reduced soil disturbance, all of which are essential for sustaining soil biological processes, as also reported by (Lewis et al., 1980). Although the effects of tillage and residue–nutrient management practices on certain soil properties were statistically non-significant, the observed trends indicate the potential benefits of zero tillage and higher levels of residue and nutrient application. These practices contribute to the maintenance and gradual improvement of soil organic matter, nutrient availability, and microbial activity, thereby supporting sustainable soil management and enhancing crop productivity over the long term.

The findings of the present investigation are in close agreement with earlier reports by Khan et al., (2018), Singh et al. (2018), Behera et al., (2021), and (Dutta et al. (2023) in wheat; Soni et al. (2021) in a sorghum–wheat system (Pramanick et al., 2022) in a maize–wheat system and (Bhattacharjya et al., 2016) in rice–wheat systems, who also reported improved soil biological properties and nutrient dynamics under conservation tillage and integrated nutrient management practices.

4. Conclusion

It is clear from the discussion above that the various tillage and residue-nutrient management techniques had no effect on the pH, organic carbon, or electrical conductivity of the soil. However, with the treatment combination of zero tillage with 100% rice residue + 125% RDF, comparatively larger amounts of organic carbon were found, coupled with minor changes in pH and EC. The treatment combination of zero tillage with 100% rice residue + 125% RDF had the maximum available N, P, and K, demonstrating the beneficial effects of integrated nutrient management in conjunction with conservation tillage techniques. Tillage, residue, and nutrient management techniques had no discernible impact on the microbial community (bacteria, fungi, and actinomycetes) in the soil following harvest. However, when 100% rice residue with 125% RDF were combined with zero tillage, comparatively larger microbial communities were seen.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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