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Rice residue management alternatives and nitrogen optimization: impact on wheat productivity, microbial dynamics, and enzymatic activities

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In response to the degraded soil health and lack of improvement in the yield of rice–wheat cropping systems in South Asia's Indo-Gangetic Plains, an experiment was formulated in a split-plot design. Four rice residue management practices were the primary factor, alongside two nitrogen levels (150 and 180 kg/ha) and two nitrogen split levels (two and three splits) as sub-treatments. The findings revealed a notable increase in soil organic carbon (SOC), microbial count, and enzymatic activity in plots subjected to conservation tillage and residue treatment compared to those in plots subjected to partial residue (anchored stubbles) and conventional methods (residue incorporated with chopping). The collective analysis demonstrated a significant influence of rice residue management practices and nitrogen application levels on wheat yield attributes and productivity. Specifically, zero tillage with full residue (unchopped) in wheat exhibited a 5.23% increase in grain yield compared to conventional tillage with full residue (chopped), concurrently boosting the soil microbial count by 19.80–25%, the diazotrophic count by 29.43–31.6%, and the actinomycete count by 20.15–32.99% compared with conventional tillage. Moreover, applying nitrogen in three splits (at sowing, before the 1st irrigation, and after the 1st irrigation) led to a 6.25% increase in grain yield than that in two splits (at sowing and after the 1st irrigation), significantly impacting wheat productivity in the soil. Furthermore, the zero tillage-happy seeder with full residue elevated dehydrogenase activity from 77.94 to 88.32 μg TPF/g soil/24 h during the study year, surpassing that in the conventional plot. This increase in enzymatic activity was paralleled by a robust positive correlation between the microbial population and enzymatic activity across various residue retention practices. In conclusion, the results underscore the efficacy of crop residue retention following conservation tillage, in tandem with nitrogen optimization and scheduling, in enhancing wheat yield within the rice–wheat cropping system.

KEYWORDS

rice residue, organic carbon, microbial dynamics, soil dynamics, wheat productivity

1 Introduction

The rice–wheat cropping system (RWCS) constitutes a dominant agricultural paradigm in Asia, particularly in southeastern Asia, encompassing an expanse of approximately 24 mha (Nawaz et al., 2019). It occupies approximately 13.5 mha across South Asia's Indo-Gangetic Plains (Padre et al., 2016). This cropping system holds paramount importance for the maintenance of livelihoods, food security, employment, and income generation for millions across Asia. Approximately 33 and 42% of the total acreage devoted to these crops are rice and wheat, respectively. In addition, it contributes significantly, at 25 and 33%, to aggregate rice–wheat production (Gupta et al., 2024). In northwestern India, the RWCS prevails as the principal cropping system, encompassing an area of approximately 12 mha (Bhatt et al., 2016).

On average, paddy cultivation yields approximately 5–6 tons of straw per hectare. It is estimated that Southeast Asian countries collectively generate 150 million metric tons of rice residues annually (Singh et al., 2021). The window between paddy harvesting and subsequent sowing of wheat, following field cleansing or paddy straw management, is markedly short, typically spanning 2–3 weeks (Meena et al., 2020), compelling farmers to resort to paddy straw burning. Paddy residue is assimilated through tillage post-partial incorporation/removal, facilitating expedited field preparation before seeding operations for the succeeding crop in the sequence (DOACFW, 2019). However, the RWCS faces numerous secondary challenges, including declining groundwater tables, deteriorating soil health, and diminished total factor productivity. One prospective strategy involves *in situ* management of paddy straw, encompassing direct drilling of wheat under no-till circumstances utilizing zero-tillage (ZT) machinery or a happy seeder (retention of residues on the surface). In addition, the incorporation of paddy straw into the soil can be achieved through conventional tillage (CT) machinery, such as harrows and rotavators, or straw chopping followed by mixing into the soil. Tillage is an energy-intensive farm operation which contributes to ~30% of the total energy use in crop production (Yadav et al., 2018). Retaining paddy straw as mulch on the surface of soil preserves soil moisture, moderates thermal regimes, enriches soil nutrient content, suppresses weed growth, and augments soil health, thereby fostering improved crop yields. Nitrogen (N) dynamics may undergo alteration due to ZT and surface residue retention, thereby necessitating nuanced N management strategies vis-à-vis residue burning and conventional tillage (Singh et al., 2015). The influx of crop residue-derived N is intricately linked with soil N management (Zhang et al., 2021). However, ZT combined with residue retention holds promise for augmenting long-term N availability to crops by elevating soil nitrogen levels and the labile nitrogen pool within upper soil strata (Sun et al., 2015). The implementation of farming systems that conserves soil and water through minimal soil disturbances and residue retention cover is one of the best management practices and improving the fertility status and microscopic population in degraded lands (Babu et al., 2023). In the last 60 years, the consumption of nitrogen fertilizer in India has grown rapidly. Emerging trends have resulted in escalating losses of nitrogen, posing significant threats to the quality of air, soil, and freshwater resources and consequently jeopardizing climate, ecosystems, and human health (Móring et al., 2021). Conservation agriculture increases available soil water, saves irrigation water, reduces heat and drought stresses, reduces GHG emissions, captures carbon, and improves soil health in the long term (Dhillon and Sohu, 2024).

Crop residues serve as nutrient-rich sources, liberating essential plant nutrients upon microbial decomposition in the soil. Consequently, reintegrating crop residues into soil, instead of incinerating them, serves to enhance several soil quality parameters. To withstand soil health within the RWCS in northwestern India, it is imperative to manage rice residue in a manner that is economically viable, environmentally sustainable, and logistically feasible. Generally, crop residues comprise approximately 40 to 45% of the carbon content, the restitution of which to the soil facilitates its utilization by soil microbes, thereby bolstering the soil organic matter (OM) content and mitigating organic carbon (OC) loss (Bin et al., 2021). Soil organic carbon (SOC) plays a pivotal role in shaping biological soil properties (Varatharajan et al., 2022). Microbial populations exert a profound influence on nutrient accessibility and contribute to the growth of various soil health indices. Consequently, understanding soil biological attributes is highly important for sustainability (Harish et al., 2022; Gopinath et al., 2022). Parameters such as total microbial count (TMC), actinomycetes, diazotrophs, and enzymatic activities, including dehydrogenase, alkaline phosphatase, and urease, serve as pivotal indicators of soil eminence (Doran and Zeiss, 2000). Soil-inhabiting microbes are central to nutrient release and soil purification. The inherent characteristics of soil, encompassing various soil classes, exert control over the soil microbiota, which in turn plays a pivotal role in modulating soil nutrient contents and rendering them bioavailable (Majumdar et al., 2024). The decomposition and biochemical transformation processes are expedited by soil enzymes, facilitating the release of nutrients from plants (Meena et al., 2022). Soil bacteria play a pivotal role in converting OM from its organic to accessible inorganic form, thereby facilitating the breakdown of OM (Six et al., 2004). Soil microorganisms are sensitive to changes in soil moisture as it affects the physiological state of microorganisms and plants which may lead to changes in their population in the soil (Gangmei et al., 2024). Recycling crop residues is imperative for reintegrating organic matter into the soil (Rajanna et al., 2022). Reduced tillage practices coupled with stubble retention promote the proliferation of diazotrophs, which is ascribed to reduced soil composition, fostering an optimal soil pore network conducive to interactions between stubble decomposers and nitrogen-fixing organisms (Gupta et al., 2019; Li et al., 2021). In the short term, applying cereal residues may require higher levels of fertilizer N to account for N immobilization, compared to not using residues (Sharma et al., 2021). However, over the long term, returning crop residues can lead to a net build-up of readily mineralized soil organic N, potentially reducing crops' fertilizer N requirements (Jat et al., 2019). The amount of N loss due to volatilization increases when the food–water pH and temperature are favorable (Hayashi et al., 2008). Broadcast application of PU results in higher food–water NH4 + -N compared to deep placement of N (Huda et al., 2016; Islam et al., 2016; Islam et al., 2018; Liu et al., 2015), which increases N loss through NH3 volatilization. Excessive use of N fertilizer through broadcast application has negative environmental consequences, including N_2O and NO emissions, nitrate pollution of groundwater, and eutrophication (Savant and Stangel, 1990).

The initial yellowing of upper wheat leaves observed under mulched conditions is associated with a reduction in soil temperature (minimum) during the late January period of 2020 and 2021, which is attributable to the insulating effect of mulch on the soil (Chaudhary et al., 2023). Consequently, a standard shift in agronomic practices concerning rice straw management is warranted to enhance resource utilization efficiency and system productivity. We hypothesized that combined application of N@150 kg/ha in 3 splits at basal, before, and after 1st irrigation and residue incorporation improve productivity of wheat. Hence, the present study aimed to explore the timing, number of splits, and nitrogen application rates of wheat crops to achieve improved productivity, microbial dynamics, and enzymatic activities and optimal nitrogen management in the northwestern Indian Plains. Given the circumstances within the RWCS, there is an urgent need for systematic research endeavors aimed at evaluating diverse nitrogen dosages and scheduling regimes to optimize productivity.

2 Materials and methods

2.1 Experimental site description

The experiment was conducted at CCS Haryana Agricultural University's Regional Research Station in Karnal, India [290 43′ 41″ North and 760 58′ 50″ East]. The soil was sandy loam with proportions of sand, silt, and clay (Table 1). Prior to starting the study, soil was sampled from the entire experimental field at five locations at 0 to 15 cm depth, the samples were mixed thoroughly, the bulk was reduced to approximately 1 kg by quartering, and then the samples were analyzed. The initial pH of the soil was correlated with the electrical conductivity (EC), bulk density, soil organic carbon (SOC), KMnO4 oxidizable N, NaHCO3 extractable phosphorus (P), and 1.0 N NH4OAc exchangeable potassium (K) and is shown in Table 1.

2.2 Experimental details and field management

In 2019–2020 and 2020–2021, field experiments comprised of four main-plot treatments, *viz.*, Zero tillage wheat-Happy Seeder (ZTW-HS) with full residue (chopped), ZTW-HS with full residue (unchopped), ZTW-HS with partial residues (anchored stubbles), and conventional tillage wheat-drill sown (CTW-DS) with full residue (chopped), and six subplots with two N levels, *viz.*, 150 and 180 kg/ha, applied into 2 (at sowing and after 1st irrigation) and 3 splits, that is, at sowing, before 1st irrigation, after 1st irrigation and at sowing, after 1st irrigation, after 2nd irrigation (Table 2). The hypothesis behind the two nitrogen levels was that N@150 kg/ha is the state-recommended practice for conventional sown wheat, and a higher dose of N@180 kg/ha is used because there is yellowing of plants during the initial days in zero-tillage wheat because of the nitrogen used by microbes for the decomposition of rice residues, which leads to nitrogen immobilization. In zero tillage, sowing was performed by a Happy Seeder, which is a machine towed on a tractor that cuts paddy stubble, lifts it, sows wheat seeds into the soil, and covers the sown area with straw as mulch. The individual plot size was 6 m × 2.2 m, totaling 13.2 m^2, and the treatment details are summarized in Table 2. To remove the residue (M3), loose straw was manually collected, and the remaining anchored stubble was left in the field. Full residue loose straw was uniformly spread and chopped using a chopper-*cum*-spreader machine before wheat crop planting (M1). In the M4 treatment, loose straw from the full residue was uniformly spread and chopped using a chopper-*cum*-spreader machine, and then, a rotavator was used to mix the chopped residue in the soil. Presowing irrigation at a depth of 6 cm through an irrigation channel preceded wheat sowing. In ZT plots with full residue (chopped or unchopped), seeding was performed using a happy seeder, and the seeds were directly sown into chopped or loose stubble residues (M1, M2) and seed-*cum*-fertilizer drill machine was used for sowing conventional plots. All the operations were conducted 1–2 days prior to sowing. Rice variety HKR-47 was transplanted on 1st July and harvested on 25th October and 22nd October throughout the Kharif seasons of 2019 and 2020, respectively. Cultivation practices followed the university's package of practices. Wheat sowing in the ZT plots utilized a happy seeder, while the plants in the CT plots with residues were drill-sown. Wheat variety HD-2967 was sown 2019 and 12th November 2020, and the seed rate was 100 kg/ha. Recommended fertilizer doses of phosphorus (60 kg P2O5/ha) and nitrogen (150 and 180 kg N/ha) were applied in both growing seasons, that is, 2019 and 2020, using urea and DAP as nitrogen and phosphorus sources, respectively. The herbicide mesosulfuron (12 g/ha) + iodosulfuron (2.4 g/ha) was applied 35 days after sowing (DAS) for weed control in 500 L/ha of water via a knapsack sprayer with a flat fan nozzle.

TABLE 1 Physical and chemical properties of the experimental soil.

Property	Values (units)
Soil texture	Sandy loam (Sandy loam: 57.5%, Silt: 23.4%, Clay: 18.2%)
Soil pH (1:2.5)	7.74
EC	0.22 dS/m
Bulk density	1.52 g/cm^3
SOC	0.34%
Available N	134.2 kg/ha
Available P	13.74 kg/ha
Available K	280.4 kg/ha

2.3 Soil physicochemical properties

Soil was sampled from three pots in each plot at 0 to 15 cm soil depth after wheat crop harvesting in 2020–2021 to determine the impact of rice residue management. These samples were properly processed before the analysis, including all the processes, that is, drying, grinding, and sieving. SOC (%) (Walkley and Black, 1934), available N (Subbiah and Asija, 1956), available P (Olsen et al., 1954), available K (Jackson, 1967), and soil moisture content (Su et al., 2014) were determined 105°C until constant weight is obtained and dry weight of the sample is recorded.

2.4 Soil biological properties

2.4.1 Bacterial activity analysis

To assess the soil biological properties, soil samples were collected from three locations within each plot after last season crop harvesting. Microbial counts were determined on various agar-based media by using the standard serial dilution plate assay (Ben-David and Davidson, 2014). Serial dilutions were prepared

TABLE 2 Details of different treatments.

Sr. no.	Main plots (sowing method)
1.	ZT Wheat-HS with full residue (chopped)
2.	ZT Wheat-HS with full residue (unchopped)
3.	ZT Wheat-HS with partial residues (anchored stubbles)
4.	CT Wheat-DS with full residue (chopped)

	Sub-plots (N dose and scheduling)
1.	N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation*
2.	N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation*
3.	N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**
4.	N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**
5.	N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***
6.	N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***

ZTW—zero-tillage wheat; CTW—conventional tillage wheat; HS—happy seeder sown; DS—drill sown. *1/2 N at sowing through DAP (drill) and urea broadcast before sowing, 1/2 N as urea broadcast after 1st irrigation. **1/3 N at sowing through DAP (drill) and urea broadcast before sowing, 1/3 N as urea broadcast before 1st irrigation, 1/3 N as urea broadcast after 1st irrigation. ***N through DAP (drill) as basal, remaining 1/2 N as urea broadcast after 1st irrigation, 1/2 N as urea broadcast after 2nd irrigation.

from 10 g soil samples in 90 mL sterile water, followed by incubation of the Petri plates at 28 ± 2°C for 2 to 6 days in a BOD incubator. The colony-forming units (CFUs) were enumerated and are expressed as dry soil/gram (Wright et al., 1933).

2.4.2 Enzymatic activity analysis

For dehydrogenase enzyme activity, soil samples (1 g each) were incubated with 0.2 mL of 2,3,5-triphenyl tetrazolium chloride (TTC, 3% w/v) and 0.5 mL of glucose solution (1% w/v) at 28 ± 2°C for 24 h (Casida et al., 1964). The absorbance at 485 nm was measured after extraction with methanol and filtration. Enzyme activity was quantified using a TPF standard curve.

The Tabatabai and Bremner (1969) method was used to determine soil alkaline phosphatase activity. The yellow color formed by adding *p*-nitrophenyl phosphate solution was measured at 420 nm and is expressed as µg p-nitrophenol released/g/soil/h.

The Bremner and Douglas (1971) method was used to determine urease activity. Soil samples (5 g) were incubated with 5 mL of 2,000 ppm urea solution at 37°C for 7 h. After adding 2 M KCl-PMA, the solution was filtered and analyzed for urea content. Enzyme activity was calculated from a standard curve and expressed as µg urea/g dry soil/min.

2.5 Statistical analysis

The data were analyzed by using two-way ANOVA to assess the effects of different treatments. Significant differences between treatments were determined using Duncan's multiple range test (DMRT) in conjunction with standard error of the mean (SEM ±) and least significant difference (LSD) computations (Gomez and Gomez, 1984).

3 Results

3.1 Impact of rice residue management practices and nutrient scheduling on soil physicochemical properties

The impact of rice residue management on soil chemical properties was investigated, with a particular focus on sowing methods and treatments with rice residues during the 2020–2021 cropping season, as depicted in Table 3. Significant levels of soil organic carbon (OC) were observed among the various treatments at the final wheat harvest stage. Notably, during the initial phase of the experiment, the effects were deemed non-significant. However, in 2020–2021, treatments such as M1 (0.41%) and M2 (0.42%) exhibited higher OC levels than did M3, which had an OC content of 0.37%. In addition, the OC content of M4 was notably lower at 0.32%. Intriguingly, the results were not significantly influenced by the nitrogen dose or scheduling treatments applied during either year.

According to the data, varying nitrogen levels did not exert a significant impact on the soil organic carbon content. However, it is noteworthy that a higher numerical value was observed when a high dose of nitrogen was administered.

3.2 Impact of rice residue management practices and nutrient scheduling on soil moisture content

The investigation revealed a discernible pattern of increasing soil moisture content as the cropping season progressed, as detailed in Table 4. Across both years of observation, treatments featuring M1 consistently exhibited SMC (%) at 75 days after sowing (DAS) and at maturity that was statistically equivalent to 13.91–15.25% in 2019–2020 and 17.88–20.34% in 2020–2021, respectively. These values were significantly greater than those in M3. Conversely, M4 yielded notably lower soil moisture contents (%), with values of 12.22 and 12.45% at 75 DAS and 16.34 and 18.67% at maturity in 2019–2020 and 2020–2021, respectively.

Furthermore, the subplot analysis indicated a non-significant difference in soil moisture content (%) across treatments, underscoring the consistent influence of rice residue practices on soil moisture dynamics throughout the cropping season.

3.3 Impact of rice residue management practices and nutrient scheduling on microbial count

Microbial activity serves as the primary catalyst driving decomposition processes within the soil matrix. Notably, the management of rice crop residues in wheat cultivation significantly influenced the soil microbial populations throughout the study, as shown in Table 5. Soil samples were meticulously analyzed at two critical crop growth stages: 75 days after sowing (DAS) and at harvest. Remarkably, the microbial count was markedly greater at 75 DAS than at harvest, underscoring the dynamic nature of microbial populations throughout the cropping season. In addition, the second year of the study, specifically 2020–2021, yielded higher microbial counts than

TABLE 3 SOC under rice residue and nitrogen management under rice–wheat cropping system.

Treatment		Soil OC (%)	
		Initial	Final
M1	ZT Wheat-HS with full residue (chopped)	0.34 ± 0.002a	0.41 ± 0.004a
M2	ZT Wheat-HS with full residue (unchopped)	0.33 ± 0.002a	0.42 ± 0.003a
M3	ZT Wheat-HS with partial residues (anchored stubbles)	0.34 ± 0.002a	0.37 ± 0.003b
M4	CT Wheat-DS with full residue (chopped)	0.30 ± 0.002a	0.32 ± 0.004c
T1	N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation*	0.35 ± 0.003a	0.26 ± 0.009a
T2	N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation*	0.34 ± 0.002a	0.34 ± 0.009a
T3	N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	0.34 ± 0.00a	0.43 ± 0.009a
T4	N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	0.34 ± 0.002a	0.39 ± 0.008a
T5	N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	0.34 ± 0.00a	0.40 ± 0.008a
T6	N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	0.35 ± 0.00a	0.41 ± 0.009a

Values with different superscripts in a column are significantly different at $p < 0.05$ according to the Duncan multiple range test (DMRT). Treatments abbreviations M1—ZT Wheat-HS with full residue (chopped), M2—ZT Wheat-HS with full residue (unchopped), M3—ZT Wheat-HS with partial residues (anchored stubbles), M4—CT Wheat-DS with full residue (chopped), T1—N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation, T2—N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation, T3—N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T4—N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T5—N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation, T6—N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation.

did the preceding year. Across both years, M1 consistently had greater microbial counts: 93.42 at 75 DAS and 88.09 × 107 cfu/g dry soil at harvest in 2019–2020; 98.53 at 75 DAS and 88.52 × 107 cfu/g dry soil at harvest in 2020–2021. Conversely, M4 exhibited lower counts: 78.76 at 75 DAS and 66.06 × 107 cfu/g dry soil at harvest in 2019–2020; 66.06 at 75 DAS and 70.99 × 107 cfu/g dry soil at harvest in 2020–2021. Moreover, within subplots defined by nitrogen dose and scheduling, no significant differences were observed in the total microbial count. Notably, in the T4 treatment, the total microbial counts at 75 DAS (89.44 in 2019–2020 and 96.63 × 107 cfu/g dry soil in 2020–2021) and at harvest (79.73 in 2019–2020 and 83.06 × 107 cfu/g dry soil in 2020–2021) were greater than those in the T1 treatment (Table 5).

Throughout both years of observation, treatments involving M1 consistently exhibited greater diazotrophic counts at 75 days after sowing (DAS) and at harvest, comparable to those of M2 and significantly greater than those of M3 (Table 6). Specifically, the diazotrophic counts for M1 were 64.49 in 2019–2020 and 88.52 × 104 cfu/g dry soil in 2020–2021 at 75 DAS and 62.87 in 2019–2020 and 71.49 × 104 cfu/g dry soil in 2020–2021 at harvest. Within subplots defined by nitrogen dose and scheduling, no significant differences were detected in the diazotrophic count. However, treatment T4 consistently yielded a greater diazotrophic count at both 75 DAS and harvest.

The data in Table 7 indicate that the actinomycete count in M1 was statistically similar to that in M2 at both 75 days after sowing (DAS) and at harvest across both years. Specifically, the counts were 67.51 at 75 DAS and 47.17 × 105 cfu/g dry soil at harvest in 2019–2020 and 63.09 at 75 DAS and 51.65 × 105 cfu/g dry soil at harvest in 2020–2021. These counts were significantly greater than those observed in M3 at both stages. Conversely, significantly lower actinomycete counts were recorded in M4 at both 75 DAS and harvest during both years. Subplot analysis revealed no significant differences in the actinomycete count. However, treatments involving nitrogen application at 180 kg/ha with three splits consistently resulted in higher counts at both 75 DAS and harvest. In comparison, a lower count was observed with nitrogen application at 150 kg/ha with two splits.

3.4 Impact of rice residue management practices and nutrient scheduling on yield

M2 exhibited the highest grain yield, with yields of 5,849 kg/ha in 2019–2020 and 5,874 kg/ha in 2020–2021, which were statistically similar to those of M3, which yielded 5,753 kg/ha in 2019–2020 and 5,636 kg/ha in 2020–2021. Compared to M4, M2 resulted in a 5.23% increase in grain yield. M2 increased the grain yield of wheat by 9.18% more than did M4. Three splits, that is, at sowing, before the 1st irrigation, and after the 1st irrigation, improved the grain yield of wheat by 8.08% compared with 2 splits, that is, at sowing and after the 1st irrigation. Within subplots, a significantly greater grain yield was observed under T4 (5,791–5,771 kg/ha during the study), which was statistically on par with T3 (5,724–5,712 kg/ha during the study), while T5 and T6 has lower grain yield. Applying nitrogen in three splits of wheat led to a 6.25% increase in grain yield than that in two splits (Table 8).

3.5 Impact of rice residue management practices and nutrient scheduling on enzymatic activity

Enzyme activity in soil, which is indicative of microbial processes, was significantly affected by rice residue practices during wheat cultivation. Notably, dehydrogenase, alkaline phosphatase, and urease activities were impacted during both cropping seasons, with higher levels observed at 75 days after sowing (DAS). For dehydrogenase activity, M1 displayed activity levels statistically similar to those of M2 but significantly greater than those of M3. The dehydrogenase activity ranged from 77.94 to 88.32 µg TPF/g soil/24 h and from 67.42 to 71.29 µg TPF/g soil/24 h at 75 DAS and harvest, respectively (Figure 1).

Similarly, alkaline phosphatase activity was significantly influenced by rice residue management. M1 and M2 exhibited similar activity levels that were significantly greater than that of M3 (Figure 2). The urease activity at 75 DAS ranged from 95.21 to 98.51 µg TPF/g

TABLE 4 Effect of rice residue practices, wheat crop establishment methods, and nutrient scheduling on soil moisture content (%) (SMC) in wheat crop under rice–wheat cropping system (2019–2020 and 2020–2021).

Treatment		SMC (%) at 0–10 cm soil depth			
		75 DAS		Harvest	
		2019–2020	2020–2021	2019–2020	2020–2021
M1	ZT Wheat-HS with full residue (chopped)	15.25 ± 0.093a	13.91 ± 0.095a	17.88 ± 0.11a	20.34 ± 0.09a
M2	ZT Wheat-HS with full residue (unchopped)	15.13 ± 0.098a	13.98 ± 0.081a	17.78 ± 0.11a	20.21 ± 0.11a
M3	ZT Wheat-HS with partial residues (anchored stubbles)	12.61 ± 0.096b	12.58 ± 0.088a	17.08 ± 0.11b	19.77 ± 0.11b
M4	CT Wheat-DS with full residue (chopped)	12.22 ± 0.099b	12.45 ± 0.097a	16.34 ± 0.11c	18.67 ± 0.27c
T1	N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation*	13.51 ± 0.53a	12.66 ± 0.66a	17.31 ± 0.40a	19.76 ± 0.20a
T2	N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation*	13.35 ± 0.53a	13.51 ± 0.66a	16.73 ± 0.40a	18.88 ± 0.43a
T3	N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	13.57 ± 0.52a	12.69 ± 0.70a	17.42 ± 0.40a	19.10 ± 0.40a
T4	N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	12.95 ± 0.52a	13.92 ± 0.73a	16.37 ± 0.41a	18.36 ± 0.40a
T5	N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	12.56 ± 0.52a	12.27 ± 0.68a	16.87 ± 0.40a	19.25 ± 0.43a
T6	N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	14.57 ± 0.52a	12.91 ± 0.68a	17.69 ± 0.40a	20.41 ± 0.40a

Values with different superscripts in a column are significantly different at $p < 0.05$ according to the Duncan multiple range test (DMRT). Treatments abbreviations M1—ZT Wheat-HS with full residue (chopped), M2—ZT Wheat-HS with full residue (unchopped), M3—ZT Wheat-HS with partial residues (anchored stubbles), M4—CT Wheat-DS with full residue (chopped), T1—N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation, T2—N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation, T3—N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T4—N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T5—N @ 150 kg/ha, 3—splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation, T6—N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation.

soil/24 h and that at harvest ranged from 82.77 to 88.43 μg TPF/g soil/24 h. Urease activity also significantly varied with residue management. M1 activity at 75 DAS ranged from 6.93 to 7.02 μg urea/g dry soil/min and at harvest from 4.73 to 4.82 μg urea/g dry soil/min; M2 had similar activity levels, which were significantly greater than those of M3. Subplot analysis revealed no significant differences in enzyme activity under different nitrogen doses or schedules. However, treatments involving nitrogen application at 180 kg/ha with three splits consistently exhibited greater enzyme activity than treatments involving two splits (Figure 3).

3.6 Correlations between microbial dynamics and enzymatic activity

The rice residue practice treatments demonstrated statistically significant correlations ($p < 0.05$) between microbial dynamics and enzymatic activities in wheat crops within the rice–wheat cropping system across both cropping seasons (Figures 4A–D). The increase in enzymatic activity was consistently paralleled by robust positive correlations between the microbial population and enzymatic activity across various residue retention practices.

Notably, TMC exhibited strong positive correlations with DHA at 75 DAS ($r = 0.76$) and maturity ($r = 0.78$) in 2019–2020 and at 75 DAS ($r = 0.68$) and maturity ($r = 0.62$) in 2020–2021, with APA at 75 DAS ($r = 0.77$) and maturity ($r = 0.64$) in 2019–2020 and at 75 DAS ($r = 0.66$) and maturity ($r = 0.63$) in 2020–2021, and with urease activity at 75 DAS ($r = 0.54$) and maturity ($r = 0.64$) in 2019–2020 and at 75 DAS ($r = 0.66$) and maturity ($r = 0.63$) in 2020–2021. Moreover, DC was significantly positively correlated with DHA at 75 DAS ($r = 0.78$) and maturity ($r = 0.80$) in 2019–2020 and at 75 DAS ($r = 0.68$) and maturity ($r = 0.56$) in 2020–2021, with APA at 75 DAS ($r = 0.77$) and maturity ($r = 0.68$) in 2019–2020 and at 75 DAS ($r = 0.63$) and maturity ($r = 0.59$) in 2020–2021, and with urease activity at 75 DAS ($r = 0.54$) and maturity ($r = 0.48$) in 2019–2020 and at 75 DAS ($r = 0.36$) and maturity ($r = 0.38$) in 2020–2021. Similarly, actinomycete activity was strongly positively correlated with DHA at 75 DAS ($r = 0.73$) and maturity ($r = 0.79$) in 2019–2020 and at 75 DAS ($r = 0.73$) and maturity ($r = 0.64$) in 2020–2021, with APA at 75 DAS ($r = 0.74$) and maturity ($r = 0.64$) in 2019–2020 and at 75 DAS ($r = 0.65$) and maturity ($r = 0.63$) in 2020–2021, and with urease activity at 75 DAS ($r = 0.51$) and maturity ($r = 0.48$) in 2019–2020 and at 75 DAS ($r = 0.43$) and maturity ($r = 0.55$) in 2020–2021 (Figures 4A–D).

4 Discussion

The impact of straw on crop yields is still under debate since field investigations across various pedoclimatic environments are indecisive, because of multiple and complex interaction of factors that affect the straw-derived N cycling under field conditions (Mu et al., 2016). Conservation tillage with residue retention (chopped and unchopped) significantly improved the physicochemical properties, microbial count, and soil enzymatic activities. Zero tillage with full residue (unchopped) in wheat exhibited a 5.23% increase in grain yield compared to conventional tillage with full residue (chopped), concurrently boosting the soil microbial count by 19.80–25%, the diazotrophic count by 29.43–31.6%, and the actinomycete count by 20.15–32.99% compared with conventional tillage.

Notably, there was a marked increase in SOC within the upper soil layer (0–15 cm) in ZTW-HS with full residue compared to that in CTW-DS (chopped) (Figure 4D). Numerous studies (Mondal et al., 2021; Zhang et al., 2021; Chen et al., 2021) have consistently reported significant increases in SOC under ZTW-HS compared to

TABLE 5 Effect of crop establishment methods, rice residue practices, and nutrient scheduling on soil microbial count under rice–wheat cropping system (2019–2020 and 2020–2021).

S. N	Treatment	Microbial count (10^7 cfu/g soil)			
		75 DAS		At harvest	
		2019–2020	2020–2021	2019–2020	2020–2021
M1	ZT Wheat-HS with full residue (chopped)	93.42 ± 0.42a	98.53 ± 0.39a	88.09 ± 0.34a	88.52 ± 0.34a
M2	ZT Wheat-HS with full residue (unchopped)	92.60 ± 0.44a	97.24 ± 0.43a	86.47 ± 0.43ab	87.99 ± 0.38ab
M3	ZT Wheat-HS with partial residues (anchored stubbles)	87.01 ± 0.45ab	95.38 ± 0.38ab	73.05 ± 0.41bc	79.27 ± 0.47ab
M4	CT Wheat-DS with full residue (chopped)	78.76 ± 0.51b	90.07 ± 0.42b	66.06 ± 0.40c	70.99 ± 0.43b
T1	N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation*	86.54 ± 3.42a	94.02 ± 1.88a	77.13 ± 5.34a	80.41 ± 4.20a
T2	N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation*	87.05 ± 3.46a	94.52 ± 1.85a	77.68 ± 5.34a	80.91 ± 4.19a
T3	N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	88.20 ± 3.29a	95.59 ± 1.85a	78.61 ± 5.34a	81.87 ± 4.18a
T4	N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	89.44 ± 3.36a	96.63 ± 1.83a	79.73 ± 5.31a	83.06 ± 4.07a
T5	N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	87.55 ± 3.41a	94.96 ± 1.86a	78.15 ± 5.31a	81.39 ± 4.15a
T6	N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	88.90 ± 3.32a	96.12 ± 1.89a	79.20 ± 5.29a	82.51 ± 4.10a

Values with different superscripts in a column are significantly different at $p < 0.05$ according to the Duncan multiple range test (DMRT). Treatments abbreviations M1—ZT Wheat-HS with full residue (chopped), M2—ZT Wheat-HS with full residue (unchopped), M3—ZT Wheat-HS with partial residues (anchored stubbles), M4—CT Wheat-DS with full residue (chopped), T1—N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation, T2—N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation, T3—N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T4—N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T5—N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation, T6—N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation.

conventional practices. Throughout the study years, ZTW-HS and full residue load, both chopped and unchopped, exhibited higher soil moisture contents. Crop residues add a considerable amount of labile organic carbon to soils and boost enzyme activity due to the increased presence of microbial communities (Fang et al., 2018). Zero tillage (ZT) significantly enhances soil moisture availability by reducing soil compaction and ensuring a uniform distribution of soil micropores and macropores (Meena et al., 2015; Huang et al., 2012). Zero tillage with residue retention (ZTW) has become a vital practice for conserving soil organic carbon (SOC) and minimizing carbon mineralization. This practice boosts nutrient availability for crops, improves soil water-holding capacity, and promotes aeration through the formation of continuous soil pores in the root zone (Varatharajan et al., 2022; Biswakarma et al., 2022). In addition, retaining crop residues encourages a higher microbial population than residue removal in both ZT and conventional tillage (CT) systems (Govaerts et al., 2008). Over a 2-year crop cycle, ZTW-HS with full residue or stubble resulted in a significant increase in SOC within the upper 0–15 cm soil layer. This increase can be attributed to the disruption of soil macroaggregates under CT without residue, which promotes direct contact between straw and microorganisms, leading to increased carbon mineralization. In contrast, ZTW-HS with residue retention prevents direct microbial contact and provides fewer nutrients to microbes.

Soil microorganisms enhance soil quality, health, fertility, and overall microbial community. Among these parameters, microbial activity serves as a subtle indicator for assessing soil quality. Adding crop residues has been shown to stimulate the microbial activity of bacteria, fungi, and actinomycetes (Choudhary et al., 2018). Studies have demonstrated that rice straw returned to the soil, along with cow manure, significantly increases SOM, total N, and available P compared to those in scenarios without residue incorporation (Cheng et al., 2014; Gu et al., 2018; Moharana et al., 2012). Moreover, numerous reports have highlighted the positive impact of residue management, whether through incorporation or retention, on the soil organic carbon balance (Gangwar et al., 2006; Gupta et al., 2007). During the wheat season, rice straw returned to the soil promoted the growth and reproduction of soil microbes, which was conducive to the stability and promotion of microbial community structures. This accelerated the decomposition of straw and enhanced nutrient availability into the soil (Pathak et al., 2006; Tan et al., 2006; Qian et al., 2012). Straw incorporation enhances the metabolic activity of microorganisms, the relevant enzyme activity, and microbial population (Sharma et al., 2020a). The soil microbial population gradually increased up to 75 days after the sowing of wheat and decreased during later growth periods. Rice residue had a pronounced impact on the soil microbial community, particularly up to 75 DAS. However, at maturity, the increase in mineralization of the prevailing microbial community decreased, possibly due to the solubility of residues or relative microbial availability in the field (Lehmann and Kleber, 2015). The presence of an adequate amount of rice residue in the soil regulates soil temperature, facilitating better microbial reproduction up to 75 DAS and maturity. The TMC and diazotrophic count exceeded the actinomycete count under the various treatments, corroborating previous findings (Choudhary et al., 2018; Bhagat and Gosal, 2018; Stagnari et al., 2020). Microbial populations, including fungal, bacterial, and actinomycetes populations, were greater under ZT with surface residue retention than under ZT with incorporation or removal (Jat et al., 2019; Stagnari et al., 2020). These microbial communities likely have advanced to grow rapidly in response to easily mineralized OM (Whitman et al., 2016). Excessive nitrogen doses failed to enhance microbial quantity

TABLE 6 Effect of crop establishment methods, rice residue practices, and nutrient scheduling on diazotrophic count under rice–wheat cropping system (2019–2020 and 2020–2021).

S. N	Treatment	Diazotrophic count (10^4 cfu/g soil)			
		75 DAS		At harvest	
		2019–2020	2020–2021	2019–2020	2020–2021
M1	ZT Wheat-HS with full residue (chopped)	64.49 ± 0.49a	88.52 ± 0.44a	62.87 ± 0.43a	71.49 ± 0.36a
M2	ZT Wheat-HS with full residue (unchopped)	60.72 ± 0.41ab	87.99 ± 0.39a	57.05 ± 0.37ab	69.92 ± 0.40a
M3	ZT Wheat-HS with partial residues (anchored stubbles)	57.58 ± 0.41bc	79.27 ± 0.39ab	52.45 ± 0.41b	62.43 ± 1.30a
M4	CT Wheat-DS with full residue (chopped)	54.15 ± 0.39c	70.99 ± 0.43b	43.00 ± 0.45c	50.45 ± 0.39b
T1	N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation*	57.65 ± 1.63a	80.41 ± 3.51a	51.00 ± 3.32a	62.72 ± 4.80a
T2	N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation*	58.17 ± 1.63a	80.91 ± 3.51a	51.53 ± 3.33a	63.22 ± 4.78a
T3	N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	59.01 ± 1.58a	81.87 ± 3.57a	52.62 ± 3.27a	63.65 ± 4.78a
T4	N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	60.42 ± 1.71a	83.06 ± 3.46a	53.72 ± 3.26a	64.69 ± 5.31a
T5	N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	58.80 ± 1.69a	81.39 ± 3.48a	52.05 ± 3.33a	62.95 ± 4.79a
T6	N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	59.85 ± 1.72a	82.51 ± 3.49a	53.13 ± 3.25a	64.19 ± 4.76a

Values with different superscripts in a column are significantly different at $p < 0.05$ according to the Duncan multiple range test (DMRT). Treatments abbreviations M1—ZT Wheat-HS with full residue (chopped), M2—ZT Wheat-HS with full residue (unchopped), M3—ZT Wheat-HS with partial residues (anchored stubbles), M4—CT Wheat-DS with full residue (chopped), T1—N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation, T2—N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation, T3—N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T4—N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T5—N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation, T6—N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation.

TABLE 7 Effect of rice residue practices, wheat crop establishment methods, and nutrient scheduling on actinomycete count of wheat under rice–wheat cropping system (2019–2020 and 2020–2021).

S. N	Treatment	Actinomycete count (10^5 cfu/g soil)			
		75 DAS		At harvest	
		2019–2020	2020–2021	2019–2020	2020–2021
M1	ZT Wheat-HS with full residue (chopped)	67.51 ± 0.40a	63.09 ± 0.34a	47.17 ± 0.35a	51.65 ± 0.37a
M2	ZT Wheat-HS with full residue (unchopped)	66.45 ± 0.35a	62.69 ± 0.35a	46.21 ± 0.38a	50.38 ± 0.55ab
M3	ZT Wheat-HS with partial residues (anchored stubbles)	56.63 ± 0.38b	56.89 ± 0.35ab	39.62 ± 0.37a	44.73 ± 0.37bc
M4	CT Wheat-DS with full residue (chopped)	51.50 ± 0.35b	50.37 ± 0.55b	31.61 ± 0.36b	41.24 ± 0.37c
T1	N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation*	59.37 ± 3.86a	56.99 ± 3.10a	39.96 ± 3.59a	45.76 ± 2.38a
T2	N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation*	59.77 ± 3.85a	57.45 ± 3.08a	40.45 ± 3.61a	46.11 ± 2.40a
T3	N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	60.59 ± 3.99a	58.60 ± 2.91a	41.40 ± 3.60a	47.35 ± 2.50a
T4	N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	61.77 ± 3.89a	59.53 ± 2.85a	42.36 ± 3.60a	48.34 ± 2.49a
T5	N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	60.36 ± 3.80a	57.90 ± 3.11a	40.89 ± 3.59a	46.60 ± 2.40a
T6	N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	61.25 ± 3.89a	59.07 ± 2.88a	41.87 ± 3.59a	47.83 ± 2.47a

Values with different superscripts in a column are significantly different at $p < 0.05$ according to the Duncan multiple range test (DMRT). Treatments abbreviations M1—ZT Wheat-HS with full residue (chopped), M2—ZT Wheat-HS with full residue (unchopped), M3—ZT Wheat-HS with partial residues (anchored stubbles), M4—CT Wheat-DS with full residue (chopped), T1—N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation, T2—N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation, T3—N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T4—N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T5—N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation, T6—N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation.

or enzyme activity. Studies suggest that high nitrogen levels can lead to the accretion of toxic substances, such as ammonia, which is detrimental to plant health and can impede the growth of certain microbial groups. In addition, excessive nitrogen can lower the soil pH, which is necessary for enzyme activity (Brzezińska and Włodarczyk, 2005).

TABLE 8 **Effect of rice residue practices, wheat crop establishment methods, and nutrient scheduling on yield of wheat under rice–wheat cropping system (2019–2020 and 2020–2021).**

S.N.	Treatment	Grain yield (kg/ha)		Straw yield (kg/ha)		Harvest Index	
		2019–20	2020–21	2019–20	2020–21	2019–20	2020–21
M1	ZT Wheat-HS with full residue (chopped)	5351c	5387b	6609ab	7223a	42.39c	43.24a
M2	ZT Wheat-HS with full residue (unchopped)	5849a	5874a	6720a	7347a	42.51bc	43.01a
M3	ZT Wheat-HS with partial residues (anchored stubbles)	5753ab	5636ab	6800a	7426a	43.03a	42.64b
M4	CT Wheat-DS with full residue (chopped)	5543bc	5566b	6458b	6952b	42.72b	43.17a
T1	N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation*	5366d	5332d	6612c	7202c	42.7d	42.11e
T2	N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation*	5554c	5490c	6626bc	7215bc	42.86c	42.62d
T3	N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	5724a	5712a	6667a	7256ab	42.65d	43.69a
T4	N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation**	5791a	5771a	6682a	7280a	43.82a	43.37b
T5	N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	5610b	5640b	6641b	7229b	42.39e	43.01c
T6	N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation***	5698abc	5721a	6655ab	7241abc	43.56b	43.62a

Values with different superscripts in a column are significantly different at $p < 0.05$ according to the Duncan multiple range test (DMRT). Treatments abbreviations M1—ZT Wheat-HS with full residue (chopped), M2—ZT Wheat-HS with full residue (unchopped), M3—ZT Wheat-HS with partial residues (anchored stubbles), M4—CT Wheat-DS with full residue (chopped), T1—N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation, T2—N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation, T3—N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T4—N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T5—N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation, T6—N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation.

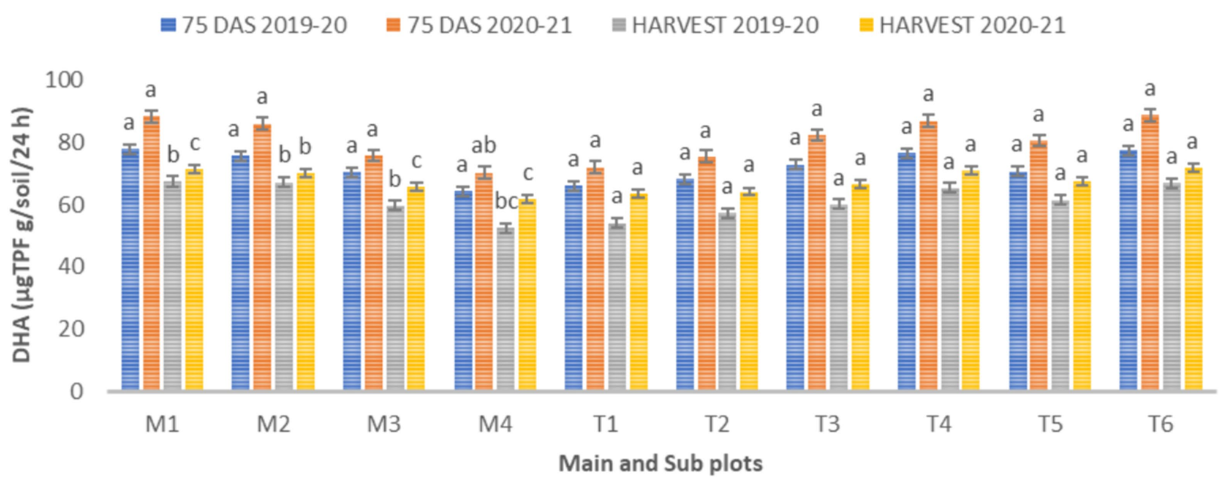

FIGURE 1

Effect of rice residue practices, wheat crop establishment methods. and nutrient scheduling on dehydrogenase activity in wheat under rice–wheat cropping system (2019–2020 and 2020–2021). The values within same color columns with different alphabetical letters differed significantly with each other. Treatments abbreviations: M1—ZT Wheat-HS with full residue (chopped), M2—ZT Wheat-HS with full residue (unchopped), M3—ZT Wheat-HS with partial residues (anchored stubbles), M4—CT Wheat-DS with full residue (chopped), T1—N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation, T2—N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation, T3—N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T4—N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T5—N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation, T6—N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation.

Soil microbial activity and enzymatic activity are strongly linked to increased nutritional mineralization of native organic C after residue integration (Guenet et al., 2010; Kirkby et al., 2014; Liu et al., 2011). Enzymatic activity exhibits a strong relationship with the soil microbial population, with increased microbial populations correlating with enhanced enzymatic activities, such as DHA, APA, and urease activity. Residue management practices have demonstrated a considerable and favorable relationship between enzymatic activity and SMC during the study period. Similar findings were reported by Tang et al. (2020), who reported a positive correlation between

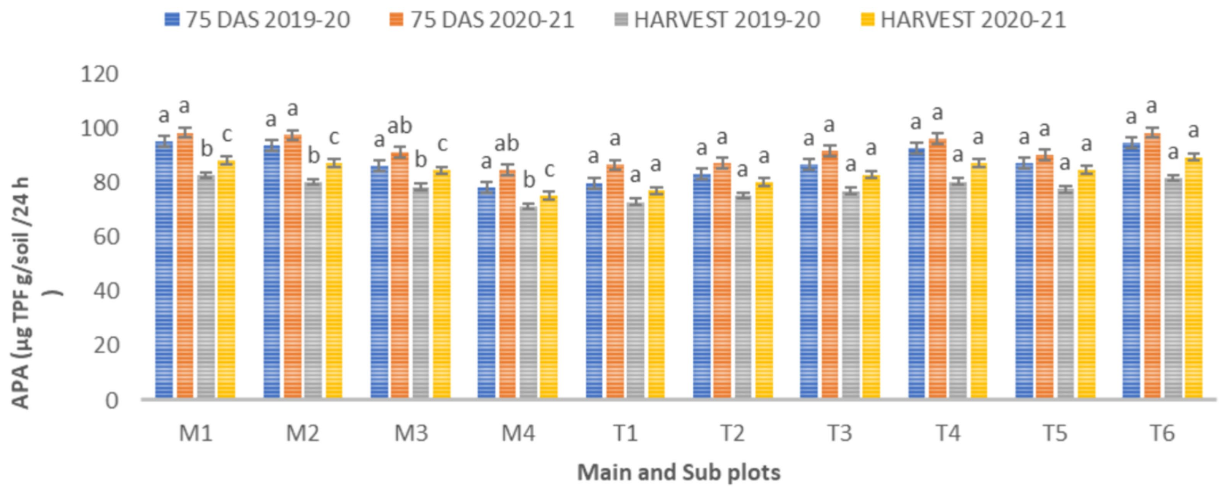

FIGURE 2
Effect of rice residue practices, wheat crop establishment methods, and nutrient scheduling on alkaline phosphatase activity in wheat under rice–wheat cropping system (2019–2020 and 2020–2021). The values within same color columns with different alphabetical letters differed significantly with each other. Treatments abbreviations: M1—ZT Wheat-HS with full residue (chopped), M2—ZT Wheat-HS with full residue (unchopped), M3—ZT Wheat-HS with partial residues (anchored stubbles), M4—CT Wheat-DS with full residue (chopped), T1—N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation, T2—N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation, T3—N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T4—N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T5—N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation, T6—N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation.

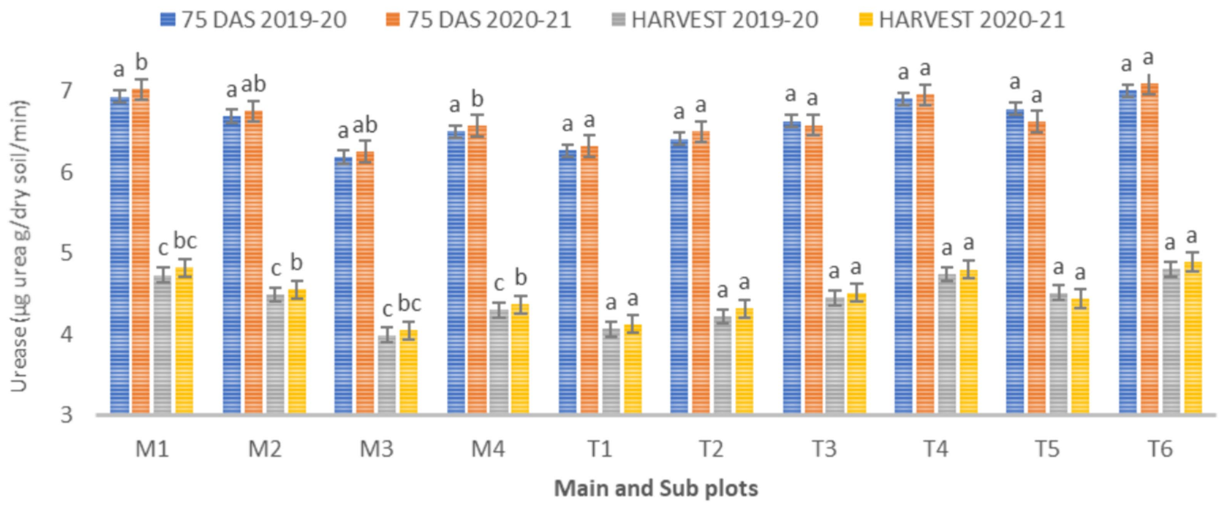

FIGURE 3
Effect of rice residue practices, wheat crop establishment methods, and nutrient scheduling on urease activity in wheat under rice–wheat cropping system (2019–2020 and 2020–2021). The values within same color columns with different alphabetical letters differed significantly with each other. Treatments abbreviations: M1—ZT Wheat-HS with full residue (chopped), M2—ZT Wheat-HS with full residue (unchopped), M3—ZT Wheat-HS with partial residues (anchored stubbles), M4—CT Wheat-DS with full residue (chopped), T1—N @ 150 kg/ha, 2 splits, that is, at sowing and after 1st irrigation, T2—N @ 180 kg/ha, 2 splits, that is, at sowing and after 1st irritation, T3—N @ 150 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T4—N @ 180 kg/ha, 3 splits, that is, at sowing, before, and after 1st irrigation, T5—N @ 150 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation, T6—N @ 180 kg/ha, 3 splits, that is, at sowing, after 1st irrigation, and after 2nd irrigation.

diazotrophic and actinomycete counts and DHA and APA. These soil microbes are significantly improved under ZT conditions (Rajanna et al., 2022; Choudhary et al., 2018). ZTW-HS with full residue (unchopped) produced more grain, straw, and biological yields, similar to ZTW with partial residues (anchored stubbles). This finding aligns with previous research highlighting the significant effect of rice residues on wheat yield (Chandra, 2018; Dhar et al., 2014; Kesarwani et al., 2017; Sah et al., 2014; Singh et al., 2021; Pandiaraj et al., 2015). The higher wheat yield in straw-retained plots can be attributed to improved soil nutrient levels and microbial abundance following straw residue incorporation as mulch in the field (Chaudhary et al., 2023). ZT has emerged as the most competent tillage method for conserving resources and increasing wheat yield (Usman et al., 2013). Higher grain and straw yields of wheat were recorded with ZT-HS than with conventional methods (Nandan et al., 2018). The higher grain yield under the retention of residue/

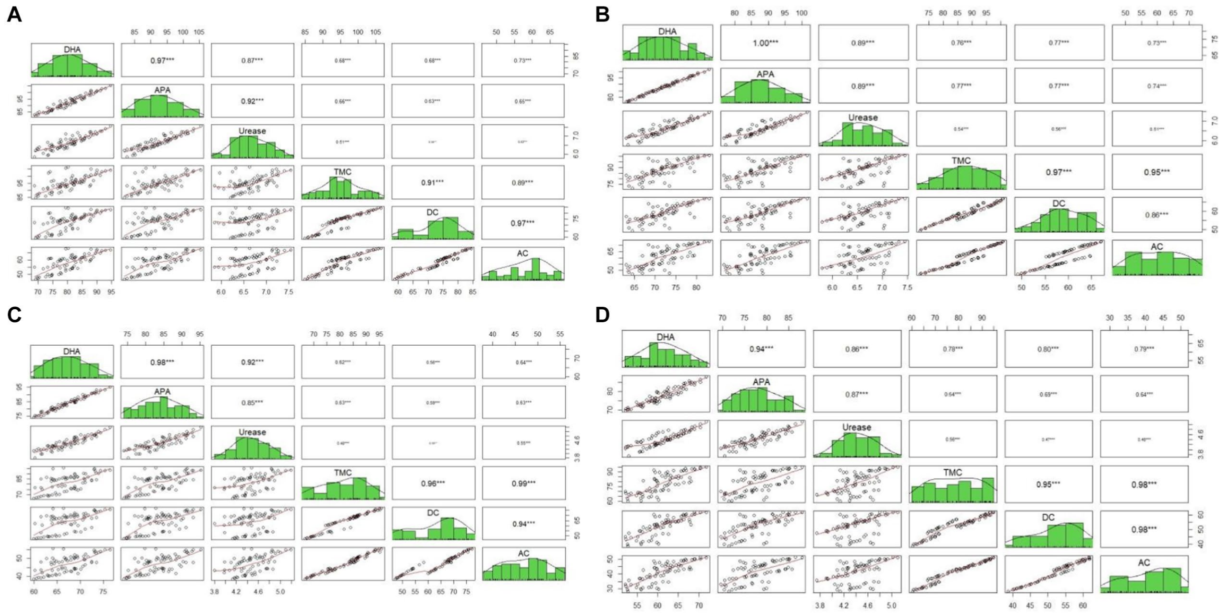

FIGURE 4
(A–D) Correlation analysis between microbial dynamics and enzymatic activities at 75 DAS and at maturity during 2019–2020 and 2020–2021, respectively.

incorporation treatments can be ascribed to increased growth parameters, facilitated by improved SOM content, nutrient availability, and moderation of the soil's hydrothermal regime (Gupta et al., 2016; Iqbal et al., 2017; Ram et al., 2013). Straw incorporation/retention enhances soil properties, leading to improved root growth, improved nutrient uptake, and ultimately enhanced plant growth and grain yield. Similar results have been reported by Gupta et al. (2016), Meena et al. (2015), and Sharma et al. (2019). The reason for the lowest yields under CTW when full residues are incorporated after a chopper and spreader could be that the N that bacteria utilize to break down incorporated residues causes the plants to turn yellow in the early days. T5 and T6 have lower yield due to more N losses as it was applied after 1st and 2nd irrigation.

Moreover, applying nitrogen in three splits (at sowing, before the 1st irrigation, and after the 1st irrigation) led to a 6.25% increase in grain yield than that in two splits (at sowing and after the 1st irrigation), significantly impacting wheat productivity in the soil. Optimal nitrogen management practices have been highlighted by Sidhu et al. (2007), who reported a greater grain yield of ZTW-HS in rice residues with fertilizer broadcasting at sowing and before the 1st irrigation. A study by Gill et al. (2019) determined that nitrogen management involving three equal splits applied at specific intervals was the most efficient practice for enhancing yield. Similarly, Singh et al. (2015) reported that specific nitrogen management practices significantly increased the mean wheat yield.

5 Conclusion

In summary, our study highlights the profound impact of various rice residue management techniques on the microbial characteristics of wheat, ultimately enhancing grain yield, SOC, and enzymatic activity. In particular, ZTW-HS (chopped) consistently demonstrated increased TMC and enzymatic activities, contrasting with the lowest count observed in CTW-DS (chopped), emphasizing the pivotal role of rice residue retention in fostering soil biological properties. Embracing zero tillage coupled with full residue retention, facilitated by machinery such as a happy seeder, has emerged as a crucial approach in rice–wheat cropping systems. This approach not only ensures the sustained productivity and income of farms but also enhances soil vigor and environmental quality. By adopting such innovations, the agricultural sector can improve rice residue management practices for long-term productivity and environmental sustainability, both regionally and globally. Moreover, optimizing nitrogenous fertilizer dosages for wheat crops alongside rice residue management approaches is imperative. Residue incorporation or retention significantly influences the chemical and biological properties of soil, reducing the need for nitrogenous fertilizers. In addition, our findings underscore the significant impact of nitrogen levels on wheat grain yield traits, with grain yield equivalent to the recommended N fertilizer dose (150 kg N/ha) with partial and full residue (unchopped) residue retention. Rice residue management in the rice–wheat cropping system is a multidisciplinary effort that combines technology advancements and sustainable agriculture techniques with economic considerations and legislative support. The agricultural sector may improve residue management techniques for long-term productivity and environmental stewardship by addressing these issues collectively in South Asia and globally in similar crop-growing regions. We must determine that the repercussions of harvesting crop residues for any purpose must be specified, and methods applied using site-specific technologies to ensure that productivity and agronomic resources are not jeopardized for future generations.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CC: Formal analysis, Investigation, Writing – original draft, Writing – review & editing. DY: Conceptualization, Methodology, Resources, Supervision, Writing – review & editing. VH: Supervision, Writing – review & editing. AC: Methodology, Supervision, Writing – review & editing. JP: Methodology, Resources, Writing – review & editing. AK: Writing - review & editing, Formal analysis, Visualisation. RK: Writing – review& editing, Supervision. AY: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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