

Temperature-mediated soil microbial activity and nutrient availability in wheat under different rice residue management strategies

Kavita Tanwar^{1*}, Dev Raj¹, Rajbir Garg², Usha Kumari¹, Pooja Rani^{1*}, Kavinder Tanwar³

¹Department of Soil Science, CCS Haryana Agricultural University, Hisar, Haryana, India - 125004, India

²Directorate of Research, CCS Haryana Agricultural University, Hisar, Haryana, India

³Krishi Vigyan Kendra, Mahendergarh, CCS Haryana Agricultural University, India

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Abstract. The burning of crop residues disrupts essential soil ecosystem functions and significantly depletes total and potentially mineralizable soil nutrients. A field experiment was conducted during the winter season in 2018-19 and 2019-20, with the objective to study the effect of rice residue management options on soil biochemical properties and nitrogen (N) and phosphorous (P) availability in wheat. The treatments comprised four rice residue management practices (R₁: Residue removal, R₂: Residue burning, R₃: Residue incorporation and R₄: Residue retention) in the main plot and five fertilizer doses (F₁: Control, F₂: 100% N + 50% Recommended dose of P and K (RDPK), F₃: 100% N + 75% RDPK, F₄: F₃+ Waste decomposer and F₅:100% RDNPk) in the sub plot. The highest N and P availability was recorded at 25 and 55 days after sowing (DAS), respectively, which declined thereafter in 2018-19, whereas their availability again increased at 115 DAS in the second year. Urease and alkaline phosphatase activity followed a similar trend in both years; however, microbial biomass carbon (MBC) and dehydrogenase activity did not increase in 2019-20. This study revealed the impact of residue burning on soil properties where available N, urease activity, MBC, and dehydrogenase activity decreased irrespective of the year. In contrast, available P and alkaline phosphatase activity increased in the second year.

Keywords: rice residue, rice-wheat cropping system, waste decomposer, enzyme activity, residue burning

1. INTRODUCTION

In India, the rice-wheat cropping system is dominant, with these crops grown on areas of 43.8 million ha (mha) and 29.3 million ha with a total production of 117.6 and 103.6 metric tonnes, respectively (FAOSTAT, 2021). Harvesting rice with a combine harvester leaves about 30-40 cm long stubbles along with scattered straw in the field whose management is of great concern because of its use as cattle feed is restricted owing to the high silica content. The time window available between paddy harvesting and subsequent wheat sowing is very short; therefore, to avoid obstruction of seeding equipment, open-field burning of rice straw has become a common practice in north-western India. Numerous reports suggest that burning of crop residues over the years has not only diminished total and potentially mineralizable nitrogen but also burnt soil organic carbon and other vital ecosystem processes, besides leading to serious environmental issues and human health hazards (Yadvinder-Singh *et al.*, 2005; Singh *et al.*, 2008; Chauhan *et al.*, 2012; Jain *et al.*, 2014). Several in-situ crop residue management options such as incorporation with the help of a rotavator or retention in the field with the help of a happy seeder and a mulcher have been suggested for successful rice straw management in the region (Singh *et al.*, 2020a). In-situ crop residue management had

*Corresponding author e-mail: kavitanwar190@gmail.com
poojajangra.hau@gmail.com



a close nexus with N cycling in the soil, and a high C:N ratio of rice straw (80:1) hinders the fast decomposition process and often leads to temporary lock up of mineral N via immobilization, causing N deficiency in the succeeding wheat crop (Yadvinder-Singh *et al.*, 2005).

Crop residue management practices provide both a source of energy and substrates for microbial activity, biological diversity, and soil enzyme activities (Loveland and Webb, 2003). Abiotic factors (soil temperature and moisture) fluctuate significantly throughout the entire crop season and directly affect soil microbial activity (Zhou *et al.*, 2013), microbial community composition (Bi *et al.*, 2012), enzyme activities (Eagles, 1967), and thus mineralization processes (Li *et al.*, 2014) and, consequently, nutrient uptake by plants (Gavito *et al.*, 2001). The amount of nutrients and the rate of their release from crop residues depend on their qualitative characteristics and biochemical composition and must be synchronized with crop demand throughout the growing season (Whalen, 2014) so that the dependency on fertilizers can be reduced. Nitrogen and phosphorus mineralization is commonly evaluated in laboratory incubation studies under controlled temperature and moisture conditions. However, it does not provide an accurate estimate of nutrient availability during the crop growing season; instead, it is an indicator of nutrient availability. Temperature is a critical weather parameter in northern India during the wheat growing season. Extremely low temperature at the early growth stage and a sudden rise above the normal value at the grain filling stage can influence good wheat yield. Therefore, studies on N and P availability during the crop growing season in the field provide information that can be of great help to achieve higher yields and improved nutrient use efficiency. The present study was therefore conducted for two years simultaneously to investigate the N and P availability to crops and

their relationship with soil enzymatic activity and weather parameters under different in-situ rice residue management practices.

2. MATERIAL AND METHOD

2.1. Experimental site and climatic conditions

The field experiment was conducted during Rabi, 2018-19 and 2019-2020, at the research farm of CCS Haryana Agricultural University, Krishi Vigyan Kendra, Panipat, Haryana, India to study nitrogen and phosphorous availability and soil biochemical properties during a period of wheat crop growth under different rice residue management practices. The experimental site is located at 29°39'N latitude and 76°97'E longitude at the mean sea elevation of 219 m in the north-west part of India having subtropical and sub-humid climate. The average annual rainfall in the area is around 700 mm, which is received mainly (around 80%) during the period from July to September. The temperature may rise up to 45°C during the summer season and often drops to 5°C during the winter months of December and January, respectively. The data related to these weather variables is presented in Table 1. The soil of the experimental site was sandy loam, Typic Ustocherpt having alkaline pH (1:2 soil:water) of 8.0 and the EC value of 0.35 dS m⁻¹ at 25°C. The soil had medium organic carbon content (0.62%), low available nitrogen (124 kg ha⁻¹), high available phosphorus (34.0 kg ha⁻¹), and medium available potassium (186 kg ha⁻¹).

2.2. Experimental layout and treatments

The treatments applied to the wheat crop consisted of four residue management options (R₁: Residue removal, R₂: Residue burning, R₃: Residue incorporation and R₄: Residue retention and direct seeding of wheat with a happy

Table 1. Monthly average air temperature (°C) and total rainfall (mm) of the experimental location across three different years

No.	Month	2018		2019		2020	
		Temperature (°C)	Rainfall (mm)	Temperature (°C)	Rainfall (mm)	Temperature (°C)	Rainfall (mm)
1	January	14.0	18.8	13.7	15.6	12.9	44.0
2	February	17.7	20.6	15.8	16.4	16.6	20.0
3	March	23.7	10.3	20.7	4.00	20.8	83.0
4	April	29.4	2.70	28.9	3.00	27.7	7.00
5	May	32.7	17.5	32.3	8.20	31.1	47.0
6	June	32.9	16.5	34.3	9.20	31.9	61.0
7	July	30.6	121	30.9	94.8	30.1	184
8	August	30.2	74.8	30.2	81.2	29.6	212
9	September	28.2	154	29.6	9.20	28.4	14.0
10	October	25.1	0.00	26.4	5.00	24.5	0.00
11	November	20.4	4.00	21.3	27.0	20.3	7.00
12	December	14.4	0.00	13.1	8.00	13.1	5.00

seeder into rice stubbles) and five levels of NPK fertilizers (F_1 : Control, F_2 : 100% Recommended dose (RD) of N + 50% of RD of P and K, F_3 : 100% (RD) of N + 75% RD of P and K, F_4 : 100% (RD) of N + 75% RD of P and K + Waste decomposer and F_5 : 100% RD of NPK fertilizer). These treatments were maintained in permanent plots in triplicate under a split plot design, keeping residue management in the main plot and fertilizer levels in the sub plots. Wheat variety HD-2967 was sown on 31st October and 3rd November in 2018-19 and 2019-20, respectively. After the harvest of rice by straw management system (SMS) fitted combine harvester, the rice stubbles were completely removed with the help of a sickle from the residue removal plots and, in the R_2 treatment, rice straw was burned in the field. Next day, sowing of wheat was done after the first plowing with a rotavator, followed by broadcasting of seed and again plowing by a rotavator in the removal, burning, and incorporation plots, while the sowing in the retention plots was completed with the help of a happy seeder in the standing rice stubbles. After harvesting of wheat, rice crop was grown in both years with recommended management practices. The fertilizers were applied on soil test basis as per recommendation of the university. In the wheat crop, soil moisture was maintained by applying four to six canal water irrigations at critical growth stages, with the exact number adjusted based on the rainfall received during the growing season.

2.3. Collection and analysis of soil samples

Field-moist soil samples were collected from all treatment plots at a depth of 0-15 cm to evaluate nitrogen (N) and phosphorus (P) availability, as well as soil biochemical properties, at different days after sowing of the wheat crop. In addition, from the plots where rice straw was burned, soil samples were also collected separately from two soil layers, 0-5 and 5-15 cm, to find out depth-specific effects of residue burning. From each plot, five wet soil samples

were taken at random locations and thoroughly mixed to prepare a composite sample representing that treatment. Each composite sample was divided into two portions: one portion was air-dried, ground, and passed through a 2 mm sieve for the determination of available N and P, while the other portion was stored at 4°C for the analysis of soil biochemical properties. The soil biochemical properties were analyzed at a gravimetric water content of 18-20% and all measurements were expressed on oven-dry weight basis. All laboratory analyses were carried out in triplicate to ensure precision and reliability of the results.

Standard procedures recommended for analysis of available nitrogen (Subbiah and Asija, 1956), available phosphorus (Olsen *et al.*, 1954), MBC (Vance *et al.*, 1987), alkaline phosphatase activity (Tabatabai and Bremner, 1969), urease activity (Tabatabai and Bremner, 1972), and dehydrogenase activity (Casida *et al.*, 1964) were followed in this study.

2.4. Statistical analysis

The data obtained in this study was subjected to statistical analysis under a split plot design using SPSS software, and Fisher's least significant difference test was used to compare the treatment effects at $p < 0.05$ level of significance.

3. RESULTS

3.1. Nitrogen availability and urease activity

The rice residue management options significantly affected N availability at different days after sowing of wheat in the following order: retention > removal > burning > incorporation during 2018-19, while during 2019-20, significantly higher available N was observed under the rice straw burning treatment compared to the incorporation treatments (Fig. 1). During 2018-19, the mean available N at 0 day was 124.3 kg ha⁻¹ (except burning), which increased

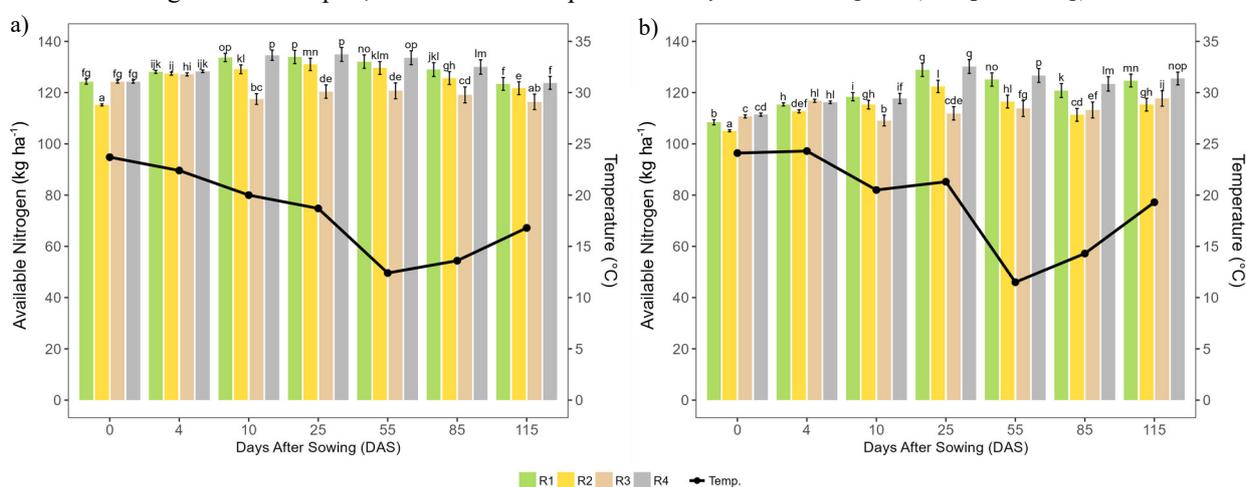


Fig. 1. Soil available nitrogen (kg ha⁻¹) during wheat growth in the year (a) 2018-2019 and (b) 2019-2020. Data represent mean \pm SE ($n = 15$). Means followed by the same letter(s) do not differ significantly at $p < 0.05$ according to Fisher's LSD test. R1 – residue removal; R2 – residue burning; R3 – residue incorporation; R4 – residue retention or direct seeding of wheat into standing rice stubbles, Temp – average air temperature (°C).

Table 2. Effect of crop residue burning on soil properties during different years

Treatment (Burning- 0 DAS)		2018-2019		2019-2020	
		Depth (cm)			
		0-5	5-15	0-5	5-15
Available N (kg ha ⁻¹)	BB	132	117	119	107
	AB	120	110	109	101
Urease activity ($\mu\text{g NH}_4^+\text{-N g}^{-1} \text{h}^{-1}$)	BB	10.1	16.0	12.5	16.2
	AB	7.40	14.6	8.40	14.4
Available P (kg ha ⁻¹)	BB	42.4	26.6	48.5	32.5
	AB	38.4	34.2	41.2	35.2
Alkaline phosphatase activity ($\mu\text{g PNP g}^{-1} \text{h}^{-1}$)	BB	100	90.4	108	100
	AB	110	98.2	116	102
MBC (mg kg ⁻¹)	BB	76.3	118	96.5	127
	AB	60.5	110	76.8	122
Dehydrogenase activity ($\mu\text{g TPF g}^{-1} \text{h}^{-24}$)	BB	23.0	30.4	24.2	32.4
	AB	13.6	25.0	15.1	28.5

BB – before crop residue burning, AB – after crop residue burning.

up to 25 days after sowing (DAS) and thereafter it started decreasing up to 115 DAS (except incorporation). During 2019-20, the mean available N at 0 day varied from 105.1 to 111.4 kg ha⁻¹ under the different residue management practices and increased up to 25 DAS and thereafter started decreasing up to 85 DAS but increased again at 115 DAS. The N availability in soil under the rice straw incorporation conditions behaved differently and, during 2018-19, it increased up to 55 DAS and thereafter decreased up to 115 DAS. However, during 2019-20, the N availability continuously increased up to 115 DAS. With respect to fertilizer levels, treatment F₅ resulted in significantly higher content of available N over the other practices in both years. The application of the waste decomposer slightly increased the N availability over RDF. The F₁ (control) treatment did not maintain the initial level of available N in both years; however, available N increased over the initial value in the other fertilizer treatments. The data revealed that the burning of residue significantly decreased the available N content in soil from about 8 to 9 and 5 to 6% at the 0-5 and 5-15 cm soil depth, respectively, in both years (Table 2). However, at 4 DAS, it increased due to the fertilizer N application at the time of sowing but was lower than in the removal and retention treatments and higher than in the incorporation treatment.

The residue management options significantly affected the urease activity, and maximum activity was observed under residue incorporation, followed by the retention, burning, and removal treatments in both years. Among the sampling days, the activity of urease increased with increasing days after sowing, and maximum values were reported at 55 DAS and then decreased thereafter during 2018-19. In turn, during 2019-20, the urease activity

increased up to 55 and thereafter decreased at 85 DAS but again increased at 115 DAS of wheat crop (Fig. 2). At 55 DAS, the urease value ranged from 22.5 to 26.4 $\mu\text{g NH}_4^+\text{-N g}^{-1} \text{h}^{-1}$ during 2018-19, while in 2019-20, the maximum urease activity ranged from 22.9 to 29.8 $\mu\text{g NH}_4^+\text{-N g}^{-1} \text{h}^{-1}$ at 115 DAS of wheat crop. The above result also showed that soil enzymatic activities were affected not only by the crop growth stages but also by the soil and climatic properties. The burning of rice residue decreased the activity of urease (26 to 32.8% at 0-5 cm depth and 8.7 to 11.4% at 5-15 cm depth) during both years (Table 2). The data also revealed that, during the first year of the experiment (2018-19), all treatments at 0 day exhibited the same mean values (12.9 $\mu\text{g NH}_4^+\text{-N g}^{-1} \text{h}^{-1}$) of urease except burning. However, during 2019-20, different values of urease were reported at 0 day under the residue removal, incorporation, and retention treatments and the value ranged from 11.4 to 18.1 $\mu\text{g NH}_4^+\text{-N g}^{-1} \text{h}^{-1}$. The activity of urease with respect to the fertilizer use followed the trend: F₄>F₅>F₃>F₂>F₁. The waste decomposer application improved the activity of urease over the chemical fertilizer in both years.

3.2. Phosphorus availability and alkaline phosphatase activity

The available P content in soil was significantly affected by the different residue management options (Fig. 3) and fertilizer levels on different days after sowing of wheat. Absolute control of all residue management treatment could not sustain the initial (34.2 kg ha⁻¹) level of available P in both years. The data showed that, during the initial year of the experiment (2018-19), all treatments exhibited the same mean values (34.2 kg ha⁻¹) of P content except

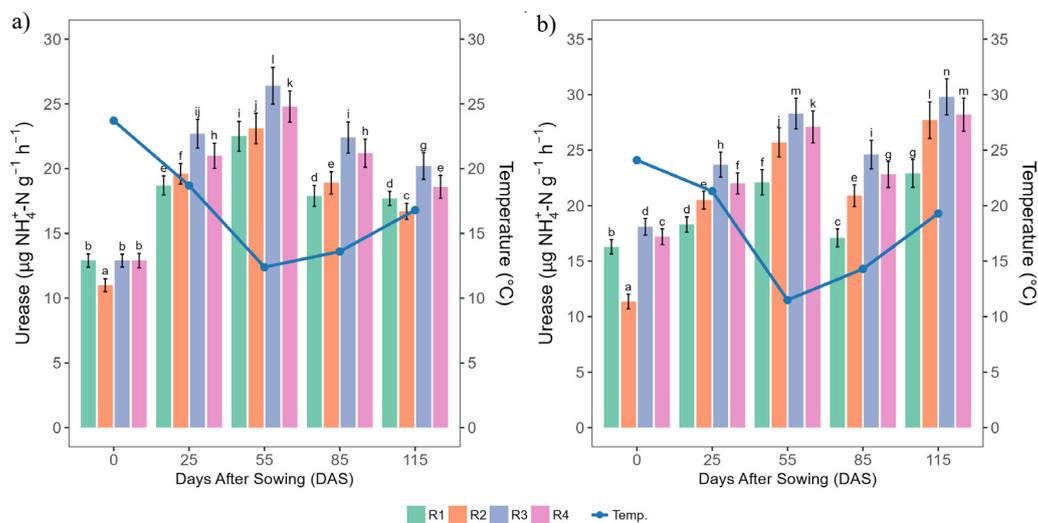


Fig. 2. Soil urease activity ($\mu\text{g NH}_4^+\text{-N g}^{-1} \text{ soil h}^{-1}$) during wheat growth in the year (a) 2018-2019 and (b) 2019-2020. Explanations as in Fig. 1.

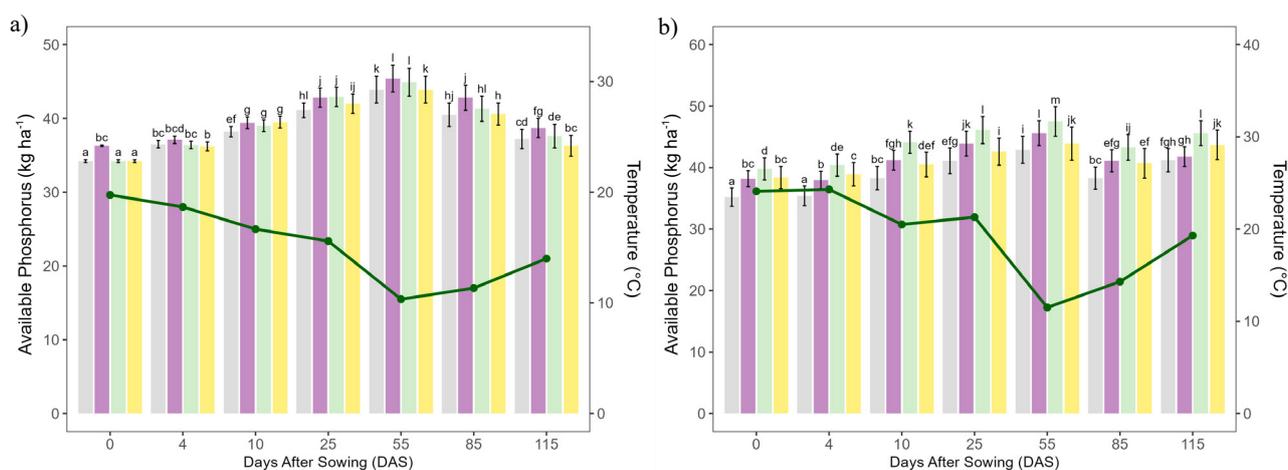


Fig. 3. Soil available phosphorus (kg ha^{-1}) during wheat growth in the year (a) 2018-2019 and (b) 2019-2020. Explanations as in Fig. 1.

the residue burning treatment, while during 2019-20, at 0 DAS the mean value of available P content in soil ranged from 34.8 to 39.8 kg ha^{-1} . The mean values of P content in soil increased from 0 to 55 DAS and decreased thereafter in all the treatments during 2018-19, while during 2019-20, after 85 DAS the value of available P increased again at 115 DAS under all treatments. At 55 DAS, the available P content under the different residue management treatments ranged from 43.9 to 45.4 and 42.9 to 47.5 kg ha^{-1} during 2018-19 and 2019-20, respectively. The data also revealed that, during 2018-19 except at 10 DAS and 25 DAS, higher values of available P were recorded under the burning (R_2) treatment over the others, while during 2019-20 higher values of available P were reported under the incorporation treatment (R_3) on all the observation days. The burning of rice straw decreased the available P content in soil about 9 to 15 % at 0-5 cm depth but increased about 8 to 28%

at 5-15 cm during both years (Table 2). These values were higher than in the removal and retention treatments. Available P was significantly increased with the increasing fertilizer levels, and the highest mean values were observed with the F_5 (100% RDF) fertilizer level in all the residue treatments on all the days during both years.

During the wheat growing season, the activity of alkaline phosphatase was significantly affected by the different residue managements and fertilizer levels on different days in both years (Fig. 4). Among the observation days, the activity of alkaline phosphatase increased with the increasing days after sowing, and maximum values were reported at 55 DAS and then decreased during 2018-19. In contrast, the trend in 2019-20 was different, as after 55 DAS the activity decreased at 85 DAS but again increased at 115 DAS. At 55 DAS, the alkaline phosphatase value ranged from 166.6 to 195.9 $\mu\text{g PNP g}^{-1} \text{h}^{-1}$ during 2018-19

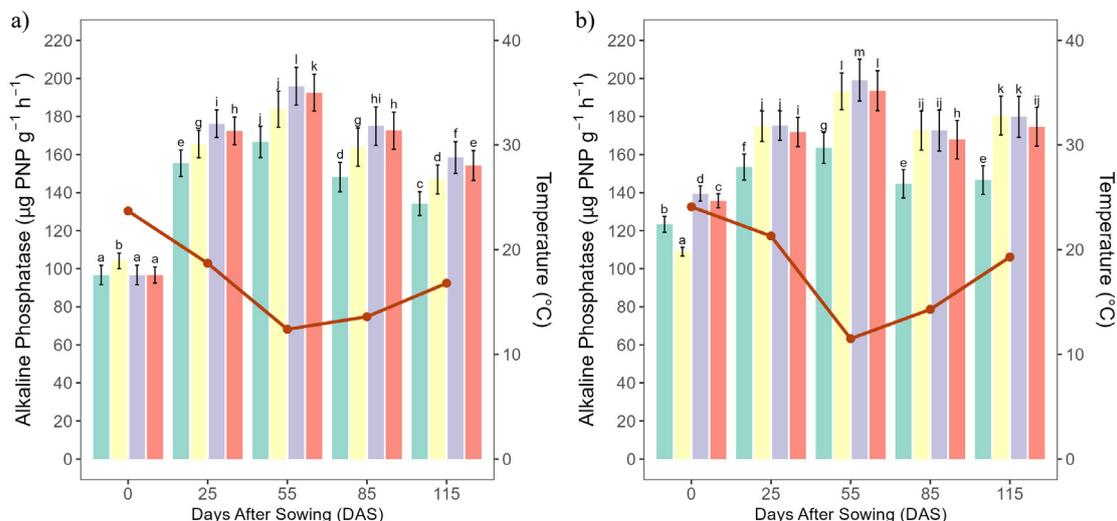


Fig. 4. Soil alkaline phosphatase activity ($\mu\text{g PNP g}^{-1} \text{ soil h}^{-1}$) during wheat growth in the year (a) 2018-2019 and (b) 2019-2020. Explanations as in Fig. 1.

and 163.5 to 199.1 $\mu\text{g PNP g}^{-1} \text{ h}^{-1}$ during 2019-20. At 115 DAS, the alkaline phosphatase values varied from 134.2 to 158.4 and 146.6 to 179.8 $\mu\text{g PNP g}^{-1} \text{ h}^{-1}$ during 2018-19 and 2019-20, respectively. The data showed that, during the initial year of the experiment (2018-19), all treatments at 0 day exhibited same values ($96.7 \mu\text{g PNP g}^{-1} \text{ h}^{-1}$) of alkaline phosphatase except burning. The burning of rice straw increased the alkaline phosphatase activity of soil about 7 to 9% at 0-5 cm depth and about 2 to 8% at 5-15 cm in both years (Table 2). However, during 2019-20, different values of alkaline phosphatase were reported at 0 day under the residue removal, incorporation, and retention treatments, and the value ranged from 97.2 to 160.1 $\mu\text{g PNP g}^{-1} \text{ h}^{-1}$. The fertilizer levels significantly affected the alkaline phosphatase activity, and maximum values were reported for F_4 , followed by treatments F_5 , F_3 , F_2 , and F_1 during 2018-19 and 2019-20, respectively. Irrespective of the residue management options, the waste decomposer improved the activity of alkaline phosphatase over the chemical fertilizer in both years.

3.3. Microbial biomass carbon and dehydrogenase activity

Irrespective of the different residue management and fertilizer treatments, the microbial biomass carbon (MBC) content in soil increased from 0 DAS, attained maximum values at 55 DAS, and decreased thereafter in all the treatments in both years (Fig. 5). At 55 DAS of wheat, the mean value of MBC content ranged from 144.9 to 171.3 mg kg^{-1} (2018-19) and 141.6 to 176.9 mg kg^{-1} (2019-20). The data showed that, during the first year of the experiment (2018-19), all treatments (0 day) exhibited the same values (96.9 mg kg^{-1}) of MBC except burning. Burning decreased the MBC of soil analyzed just after burning at both soil depths (20-22% at 0-5 cm and 4-6% at 5-15 cm) in both years (Table 2). However, as the crop growth proceeded, the MBC value

started increasing and attained the same level as indicated by the other residue management options. In 2019-20, at 0 DAS different values of MBC were reported under the residue removal, incorporation, and retention treatments, and the mean value ranged from 99.5 to 120.9 mg kg^{-1} . Among the residue management options, the incorporation practices resulted in significantly higher MBC, followed by burning, retention, and removal in 2018, while incorporation was followed by retention, burning, and removal in 2019. Overall, a higher value of MBC was observed during the entire cropping season of 2019-20 compared to that in the 2018-19 cropping season.

During the wheat growing season, the dehydrogenase enzyme activity was significantly affected by the different residue managements and fertilizer levels on different days after sowing of wheat in both years. Significantly highest activity of dehydrogenase was reported under incorporation > retention > burning > removal during 2018-19 and 2019-20, respectively (Fig. 6). Among the sampling days, the activity of dehydrogenase increased with the increasing days after sowing, and maximum values were reported at 55 DAS and then decreased in both years. At 55 DAS, the mean value of dehydrogenase activity ranged from 38.1 to 48.4 $\mu\text{g TPF g}^{-1} \text{ h}^{-24}$ (2018-19) and 35.0 to 50.8 $\mu\text{g TPF g}^{-1} \text{ h}^{-24}$ (2019-20). The burning of rice straw decreased the dehydrogenase activity from 37.6 to 40.8% at 0 to 5 cm and 12-18% at 5-15 cm depth in both years (Table 2). The data showed that, during the initial year of the experiment (2018-19), all treatments at 0 DAS exhibited the same mean values ($26.7 \mu\text{g TPF g}^{-1} \text{ h}^{-24}$) of dehydrogenase except burning. However, during 2019-20, at 0 DAS different mean values of dehydrogenase were reported under the removal, incorporation, and retention treatments, and the value ranged from 21.8 to 32.2 $\mu\text{g TPF g}^{-1} \text{ h}^{-24}$. The fertilizer levels significantly affected the dehydrogenase activity, which

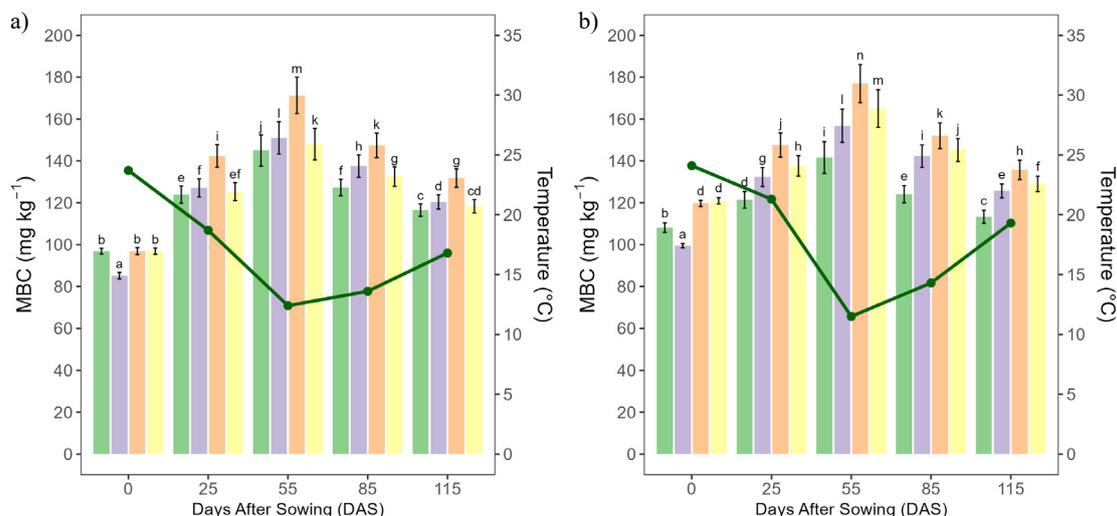


Fig. 5. Soil microbial biomass carbon (mg kg^{-1} soil) during wheat growth in the year (a) 2018-2019 and (b) 2019-2020. Explanations as in Fig. 1.

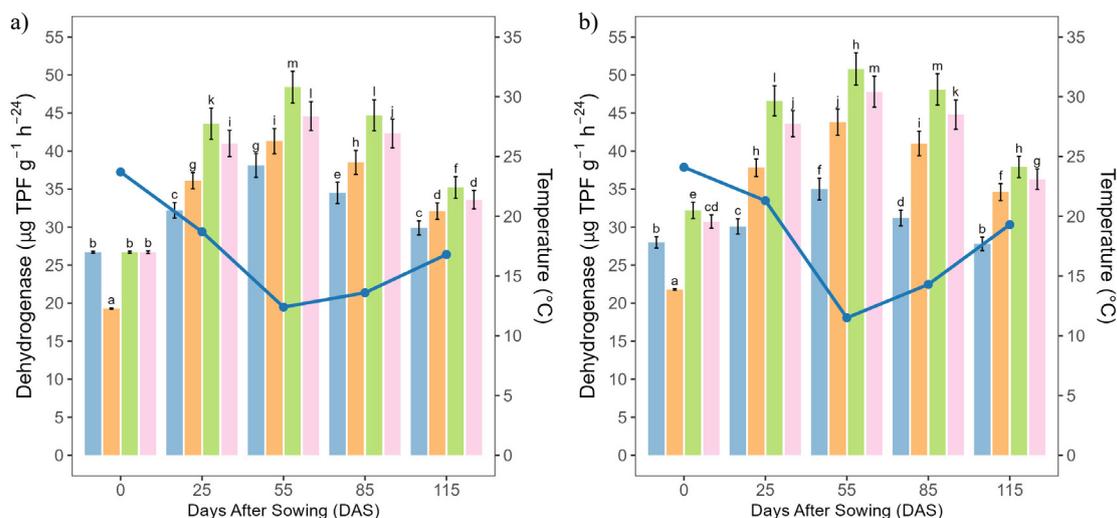


Fig. 6. Soil dehydrogenase activity ($\mu\text{g TPF g}^{-1} \text{soil h}^{-24}$) during wheat growth in the year (a) 2018-2019 and (b) 2019-2020. Explanations as in Fig. 1.

increased with the increasing fertilizer levels, and maximum values were reported in F_4 , followed by treatments F_5 , F_3 , F_2 , and F_1 . The data showed that the waste decomposer application improved the activity of dehydrogenase over the chemical fertilizer application in both years with all residue management options.

4. DISCUSSION

Irrespective of the different days after sowing of wheat crop, the higher availability of N in soil remained under the retention treatment (R_4) mainly due to the favorable environment (optimum moisture and temperature maintained by rice straw mulching), which improved the microbial activity and resulted in higher N mineralization. The increased activity of urease under the crop residue incorporation treatment over the others might be due to increased microbial

biomass (Fig. 2) and availability of urea substrate. Contrary to urease activity, higher N availability was observed under the retention treatment than that with incorporation of rice straw. The released N under the straw incorporation conditions was utilized by higher microbial biomass (Fig. 1), it was immobilized temporarily and became unavailable for plants. A high C: N ratio in rice straw along with high silica and lignin content hinders fast decomposition and mineralization of N (Yadvinder-Singh *et al.*, 2005), even after the addition of the recommended dose of N in the present study. It is further indicated from this study that an extra dose of N is required to counteract the N immobilization effect under straw incorporated conditions. In the present study, the nitrogen released from urea was immobilized, in line with findings reported by other researchers (Bird *et al.*, 2001), who suggested that repeated incorporation of straw increases the immobilization of fertilizer N in soil and leads

to a readily mineralizable N pool to supplement crop N needs. The higher availability of N under the removal treatment over the burning and incorporation treatments was due to hydrolysis of applied urea and less N losses through biotic and abiotic processes. Irrespective of the residue management options, the urease activity increased during the initial crop period of 55 DAS due to greater availability of applied urea substrate, higher microbial activity (higher MBC), more readily available organic matter, and faster decomposition and release of ammonia (Saha *et al.*, 2008; Watts *et al.*, 2010; Meena *et al.*, 2013). Contrary to this, the N availability increased up to 25 DAS, thereafter decreasing due to absorption of N by growing plants and utilization by higher microbial populations. In 2019-20, the N availability again increased at the later stage of 115 DAS due to an increase in urease activity under increased ambient temperature conditions (Fig. 2). The burning of rice straw decreased the urease activity and available N content in soil samples collected just after burning from 0-5 and 5-15 cm depth; however, the application of urea at the time of sowing increased the N status to the level of the other treatments even at 4th DAS. Similarly, urease activity also improved within 25 DAS of crop growth due to the application of substrate (urea) and development of favorable conditions by tillage operations (Fig. 2).

The burning of rice straw directly added inorganic P in soil and resulted in higher available P status of soil, while during the second year, fast decomposition and mineralization resulted in higher available P content in soil under the incorporation conditions. This fact was supported by the higher alkaline phosphatase activity during the 2nd year compared to the first year (Fig. 4). Alkaline phosphatase enzyme is responsible for hydrolyzing the ester bonding and changing organic P into inorganic P. The overall higher alkaline phosphatase activity during 2019-20 might be responsible for the higher P availability in the entire cropping season. Rice straw incorporation (R_3 and R_4) provides more substrate availability resulting in higher microbial and enzymatic activities compared to removal and burning treatments. Similar results were also reported in several research studies (Wei *et al.*, 2015; Singh *et al.*, 2020b; Sharma *et al.*, 2021). The lowest value of available P in soil under the rice straw removal conditions was due to the uptake of P by the crop and no addition of organic P by straw incorporation. The increasing trend of P availability up to 55 DAS was due to the release of P from the applied fertilizer and solubilization of native P during microbial decomposition of added organic matter (Srinivasan *et al.*, 2016). The decreased availability of P after 55 DAS (Saikia *et al.*, 2017; Srinivasan *et al.*, 2016) might be due to the utilization of available P by plants. Another possible reason for decreasing P availability is the reduction of easily degradable organic substrate decreasing microbial and enzyme activities (Fig. 3). In 2019-20, P availability

again increased at 115 DAS due to an increase in alkaline phosphatase activity under increased ambient temperature conditions (Fig. 3).

MBC is an active component of soil organic matter, and changes in MBC reflect the process of microorganism's propagation and degradation utilizing soil carbon. The metabolic activity of microorganisms in soil and other habitats can be determined by measuring dehydrogenase activity (Lenhard, 1956), because it is only present in viable cells and widely used as a generalized comparative index of soil microbial activity (Skujinš, 1973). In the present study, MBC and dehydrogenase activity followed a similar trend (incorporation>retention>burning>removal) under different residue and fertilizer management practices ($F_4>F_5>F_3>F_2>F_1$). The higher mean values of MBC and dehydrogenase activity observed under the R_3 (incorporation) treatment were due to improvement in substrate (carbon) content in soil by addition of rice residues along with fertilizers. Rice straw retained on soil surface behaves like mulch and degrades slowly releasing dissolved organic carbon in addition to maintaining soil moisture and temperature properties, which resulted in higher MBC and dehydrogenase activity compared to that in the burning and removal treatments. The burning of rice straw decreased the MBC and dehydrogenase activity in soil analyzed just after burning, but the subsequent tillage operation before sowing of wheat and fertilizer addition along with stubbles enhanced their activity, which reached a higher level than that in the removal treatment at 25 DAS of wheat crop. The mean values of MBC and dehydrogenase activity increased continuously up to 55 DAS due to secretion of more root exudates under vigorous vegetative growth of wheat (Islam and Borthakur, 2016). The decline in MBC and dehydrogenase activity at maturity might be due to the gradually decreased decomposition rate under scarcity of readily decomposable substrate at the end of the season and also due to moisture stress at maturity. Like urease and alkaline phosphatase activity, MBC and dehydrogenase activity did not increase at 115 DAS in 2019-20 under increased ambient temperature, indicating greater sensitivity of urease and alkaline phosphatase activity to a rise in ambient temperature. Soil moisture availability determines whether the net effect of added organic substrate is rapid mineralization or transient immobilization where ample moisture at moderate temperatures tends to favor mineralization and nutrient release, and moisture limitation or rapid drying reduces diffusion and shifts microbial metabolism toward carbon use that locks up inorganic N (Basak and Biswas, 2014; Bossolani *et al.*, 2023; Bogati *et al.*, 2025). Temperature modulated these moisture-dependent effects and rising ambient temperatures in 2019-20, corresponding with increased urease and alkaline phosphatase activities at later crop stages (115 DAS), but the magnitude of this temperature response varied with the residue treatment. These interactive effects also explain temporal trends as an

early-season increase in enzyme activity and MBC (up to 55 DAS). Rice-straw retention (R4) functioned as a surface mulch that moderated diurnal soil temperature fluctuations and conserved soil moisture, thereby creating a more favorable microenvironment for microbial activity and nutrient mineralization. Under these relatively stable and moist conditions, diffusion of soluble substrates and enzyme mobility are enhanced, supporting higher microbial biomass and faster enzyme-mediated hydrolysis; this mechanistic coupling explains the greater nutrient availability observed under retention compared with removal or burning treatments, while residue incorporation can increase biological demand for N, particularly when moisture conditions are not consistently favorable. The short-term increase in soil N and P availability observed under elevated ambient temperature in 2019-20 likely reflects the effect of warming to accelerate enzymatic activities and SOM decomposition; however, anthropogenic climate change (greenhouse-gas driven warming) is expected to produce both gradual increases in mean temperatures and more frequent heat extremes and droughts. These longer-term changes can alter nutrient dynamics in more complex ways. An increase in temperature above the average value of the region can stimulate mineralization and transiently increase available N, but it can also enhance gaseous N losses, reduce soil organic N pools over time, and interact with changing precipitation to create moisture constraints that limit substrate diffusion and microbial activity (Sun *et al.*, 2013; Mao *et al.*, 2025). For wheat production in this region, terminal heat stress (higher temperatures during grain-filling) has been repeatedly shown to reduce grain set and thousand-grain weight and thereby contribute to lower yields. Therefore, the short-term nutrient benefit of winter warming does not imply an overall positive effect of climate change on wheat yields.

5. CONCLUSIONS

This research study highlighted that rice residue management exerts a significant influence on nutrient availability and soil biological functioning in wheat crop. Residue burning consistently reduced available nitrogen, microbial biomass carbon, and enzymatic activities across both years. The residue retention enhanced nutrient availability by limiting nitrogen immobilization by providing favorable conditions for mineralization. In contrast, incorporation promoted temporary immobilization of released nitrogen, necessitating additional fertilizer inputs in the wheat crop to compensate these losses. The nitrogen and phosphorus availability was the highest at 55 DAS, with urease and alkaline phosphatase activities exhibiting greater temperature sensitivity than microbial biomass carbon and dehydrogenase. Overall, soil biological properties followed the order: incorporation > retention > burning > removal, while residue retention ensured the highest nutrient availability. Furthermore, the integration of NPK with a waste

decomposer maximized microbial and enzymatic activity, underscoring the role of residue management in sustaining soil health and resilience under intensive cropping systems. This study concluded that retaining rice residues on the soil surface with wheat sowing using a happy seeder along with application of the recommended NPK dose, provides an effective and sustainable residue and nutrient management strategy for northwestern India. This practice enhances nutrient availability, improves soil health, and prevents the environmental damage associated with rice straw burning. Future research should focus on optimizing nitrogen application strategies under crop residue incorporation, long-term monitoring of enzymatic responses to climatic variability, and exploring the potential of microbial inoculants and crop residues to further enhance soil resilience and nutrient-use efficiency.

Conflict of interest: The authors declare that they have no conflict of interest.

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