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Paddy Residue and Nitrogen Management Effects on Soil Nutrient Dynamics, Biological Properties, Decomposition and Productivity in a Rice–Maize System.

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ABSTRACT

Rice production in India has markedly increased residue generation, necessitating sustainable residue management in succeeding maize. A two-year field experiment with rice-maize system evaluated interactive effects of in situ rice straw and nitrogen management on nutrient cycling, soil enzyme activity and residue decomposition dynamics in a rice-maize cropping system. The treatments comprise of three paddy straw management options: burning (SB), incorporation (SI) and removal (CR); three nitrogen (N) levels: 100, 115 and 130 % of recommended dosage of nitrogen (RDN). The results revealed that straw incorporation immobilized 13.3 and 13.7 kg N ha^{-1} at 15 and 30 DAS in maize, respectively and delayed the onset of net N mineralization up to 40.9 days. Application of 130% RDN significantly reduced N immobilization (11.9 kg ha^{-1} at 30 DAS) and initiated mineralization earlier (39.0 days). At harvest, SI significantly enhanced urease (25.3%), dehydrogenase (22%), acid phosphatase (37.3%) and alkaline phosphatase (23.6%) activities over SB. Residue decomposition followed first-order kinetics indicating 50% and 95% decomposition within 204-224 and 881-996 days, respectively. SI improved net energy returns by 3.14% over SB and 11.50% over CR. Residue incorporation coupled with 130% RDN, improved N dynamics, biological properties and sustaining productivity in rice-maize system.

Keywords: N dynamics, residue decomposition kinetics, system energetics, soil biological properties, energetics, Productivity.

Introduction

The rice (*Oryza sativa* L.)-maize (*Zea mays* L.) cropping system is an important diversification option in India, occupying approximately 0.53 million ha and offering opportunities to improve productivity and resource-use efficiency. However, the large volume of rice residue and the short interval between rice harvest and maize establishment make effective residue and nitrogen management essential for maintaining soil biological activity, nutrient cycling and crop productivity **(1)**. Maize (*Zea mays* L.) is a major cereal crop used for human food, livestock feed and industrial products. Its genetic diversity and adaptability enable cultivation across a wide range of agroecological conditions. Globally, maize was grown on approximately 193.7 million ha in nearly 170 countries, with annual production of about 1,147.7 million tonnes **(2)**. The United States is a leading producer, followed by China and Brazil **(3)**. In India, maize occupied approximately 9.86 million ha and produced 31.65 million tonnes, equivalent to an average yield of about 3.2 t ha^{-1} **(4,5)**. In Telangana, maize is the second most widely cultivated crop after rice. It is grown during the *kharif* and *rabi* seasons on approximately 14

lakh acres, with an estimated annual production of 16 lakh tonnes. Nitrogen (N) is a major nutrient limiting crop growth and yield **(6)**. However, excessive or poorly timed N application can lower nitrogen-use efficiency and increase fertilizer losses **(7,8)**. Increasing crop production also generates substantial quantities of residues, making their management an important consideration for sustainable cropping systems. Crop residues are generated in substantial quantities in major agricultural countries, including the United States, China, India, Brazil and Russia. Their recycling varies among regions and farming systems **(9)**. Incorporating residues into soil returns organic matter and nutrients, supporting nutrient cycling and potentially reducing fertilizer requirements. These benefits depend on residue composition, soil conditions and management practices; residue incorporation should therefore be considered alongside appropriate fertilizer management rather than as a direct replacement for mineral nutrients. Recycling crop residues can improve soil physical, chemical and biological properties while helping to limit soil degradation and erosion **(10)**. In contrast, burning residues after harvest removes potentially recyclable nutrients and releases greenhouse gases and air pollutants, with consequences for environmental quality and human health **(11)**. Crop straw contains organic carbon and nutrients, including nitrogen, phosphorus, potassium and micronutrients. Returning it to the soil can therefore contribute to soil organic matter and nutrient cycling, although its nutrient value varies with the crop and residue management practices **(12,13,14)**. Incorporating crop straw can improve soil physical conditions by reducing bulk density, increasing porosity and moderating soil moisture and temperature. These changes may support root growth, water use and crop productivity, although their magnitude depends on soil and management conditions **(15)**. Straw also supplies carbon that supports soil microbial activity during decomposition **(16)**. In a meta-analysis of 176 field studies, straw return increased soil organic carbon concentration by an average of 12.8%, indicating its potential to improve soil carbon status **(17)**.

Straw incorporation can temporarily reduce soil mineral nitrogen (N) availability because microorganisms use N while decomposing carbon-rich residues. This may restrict N uptake and yield in the succeeding crop, particularly in soils with low N availability **(18)**. Adjusting the timing or rate of fertilizer N may help meet crop demand during this early immobilization phase, although additional N is not necessarily required throughout the season. Over time, residue return can improve soil fertility and N cycling; a six-year maize study reported higher grain yield and N uptake with straw incorporation **(19)**. In semi-arid rice-maize systems, however, the amount and timing of N needed after rice straw incorporation, the transition from

net immobilization to net mineralization, and the associated changes in soil microbial activity remain insufficiently characterized. We hypothesized that incorporating rice straw with nitrogen fertilizer would improve soil nitrogen availability and biological activity, promote straw decomposition and increase maize productivity. To test this hypothesis, we conducted a field experiment during the *rabi* seasons of 2021-2022 and 2022-2023.

Materials and methods

Experimental site and climatic situation

The field experiment was conducted at the Regional Agricultural Research Station, Professor Jayashankar Telangana Agricultural University, Warangal, Telangana, India, during the *rabi* seasons of 2021-2022 and 2022-2023. During the reported November-May observation period, mean maximum and minimum air temperatures were 32.94 and 20.69 °C, respectively, and rainfall totalled 149.4 mm (Figs. 1 and 2). At the start of the experiment, the soil contained 683 g kg^{-1} sand, 132 g kg^{-1} silt and 185 g kg^{-1} clay. Its pH was 7.67, electrical conductivity was 0.33 dS m^{-1}, organic carbon content was 5.5 g kg^{-1} and bulk density was 1.51 Mg m^{-3}. Available N, P and K were 205.5 kg N ha^{-1}, 55.73 kg P_2O_5 ha^{-1} and 448.9 kg K_2O ha^{-1}, respectively.

Experimental setup:

The experimental methodology used was a randomized block design with a factorial setup and three replications. Factor 1: consists of 3 levels of paddy straw management options. Factor 2: consists of 6 levels of nitrogen management options. The details of the treatments were given in Table 1.

Table 1: Experimental details for maize

Factor-1: Paddy straw management options	
Straw Burning (SB)	Paddy straw of the previous crop was quantified and burnt in the field
Straw Incorporation (SI)	Paddy straw of previous crop was quantified and incorporated in-situ*
Cutting and Removal (CR)	Paddy straw of previous crop was removed from the field
Factor-2: Nitrogen management options	
T_1	100 % RDN (33.3 % at basal, 33.3% at 30 DAS and 33.3% at 60 DAS)

T_2	100% RDN (40 % at basal, 30% at 30 DAS, 30% at 60 DAS)
T_3	100% RDN (10% at basal, 30% at 15 DAS, 30% at 30 DAS and 30% at 60 DAS)
T_4	100% RDN (15% at basal, 30% at 15 DAS, 30% at 30 DAS and 25% at 60 DAS)
T_5	115% RDN (18 % at basal, 36% at 15 at DAS, 36% at 30 DAS and 25% at 60 DAS)
T_6	130% RDN (20% at basal, 42% at 15 DAS, 42% at 30 DAS and 26 % at 60 DAS)

***** Paddy straw was incorporated with the help of a straw mulcher, which breaks the straw into small pieces of approximately 10 cm that can easily be decomposed.

DAS- Days after sowing

Recommended doses of phosphorus and potassium were applied as basal in all the treatments. RDF for winter maize was (240:80:80 N: P_2O_5: K_2O kg ha^{-1}).

Crop Management

Rice was grown in the experimental plots during the preceding rainy seasons using standard agronomic practices. It was harvested manually, and the straw was kept within its respective plot until the assigned straw management treatment was applied. Hybrid maize (cv. NK-7884) was sown in the same plots during the last week of December 2021 and 2022 at a spacing of 0.6×0.2 m. The assigned straw and nitrogen treatments were imposed, and standard agronomic practices were followed for the remaining crop operations. Maize was harvested manually during the last week of April 2022 and 2023

Sampling and analysis of soil

Composite soil samples were collected from the 0-15 cm layer with an auger before rice straw incorporation, at 15, 30, 45 and 60 days after sowing (DAS), and after maize harvest. Subsamples for available nitrogen (N) analysis were air-dried, gently crushed, passed through a 2 mm sieve and stored in labelled polyethylene bags. Available N was determined following **(20)**. Separate fresh subsamples were analysed for ammonium-N and nitrate-N using the method of **(21)**. Fresh soil reserved for microbial enumeration was stored at 4 °C. Bacteria, fungi and actinomycetes were enumerated by serial dilution and plating on nutrient agar, Rose Bengal agar and Kenknight and Munaier's medium, respectively **(22,23).**

The plates were incubated at 37 °C for 24 h for bacteria, 25 °C for 72 h for fungi and 30 °C for 48 h for actinomycetes. Microbial abundance was expressed as colony-forming units (CFU) per gram of soil, calculated from the colony count, dilution factor and volume plated.

$$\text{Cfu/ml} = \frac{\text{no. of colonies x dilution factor)}}{\text{inoculum volume}}$$

Soil dehydrogenase activity was determined using 3% triphenyltetrazolium chloride (TTC) as the substrate and expressed as µg triphenyl formazan (TPF) g^{-1} soil day^{-1} **(24)**. Acid and alkaline phosphatase activities were assayed using *p*-nitrophenyl phosphate as the substrate; the released *p*-nitrophenol was measured spectrophotometrically at 420 nm and expressed as µg *p*-nitrophenol g^{-1} soil h^{-1} **(25,26)**. Urease activity was assayed following **(27)**.

Paddy straw decomposition rate

Rice straw decomposition was assessed using the litterbag method of Bocock and Gilbert **(28)**. Air-dried straw was cut into approximately 100 mm pieces, and 37.0 g and 36.6 g were placed in each nylon mesh bag (20 × 30 cm; 2 mm mesh) during 2021-2022 and 2022-2023, respectively. Six bags were buried at a depth of 10–15 cm in each plot assigned to a straw incorporation treatment. One bag per plot was retrieved at 10, 20, 30, 40 and 50 days after maize sowing and at harvest. The recovered straw was cleaned of adhering soil and debris, shade-dried, and then oven-dried at 70 °C to constant mass. Straw decomposition was expressed as percentage mass loss relative to the initial straw mass.

Here, M_o is the initial straw mass (g), and M_t is the straw mass remaining (g) after t days. To quantify differences in decomposition among treatments, a modified exponential decay model based on **(29)** was fitted separately to the mass-remaining data for each treatment. The fitted model was used to estimate a treatment-specific decomposition rate constant, as follows

$$\text{Straw cumulative decomposition rate (\%)} = \frac{\text{M0} - \text{Mt}}{\text{M0}} \times 100$$

Where

Here, M_o represents the initial mass of straw (g), whereas M_t denotes the remaining straw mass (g) after t days of decomposition. To characterize decomposition dynamics under different treatments, the modified exponential decay model proposed by Olson **(29)** was fitted separately to the data from each treatment. This approach enabled the estimation of treatment-specific decomposition rate constants. The model is expressed as follows:

177 $$Y = a \times e^{-kt} = \frac{Mt}{M0}$$

178 In the model, *y* denotes the fraction of straw mass remaining, *k* is the decomposition rate
179 constant (d^{-1}), a_n is the coefficient representing the initial residue fraction, and *t* is time (days).
180 The fitted parameters were used to estimate the time required for 50% (T_{50}) and 95% (T_{95}) straw
181 decomposition using the following equations:

182 $$\mathrm{T\ 50} = \frac{\ln 0.5 - \ln a}{(-k)}$$

183 $$\mathrm{T\ 95} = \frac{\ln 0.05 - \ln a}{(-k)}$$

184 **Energy indices.** The energy indices were calculated to compare the efficiency of different
185 straw and nitrogen management practices for their utilization of energy ().

186 $$\text{Energy use efficiency} = \frac{\text{Total output energy } (\frac{\text{MJ}}{\text{ha}})}{\text{Total input energy } (\frac{\text{MJ}}{\text{ha}})}$$

187 $$\text{Energy productivity (kg MJ}^{-1}) = \frac{\text{Economic output } (\frac{\text{kg}}{\text{ha}})}{\text{Energy input } (\frac{\text{MJ}}{\text{ha}})}$$

188 $$\text{Nutrient energy ratio} = \frac{\text{Economic output } (\frac{\text{kg}}{\text{ha}})}{\text{Nutrient energy input } (\frac{\text{MJ}}{\text{ha}})}$$

189 $$\text{Specific energy (MJ kg}^{-1}) = \frac{\text{Energy input } (\frac{\text{MJ}}{\text{ha}})}{\text{Economic output } (\frac{\text{kg}}{\text{ha}})}$$

190 $$\text{Energy profitability} = \frac{\text{Net energy output } (\frac{\text{MJ}}{\text{ha}})}{\text{Energy input } (\frac{\text{MJ}}{\text{ha}})}$$

191

192 $$\text{Human Profitability} = \frac{\text{Energy Output (MJ } ha^{-1})}{Labour\ energy\ input\ (MJ\ ha^{-1})}$$

193 **Statistical analysis:**

194 Maize yield, soil properties, microbial counts and enzyme activities were analysed by analysis
195 of variance (ANOVA). A two-factor factorial ANOVA was used to test the main effects of rice
196 straw management and nitrogen treatment and their interaction **(30)**. Treatment means were
197 compared using Duncan's multiple range test at a significance level of $P < 0.05$. Correlations
198 among response variables were assessed using correlation coefficients. Analyses were
199 performed in R **(31)**, including the agricolae package **(32)**, and IBM SPSS Statistics 27. Figures
200 were prepared using ggplot2 **(33)**.

201 The relationships of maize yield with soil ammonium-N and nitrate-N were examined
202 separately by fitting linear, quadratic and cubic regression models, with yield as the response

variable. Model fit was evaluated using the coefficient of determination (R^2). The models were specified as follows:

Linear Model: $Y=\beta_0+\beta_1X+\epsilon$

Quadratic Model: $Y=\beta_0+\beta_1X+\beta_2X^2+\epsilon$

Cubic Polynomial Model: $Y=\beta_0+\beta_1X+\beta_2X^2+\beta_3X^3+\epsilon$

where, Y represents yield, X is nitrogen content and β_1, β_2 and β_3 are regression coefficients corresponding to linear, quadratic and cubic terms. The regression coefficients provide insights into how each nitrogen source influences yield response.

Results

Available nitrogen content (kg ha^{-1}) in soil

Rice straw and nitrogen management affected soil available nitrogen (N) at several stages of maize growth (Table 2). At 15 and 30 days after sowing (DAS), available N under straw burning (SB) was 6.32% and 7.29% higher, respectively, than under straw incorporation (SI; $P < 0.05$). Straw management had no significant effect at 45 DAS. At 60 DAS and after harvest, available N under SI was 8.12% and 7.19% higher, respectively, than under straw removal (SR).

Among the nitrogen treatments, 100% of the recommended N dose (RDN), applied as 40% at sowing, 30% at 30 DAS and 30% at 60 DAS, gave the highest available N at 15 DAS (228.6 kg ha^{-1}). The 130% RDN treatment gave the highest values at 30, 45 and 60 DAS and after harvest (208.5, 202.7, 204.4 and 191.8 kg ha^{-1}, respectively). After harvest, available N under 115% RDN (185.7 kg ha^{-1}) and under the two alternative 100% RDN schedules (180.6 and 177.6 kg ha^{-1}) did not differ significantly from that under 130% RDN. The alternative schedules applied N at sowing, 15, 30 and 60 DAS in proportions of 15:30:30:25 and 10:30:30:30, respectively.

Ammonical and Nitrate nitrogen (kg ha^{-1}) content in soil

Soil ammonium-N was significantly higher under straw burning (SB) than under straw incorporation (SI) at 15 and 30 days after sowing (DAS), by 14.12% and 18.14%, respectively (Table 3). Compared with straw removal (SR), the increases were 5.20% and 4.81%, respectively. By 60 DAS, the pattern had reversed: ammonium-N under SI was 10.86% higher than under SR and 7.5% higher than under SB. After harvest, the corresponding differences were 15.7% and 12.6%.

Among nitrogen treatments, ammonium-N was highest at 15 and 30 DAS under 100% of the recommended nitrogen dose (RDN) applied as 40% basal, 30% at 30 DAS and 30% at 60 DAS. The lowest values at these stages occurred under 100% RDN applied as 10% basal and 30% each at 15, 30 and 60 DAS. From 45 DAS through harvest, ammonium-N was highest under 130% RDN. In post-harvest soil, this treatment exceeded 115% RDN by 5.1% and the four 100% RDN schedules listed in Table 3 by 9.0%, 13.4%, 16.0% and 21.9%, respectively.

Nitrate-N showed a similar early response to straw management (Table 4). At 15 and 30 DAS, values under SB were 11.18% and 16.65%, respectively, higher than under SI, and 5.20% and 4.81% higher than under SR. At 60 DAS and after harvest, the highest nitrate-N values were recorded under 130% RDN

Quadratic models fitted the relationships between maize yield and soil ammonium-N and nitrate-N more closely than the corresponding linear models, based on their higher R^2 values (Fig. 5). Both curves indicate that yield increased as the measured soil N content rose, although the rate of increase diminished at higher values. The fitted curves suggest that yield continued to rise up to approximately 75-80 kg ha^{-1}, beyond which it levelled off or declined. The ammonium-N and nitrate-N models explained approximately 53% and 55% of the variation in yield, respectively, with a slightly higher R^2 for nitrate-N.

Changes in soil available nitrogen following straw incorporation

Relative to straw burning (SB), straw incorporation (SI) was associated with 13.3 and 13.7 kg ha^{-1} less soil available nitrogen (N) at 15 and 30 days after sowing (DAS), respectively (Fig. 3). This early reduction is consistent with microbial N immobilization during straw decomposition. The fitted curves for SB and SI crossed at an estimated 40.9 DAS, after which available N under SI increased relative to SB. Among nitrogen treatments, 130% of the recommended N dose (RDN) had the smallest estimated early N deficit at 30 DAS (11.9 kg ha^{-1}; Fig. 4). The estimated crossover occurred at 39.0 DAS under 130% RDN; the corresponding estimates were 39.6 DAS under 115% RDN and 40.9, 41.7, 42.1 and 42.7 DAS under the four 100% RDN schedules, respectively

Soil microbial count

Bacterial, fungal and actinomycete counts peaked at 60 days after sowing (DAS), followed by the post-harvest and 30 DAS sampling points (Table 5). Straw incorporation (SI) significantly increased the bacterial count compared with straw burning (SB; $P < 0.05$). The reported count

under SI was 15.64 × 10^5 CFU g^{-1} fresh soil, compared with 13.36 × 10^5 CFU g^{-1} under straw removal (SR); the lowest count occurred under SB. A similar treatment pattern was observed at 60 DAS and after harvest.

Across nitrogen treatments, bacterial counts increased up to 60 DAS and then declined. The 130% recommended nitrogen dose (RDN) produced the highest counts at 30 DAS (14.93 × 10^5 CFU g^{-1}), 60 DAS (22.39 × 10^5 CFU g^{-1}) and after harvest (16.38 × 10^5 CFU g^{-1}). Post-harvest counts under the remaining treatments were 15.95 × 10^5 CFU g^{-1} for 115% RDN and, in descending order, 15.06, 14.62, 14.23 and 13.73 × 10^5 CFU g^{-1} for the four 100% RDN schedules listed in Table

The highest reported fungal count occurred under straw incorporation (SI; 29.57 × 10^3 CFU g^{-1} fresh soil), whereas straw burning (SB) had the lowest count (24.52 × 10^3 CFU g^{-1} fresh soil). At 60 days after sowing (DAS), fungal counts under SI and straw removal (SR) were comparable (Table 6). Among nitrogen treatments, fungal counts were highest under 130% of the recommended nitrogen dose (RDN): 28.78, 39.72 and 33.89 × 10^3 CFU g^{-1} fresh soil at 30 DAS, 60 DAS and after harvest, respectively. This treatment was followed by 115% RDN and 100% RDN applied in four splits of 15%, 30%, 30% and 25% at sowing, 15, 30 and 60 DAS. The lowest counts at the same sampling times occurred under 100% RDN applied in three equal splits (25.41, 34.95 and 28.93 × 10^3 CFU g^{-1} fresh soil, respectively).

Actinomycete counts were highest under SI at 30 and 60 DAS and after harvest, although they were comparable with those under SR (Table 7). Among nitrogen treatments, 130% RDN produced the highest counts at these sampling times (43.39, 50.44 and 44.39 × 10^4 CFU g^{-1} fresh soil, respectively), followed by 115% RDN and the four-split 100% RDN treatment. The lowest counts occurred under 100% RDN applied in three equal splits (35.06, 43.35 and 36.83 × 10^4 CFU g^{-1} fresh soil, respectively).

Soil enzyme activities

Urease, dehydrogenase, acid phosphatase and alkaline phosphatase activities increased from 30 to 60 days after sowing (DAS) and declined after maize harvest (Figs. 6–7). Urease activity was highest under straw incorporation (SI), with values of 55.42, 102.52 and 37.28 μg NH_4^+-N g^{-1} soil per 2 h at 30 DAS, 60 DAS and after harvest, respectively (Fig. 6). Among nitrogen treatments, the highest urease activity occurred under 130% of the recommended nitrogen dose (RDN).

Dehydrogenase activity was significantly higher under SI than under straw removal (SR) or straw burning (SB) at all three sampling times (Fig. 7). Values under SI were 55.34, 100.53 and 36.70 µg triphenyl formazan (TPF) g^{-1} soil day^{-1} at 30 DAS, 60 DAS and after harvest, respectively. The corresponding values were 50.56, 88.38 and 33.26 under SR, and 47.85, 79.77 and 30.09 under SB. Among nitrogen treatments, 130% RDN produced the highest dehydrogenase activities (58.56, 95.00 and 37.78 µg TPF g^{-1} soil day^{-1}, respectively).

Compared with SB, SI increased acid phosphatase activity by 15.53%, 17.43% and 37.32% at 30 DAS, 60 DAS and after harvest, respectively. The corresponding increases in alkaline phosphatase activity were 11.89%, 12.28% and 23.65%. Phosphatase activity was expressed as µg *p*-nitrophenol g^{-1} soil h^{-1}.

The supplied text also links higher urease activity to both N dose and the number of application splits. Because the N treatments vary in more than one way, that separate effect of split number should be claimed only if the statistical analysis tests it.

Straw decomposition and decay constant

Straw mass loss varied across sampling intervals during the two seasons. Mean loss was 5.74% during days 0–10 and 6.72% during days 10–20, followed by 5.05%, 5.04% and 3.94% during days 20–30, 30–40 and 40–50, respectively. Differences among nitrogen treatments were significant up to 30 days after sowing (DAS), but were not significant at the subsequent sampling points. During days 0–10, the greatest mass loss occurred under 100% of the recommended nitrogen dose (RDN) applied as 40% basal and 30% each at 30 and 60 DAS (6.10%). The 130% RDN treatment had the greatest loss during days 10–20 (7.52%) and 20–30 (5.97%). During days 30–40 and 40–50, the highest values occurred under 100% RDN applied in four splits of 15%, 30%, 30% and 25% at sowing, 15, 30 and 60 DAS (5.23% and 4.04%, respectively). The greatest reported loss in the final interval, from 50 DAS to harvest, occurred under 115% RDN (10.07%) (Table S1-S4).

The fitted decay constants (k) ranged from 0.0031 to 0.0034 d^{-1} across nitrogen treatments (Table 8). Based on these constants, the estimated times to 50% and 95% mass loss were 204–224 and 881–966 days, respectively. Among treatments receiving 100% RDN, the two four-split schedules had higher k values than the two three-split schedules; k was higher still under 115% and 130% RDN

Energy indices

Rice straw management affected energy inputs and outputs (Table 9). Compared with straw burning, incorporation increased total energy input by 3.53% and energy output by 3.18%. Net energy return under incorporation was 3.14% higher than under burning and 11.50% higher than under straw cutting and removal. Nevertheless, burning produced the highest energy-use efficiency, energy productivity and energy profitability among the straw management treatments.

Across nitrogen treatments, total energy input ranged from 25,679 to 30,082 MJ ha^{-1}. Net energy return was highest under 130% of the recommended nitrogen dose (RDN; 227,529 MJ ha^{-1}), followed in descending order by 115% RDN; 100% RDN applied in four splits of 15:30:30:25 and 10:30:30:30; 100% RDN applied in three splits of 40:30:30; and 100% RDN applied in three equal splits. In contrast, the 15:30:30:25 schedule produced the highest energy-use efficiency, energy productivity, nutrient energy ratio and energy profitability, exceeding the corresponding values under 130% RDN by 12.2%, 11.6%, 21.5% and 13.8%, respectively

Grain and stover yield

Rice straw and nitrogen management significantly affected maize grain and stover yields ($P < 0.05$). In the two-year pooled analysis, grain yield under straw incorporation was 8.21% higher than under straw cutting and removal and 2.19% higher than under straw burning (Fig. 8). Among nitrogen treatments, grain yield was highest under 130% of the recommended nitrogen dose (RDN), exceeding the yield under 100% RDN applied in three equal splits by 15.27% (Fig. 9).

Multivariate relationships between maize yield and soil–plant attributes

Partial least-squares regression (PLSR) was employed to examine the relationships of maize grain yield with nitrogen uptake, chlorophyll status, soil mineral nitrogen, microbial populations and soil enzymatic activities under different rice straw and nitrogen management treatments (Fig. 10). The first two latent components jointly explained 65.7% of the variation in predictor variables (X) and 58.0% of the variation in grain yield (Y). Component 1 accounted for 54.7% of X variation and 50.6% of Y variation, whereas component 2 explained 10.9% and 7.4%, respectively.

The yield vector extended towards the positive component 1 axis and was positively oriented with grain and stover nitrogen uptake, nitrogen uptake at 45 and 60 days after sowing (DAS), and several chlorophyll (SPAD) measurements. Nitrogen uptake at 45 DAS exhibited relatively close alignment with yield, suggesting a strong multivariate association between mid-season nitrogen acquisition and final grain productivity.

Bacterial, fungal and actinomycete counts at 30 and 60 DAS were primarily distributed in the positive component 1 and component 2 quadrant, indicating positive associations with the principal yield-related gradient, although their directions differed from the main plant nitrogen uptake variables. Several soil nitrogen measurements, particularly those at 30 DAS, were positioned towards negative component 2, suggesting differences in temporal responses among soil nitrogen availability, biological activity and crop nitrogen acquisition.

Observations from different residue management practices and nitrogen treatments showed considerable overlap, indicating that the variation was represented more strongly by continuous soil–plant trait gradients than by clearly separated treatment clusters.

Variable importance in projection

The variable importance in projection (VIP) analysis revealed marked differences in the relative contributions of the measured soil and plant attributes to the fitted PLSR model (Fig. 11). Grain nitrogen uptake emerged as the highest-ranked variable, with a VIP score of approximately 2.7, followed by stover nitrogen uptake (approximately 1.3) and nitrogen uptake at 45 DAS (approximately 1.2).

Nitrogen uptake at 30 and 60 DAS, SPAD readings at 20, 30 and 50 DAS, alkaline phosphatase activity at 30 DAS and bacterial populations at 60 DAS also exceeded the conventional VIP threshold of 1.0.

In contrast, the measured ammonium-N and nitrate-N pools, most soil enzymatic activities, fungal and actinomycete counts, and several additional nitrogen indices exhibited VIP scores at or below 1.0. These findings indicate that plant nitrogen acquisition and chlorophyll status contributed more strongly to the fitted yield-related multivariate structure than most individual soil biochemical measurements. Variables with VIP values close to 1.0 should be considered borderline rather than interpreted as clearly distinct in importance.

Discussion

Nitrogen availability during straw decomposition

The carbon-to-nitrogen (C: N) ratio of incorporated organic material influences whether decomposition is accompanied by net nitrogen (N) immobilization or mineralization (34,35,36,37). Carbon-rich residues such as rice straw can stimulate microbial demand for N, temporarily reducing soil mineral N available to the crop. A C: N ratio above approximately 30:1 is often associated with net immobilization, although the response also depends on residue composition and soil conditions (38).

In the present study, soil available N under straw incorporation was initially lower than under straw burning. The fitted treatment curves crossed at approximately 40.9 days after maize sowing, with estimated crossover times ranging from 39.0 to 42.7 days across N treatments. The earliest crossover was estimated under 130% of the recommended N dose (RDN; 39.0 days), followed by 115% RDN (39.6 days). Changing from three to four N applications showed

no clear effect on this estimated timing. Previous work with N-rich amendments such as *Gliricidia* suggests that residue quality may also influence N release (39).

These crossover times indicate a change in the relative soil available N under the compared straw treatments. They should not be presented as direct measurements of the day microbial immobilization ended or mineralization began.

Soil microbial counts

In the present study, rice straw incorporation was associated with higher bacterial, fungal, and actinomycete colony counts than straw burning. This response is consistent with evidence that retained residues provide carbon substrates and can improve soil biological properties (40). Counts increased up to 60 days after maize sowing and declined by harvest. Changes in residue-derived carbon availability, soil nitrogen and root inputs may have contributed to this pattern, although their individual effects were not measured. As decomposition proceeds, changes in the availability of residue components can also alter the microorganisms supported by the soil (41).

Microbial counts also varied with nitrogen management. The highest counts generally occurred at 130% of the recommended nitrogen dose, suggesting that added N supported culturable microorganisms within the tested range. Responses to N addition can differ across soils and application rates (42). Because the present study measured colony-forming units, these results should be described as counts of culturable microorganisms, rather than total microbial activity, biomass or community composition. The observed results do not show inhibition by excess N within the tested range

Soil enzyme activities

Dehydrogenase activity reflects the metabolic activity of viable soil microorganisms and is an important indicator of soil biological quality (43). Its higher activity under residue incorporation may be attributed to greater availability of carbon substrates from incorporated paddy straw, which stimulated microbial activity and residue decomposition. Similar responses have been reported under residue incorporation and improved N management (44,45,46,1).

Phosphatases regulate organic P mineralization and contribute to P availability during residue decomposition (48,49). Residue incorporation increased acid and alkaline phosphatase activities, probably through enhanced microbial proliferation and enzyme synthesis. The comparatively higher alkaline phosphatase activity may be related to the slightly alkaline soil

reaction of the experimental site (50,51,52). Recent evidence also supports enhanced soil biological and enzymatic activity through integrated residue and N management (1).

Straw decomposition and decay constant

Straw decomposition was rapid during the first 50 days, exceeding 26.48%, and reached 36.44% by 130 days, consistent with (53). Faster decomposition under the rice-maize system may reflect favourable oxygen and temperature conditions that stimulated microbial activity (54). The initial rapid decay was associated with utilization of readily decomposable substrates, followed by slower decomposition of resistant fractions (55,56). The low decomposition constants may be attributed to the straw's high C ratio (72.4:1), as reported previously (57,58).

Nitrogen application further accelerated residue decomposition. Four-split N application (T3 and T4) increased microbial and enzymatic activity, enhancing carbon release, while higher N rates with additional splits (T5 and T6) further reduced residue C ratio and promoted N mineralization. Similar effects of synchronized N supply on residue decomposition and nutrient release have been reported (59, 60, 61, 62, 56). Thus, N dose and application timing were important regulators of residue decomposition and nutrient release.

Energy indices

Residue retention increased total energy input because incorporated biomass carries substantial embodied energy, consistent with previous energy-accounting studies (63,64,65). However, residue recycling can improve energy-use efficiency and economic returns through enhanced soil structure, moisture conservation, nutrient cycling and carbon storage (66,67,68,69,70). Residue retention also supports soil microbial activity by supplying carbon and metabolic energy, whereas burning causes irreversible energy losses and contributes to soil degradation and greenhouse-gas emissions (71,72,73).

Nitrogen fertilization further increased energy input through greater fertilizer, machinery, diesel and labour requirements, with higher N rates generally increasing total energy input (74,75). Despite greater inputs, increased N availability enhanced grain yield and energy output, likely through improved photosynthetic efficiency and yield components (76,77). Consequently, nitrogen management significantly affected energy-use efficiency, energy productivity, energy profitability and human-energy profitability. The greater human-energy

profitability under 130% RDN was primarily associated with higher energy output relative to human labour requirements (78).

Yield

Straw incorporation can improve soil fertility and nutrient cycling, thereby enhancing crop growth and productivity. In the present study, the higher productivity under straw incorporation may be attributed to improved nutrient availability and greater N recovery from decomposing residue. Similar yield benefits from straw return have been reported in rice and wheat systems, with responses increasing under repeated incorporation (79,80). (81) observed that full wheat-straw return increased wheat yield by 15.2% and 13.1% in FY and YY varieties, respectively, compared with no straw return, while (82) reported 9.35% and 17.15% increases in rice yield under half and total straw return, respectively. The corresponding increases in wheat yield were 10.80% and 12.00%. These yield responses may be related to temporary N immobilization during residue decomposition followed by gradual N mineralization, which synchronizes N release with crop demand and improves N uptake. Thus, residue incorporation, particularly when integrated with appropriate N management, can enhance nutrient-use efficiency and sustain productivity in rice–maize systems.

Nitrogen acquisition as the principal yield-associated process

The PLSR findings highlight the central association of nitrogen acquisition with maize productivity under contrasting rice straw and nitrogen management strategies. Nitrogen uptake at 30–60 DAS, together with chlorophyll status during early and intermediate growth stages, contributed prominently to the multivariate yield pattern. Sustained nitrogen acquisition during these periods is biologically relevant because nitrogen supports chlorophyll synthesis, photosynthetic activity, biomass accumulation and subsequent grain formation.

The positive association between SPAD readings and grain yield further supports the role of crop nitrogen status in explaining productivity differences. SPAD-based chlorophyll measurements provide a rapid, non-destructive indicator of plant nitrogen status, although their interpretation can be affected by leaf characteristics and environmental conditions (86).

The PLSR findings are consistent with the two-year pooled field results, in which straw incorporation increased maize grain yield by 8.21% over residue removal and 2.19% over burning. Similarly, the 130% recommended nitrogen dose (RDN) treatment produced 15.27% greater grain yield than the treatment receiving 100% RDN in three equal splits. Ma et al. (19)

also reported improved maize productivity and nitrogen uptake following six years of straw incorporation, associated with sustained improvements in soil fertility.

Nevertheless, grain nitrogen uptake requires particular caution in interpreting the VIP rankings. When grain nitrogen uptake is calculated from grain yield and grain nitrogen concentration, it is mathematically linked to the response variable. Therefore, its dominant VIP score describes a strong association between grain production and harvested nitrogen accumulation but does not independently establish that grain nitrogen uptake caused the yield response.

Temporal nitrogen dynamics and synchronization with crop demand

The importance of mid-season nitrogen uptake is consistent with the temporal nitrogen dynamics observed under rice straw incorporation. During the initial decomposition phase, incorporation reduced soil available nitrogen by 13.3 and 13.7 kg ha^{-1} relative to straw burning at 15 and 30 DAS, respectively. The fitted soil available-N curves crossed at approximately 40.9 DAS, after which the incorporated-residue treatment exhibited comparatively greater nitrogen availability.

The earliest estimated crossover occurred under 130% RDN at 39.0 DAS. These estimated crossover times indicate changes in relative soil nitrogen availability and should not be interpreted as direct measurements of the onset of net nitrogen mineralization.

Carbon-rich residues can stimulate microbial nitrogen assimilation during decomposition, temporarily restricting nitrogen availability to crops. Subsequent decomposition and nutrient turnover may contribute to greater nitrogen availability during later growth stages (18,37). Zhu et al. (62) demonstrated that microbial stoichiometric responses to nutrient availability regulate rice straw mineralization and related soil carbon transformations.

Consequently, nitrogen uptake measurements during 30–60 DAS may integrate several processes, including fertilizer nitrogen supply, microbial immobilization, mineralization and plant acquisition. This helps explain why these variables displayed higher VIP values than individual soil ammonium-N and nitrate-N concentrations.

The relatively lower importance of mineral nitrogen concentrations does not imply that these pools are agronomically unimportant. Rather, soil mineral nitrogen is highly dynamic, and a single sampling measurement may not represent cumulative nitrogen availability or crop uptake throughout the growing season.

Contribution of soil microbial populations and enzymatic activity

519 The positive component-1 orientation of bacterial, fungal and actinomycete populations
520 suggests that soil biological conditions contributed to the overall yield-associated multivariate
521 structure. This interpretation is consistent with the higher culturable microbial counts and
522 enzyme activities recorded under straw incorporation.

523 Crop residue incorporation supplies organic carbon substrates that can stimulate microbial
524 proliferation and associated nutrient transformations. Choudhary et al. (40) documented
525 improvements in microbial biomass, soil enzymatic activity and biological quality under
526 conservation agriculture-based cereal systems incorporating crop residues. Akhtar et al. (50)
527 likewise reported greater soil enzymatic activity, improved soil nutrient status and increased
528 maize productivity under straw mulching.

529 However, bacterial abundance at 60 DAS was the only microbial-count variable that marginally
530 exceeded the VIP threshold. The fungal and actinomycete measurements, despite their positive
531 projections in the biplot, contributed comparatively less to the fitted yield model.

532 This distinction is important because PLSR evaluates the relative contribution of correlated
533 variables to the modeled response, rather than directly quantifying the ecological importance
534 of individual microbial groups. Moreover, the plate-count measurements represent culturable
535 microorganisms rather than the complete soil microbial community.

536 Alkaline phosphatase activity at 30 DAS was the only soil enzyme measurement with VIP
537 greater than 1.0, suggesting that early organic phosphorus turnover contributed complementary
538 information to the multivariate association with grain yield.

539 Soil phosphatases facilitate the hydrolysis of organic phosphorus compounds, potentially
540 contributing to phosphorus recycling during residue decomposition (48). Although the elevated
541 VIP ranking of alkaline phosphatase is consistent with greater microbial nutrient turnover, the
542 analysis does not establish phosphorus limitation or a direct causal effect of phosphatase
543 activity on yield.

544 **Integrated interpretation and agronomic implications**

545 PLSR is particularly useful for analysing datasets containing highly correlated biological,
546 biochemical and agronomic measurements, because it summarises the common predictor–
547 response structure through latent variables (83).

The present findings suggest an interpretable hierarchy of yield-associated traits, with plant nitrogen uptake and mid-season chlorophyll status representing the strongest measured associations, followed by selected soil biological indicators.

Nevertheless, VIP scores represent model-specific measures of importance and should not be considered tests of statistical significance. Their stability is influenced by correlations among predictor variables, the number of retained components and the validation strategy (84,85).

The agronomic interpretation of the observed pattern is that crop nitrogen acquisition integrates the net consequences of fertilizer supply, residue decomposition and soil biological processes more directly than individual measurements of soil nutrient pools.

Taken together, the results support an association between effective nitrogen management, improved crop nitrogen status and higher maize productivity under rice straw incorporation. Confirmation of the predictive contribution of these traits requires cross-validation and sensitivity analyses excluding harvest-derived nitrogen uptake variables. Such analyses would distinguish explanatory relationships from indicators suitable for predicting grain yield before harvest.

Conclusions:

Rice straw incorporation initially caused transient N immobilization, but N availability surpassed burning at about 41 DAS. Increasing N to 130% RDN reduced early N immobilization and improved N availability, soil enzyme activities, microbial populations and maize yield. Straw incorporation increased urease, dehydrogenase, acid phosphatase and alkaline phosphatase activities by 25.3%, 22.0%, 37.3% and 23.6%, respectively, over burning at harvest. Residue decomposition followed first-order kinetics, with decay constants (k) of 0.0031-0.0034 d^{-1}. Pooled maize grain yield increased by 8.21% over straw removal and 2.19% over burning under straw incorporation. Overall, straw incorporation combined with appropriately synchronized N management improved N cycling, soil biological activity, residue decomposition and maize productivity in the rice-maize system.

Conflict of interest statement

The authors declare no conflicts of interest.

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Declarations

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References:

1. Gupta, N., Sharma, S., Chauhan, N. & Kumawat, K. C. Optimized rice residue management, tillage intensity and nitrogen application enhance soil biological quality and subsequent wheat productivity in rice-wheat system of north-western India. *Front. Soil Sci.* **6**, 1872133. https://doi.org/10.3389/fsoil.2026.1872133 (2026).

2. Meena Shekhar & Singh, N. The impact of climate change on changing pattern of maize. In *Maize Genetic Resources: Breeding Strategies and Recent Advances* 151. https://doi.org/10.5772/intechopen.101053 (2022).

3. Food and Agriculture Organization of the United Nations. *FAOSTAT statistical database* (2020).

4. Directorate of Economics and Statistics, Ministry of Agriculture and Farmers Welfare. *Agricultural Statistics at a Glance*. Government of India (2022).

5. Farmaha, B. S. et al. Contribution of persistent factors to yield gaps in high-yield irrigated maize. *Field Crops Res.* 186, 124–132. https://doi.org/10.1016/j.fcr.2015.10.020 (2016).

609 6. Sinclair, T. R. & Rufty, T. W. Nitrogen and water resources commonly limit crop yield
610 increases, not necessarily plant genetics. *Glob. Food Secur.* 1, 94–98.
611 https://doi.org/10.1016/j.gfs.2012.07.001 (2012).

612 7. Cui, Z. L. et al. Pursuing sustainable productivity with millions of smallholder farmers.
613 *Nature* 555, 363–366. https://doi.org/10.1038/nature25785 (2018).

614 8. Yuan, L. et al. Stover mulching and inhibitor application maintain crop yield and decrease
615 fertilizer N input and losses in no-till cropping systems in Northeast China. *Agric. Ecosyst.*
616 *Environ.* 312, 107360. https://doi.org/10.1016/j.agee.2021.107360 (2021).

617 9. Prasad, S. et al. Sustainable utilization of crop residues for energy generation: a life cycle
618 assessment (LCA) perspective. *Bioresour. Technol.* 303, 122964.
619 https://doi.org/10.1016/j.biortech.2020.122964 (2020).

620 10. Cerda, A., Rodrigo-Comino, J., Gimenez-Morera, A. & Keesstra, S. D. Hydrological and
621 erosional impact and farmer's perception on catch crops and weeds in citrus organic farming
622 in Canyoles river watershed, Eastern Spain. *Agric. Ecosyst. Environ.* 258, 49–58.
623 https://doi.org/10.1016/j.agee.2018.02.015 (2018).

624 11. Xia, L. L., Wang, S. W. & Yan, X. Y. Effects of long-term straw incorporation on the net
625 global warming potential and the net economic benefit in a rice-wheat cropping system in
626 China. *Agric. Ecosyst. Environ.* 197, 118–127. https://doi.org/10.1016/j.agee.2014.08.001
627 (2014).

628 12. Lal, R. Sequestering carbon in soils of agro-ecosystems. *Food Policy* 36, 33–39.
629 https://doi.org/10.1016/j.foodpol.2010.12.001 (2011).

630 13. Li, H., Dai, M. W., Dai, S. L. & Dong, X. J. Current status and environment impact of
631 direct straw return in China's cropland—a review. *Ecotoxicol. Environ. Saf.* 159, 293–300.
632 https://doi.org/10.1016/j.ecoenv.2018.05.014 (2018).

633 14. Arunrat, N., Kongsurakan, P., Sereenonchai, S. & Hatano, R. Soil organic carbon in sandy
634 paddy fields of northeast Thailand: a review. *Agronomy* 10, 1–25.
635 https://doi.org/10.3390/agronomy10081061 (2020).

636 15. Chen, S. et al. Effects of straw and manure management on soil and crop performance in
637 North China Plain. *Catena* **187**, 104359. https://doi.org/10.1016/j.catena.2019.104359 (2020).

638 16. Zhang, P. et al. Effects of straw incorporation on the stratification of the soil organic C,
639 total N and C ratio in a semiarid region of China. *Soil Tillage Res.* **153**, 28–35.
640 https://doi.org/10.1016/j.still.2015.04.008 (2015).

641 17. Liu, N. et al. Depth of straw incorporation significantly alters crop yield, soil organic carbon
642 and total nitrogen in the North China Plain. *Soil Tillage Res.* **205**, 104772.
643 https://doi.org/10.1016/j.still.2020.104772 (2021).

644 18. Gupta, R. K. & Sidhu, H. S. Nitrogen and residue management effects on agronomic
645 productivity and nitrogen use efficiency in rice-wheat system in Indian Punjab. *Nutr. Cycl.*
646 *Agroecosyst.* **84**, 141–154. https://doi.org/10.1007/s10705-008-9233-8 (2009).

19. Ma, Q., Jiang, C., Li, S. & Yu, W. Maize yield and nitrogen-use characteristics were promoted as consistently improved soil fertility: 6-year straw incorporation in Northeast China. *Plant Soil Environ.* **67**, 383–389. https://doi.org/10.17221/434/2020-PSE (2021).

20. Subbiah, B. V. & Asija, G. L. A rapid procedure for the estimation of the available N in soil. *Curr. Sci.* **25**, 259–260 (1956).

21. Bremner, J. M. Inorganic and total N. In *Methods of Soil Analysis* (ed. Black, C. A.) Part 2, 1238–1178 (American Society of Agronomy, Madison, 1965). https://doi.org/10.2134/agronmonogr9.2.c33.

22. Thornton, H. G. On the development of a standardized agar for counting soil bacteria with especial regard to the repression of spreading colonies. *Ann. Appl. Biol.* **9**, 241–274. https://doi.org/10.1111/j.1744-7348.1922.tb05958.x (1922).

23. Martin, J. P. Use of acid, rose bengal and streptomycin in the plate method for estimating soil fungi. *Soil Sci.* **69**, 215–232. https://doi.org/10.1097/00010694-195003000-00006 (1950).

24. Casida, L. E., Klein, D. A. & Santaro, T. Soil dehydrogenase activity. *Soil Sci.* **98**, 371–376. https://doi.org/10.1097/00010694-196412000-00004 (1964).

25. Tabatabai, M. A. & Bremner, J. M. Use of P-nitrophenyl phosphate for assay of soil phosphatase activity. *Soil Biol. Biochem.* **1**, 301–307. https://doi.org/10.1016/0038-0717(69)90012-1 (1969).

26. Eivazi, F. & Tabatabai, M. A. Phosphatases in soils. *Soil Biol. Biochem.* **9**, 167–172. https://doi.org/10.1016/0038-0717(77)90070-0 (1977).

27. Tabatabai, M. A. & Bremner, J. M. Assay of urease activity in soils. *Soil Sci. Soc. Am. J.* **41**, 350–352. https://doi.org/10.1016/0038-0717(72)90064-8 (1972).

28. Bocock, K. L. & Gilbert, O. The disappearance of leaf litter under different woodland conditions. *Plant Soil* **9**, 179–185. https://doi.org/10.1007/BF01398924 (1957).

29. Olson, J. S. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology* **44**, 322–331. https://doi.org/10.2307/1932179 (1963).

30. Rangaswamy, R. *A Text Book of Agricultural Statistics*. 537 (New Age International Publishers, New Delhi, 2010).

31. R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org (2022).

32. Mendiburu, F. D. & Yaseen, M. *agricolae: Statistical Procedures for Agricultural Research*. R package version 1.4.0 (2020).

33. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*. (Springer-Verlag, New York, 2016). https://ggplot2.tidyverse.org.

34. Cheng, Y., Zhang, J. B., Muller, C. & Wang, S. Q. 15N tracing study to understand the N supply associated with organic amendments in a vineyard soil. *Biol. Fertil. Soils* **51**, 983–993. https://doi.org/10.1007/s00374-015-1044-x (2015).

35. Lu, C. Y. et al. Effects of N fertilization and maize straw on the transformation and fate of labelled (15NH4)2SO4 among three continuous crop cultivations. *Agric. Water Manag.* **208**, 275–283. https://doi.org/10.1016/j.agwat.2018.06.031 (2018).

36. Pei, G. T. et al. Nitrogen, lignin, C/N as important regulators of gross nitrogen release and immobilization during litter decomposition in a temperate forest ecosystem. *For. Ecol. Manag.* **440**, 61–69. https://doi.org/10.1016/j.foreco.2019.03.001 (2019).

37. Vandersloot, M., Kleijn, D., De Deyn, G. B. & Limpens, J. Carbon to nitrogen ratio and quantity of organic amendment interactively affect crop growth and soil mineral N retention. *Crop Environ.* **1**, 161–167. https://doi.org/10.1016/j.crope.2022.08.001 (2022).

38. Hu, Y. & Zhu, B. Effects of organic amendments with different C/N ratios and application rates on N mineralization–immobilization in calcareous cropland soil. *Agronomy* **15**, 2795. https://doi.org/10.3390/agronomy15122795 (2025).

39. Mohanty, M. et al. Modelling N mineralization from green manure and farmyard manure from a laboratory incubation study. *Ecol. Model.* **222**, 719–726. https://doi.org/10.1016/j.ecolmodel.2010.10.027 (2011).

40. Choudhary, M. et al. Changes in soil biology under conservation agriculture-based sustainable intensification of cereal systems in Indo-Gangetic Plains. *Geoderma* **313**, 193–204. https://doi.org/10.1016/j.geoderma.2017.10.041 (2018).

41. Lehmann, J. & Kleber, M. The contentious nature of soil organic matter. *Nature* **528**, 60–68. https://doi.org/10.1038/nature16069 (2015).

42. Zhang, J., Ai, Z., Liang, C., Wang, G. & Xue, S. Response of soil microbial communities and nitrogen thresholds of *Bothriochloa ischaemum* to short-term nitrogen addition on the Loess Plateau. *Geoderma* **308**, 112–119. https://doi.org/10.1016/j.geoderma.2017.08.034 (2017).

43. Kharia, S. et al. Tillage and rice straw management affect soil enzyme activities and chemical properties after three years of conservation agriculture based rice-wheat system in north-western India. *Int. J. Plant Soil Sci.* **15**, 1–13. https://doi.org/10.9734/IJPSS/2017/33494 (2017).

44. Kumar, A. et al. Effect of paddy straw burning on soil microbial dynamics in sandy loam soil of Indo-Gangetic plains. *Environ. Technol. Innov.* 16, 100469. https://doi.org/10.1016/j.eti.2019.100469 (2019).

45. Shaaban, M. et al. Enzyme activities and organic matter mineralization in response to application of gypsum, manure and rice straw in saline and sodic soils. *Environ. Res.* 224, 115393 (2023).

718 46. Chaudhri, K., Kaswala, A. R., Usadadiya, V. P., Chaudhari, P. & Patel, K. S. Effect of
719 agricultural practices on enzyme activities. *Int. J. Adv. Biochem. Res.* 8, 1415–1421 (2024).

720 47. Gupta, N., Sharma, S., Chauhan, N. & Kumawat, K.C. (2026). Optimized rice residue
721 management, tillage intensity and nitrogen application enhance soil biological quality and
722 subsequent wheat productivity in rice-wheat system of north-western India. *Frontiers in Soil*
723 *Science*, 6, 1872133. https://doi.org/10.3389/fsoil.2026.1872133

724 48. Park, Y., Solhtalab, M., Thongsomboon, W. & Aristilde, L. Strategies of organic
725 phosphorus recycling by soil bacteria: acquisition, metabolism, and regulation. *Environ.*
726 *Microbiol. Rep.* 14, 3–24. https://doi.org/10.1111/1758-2229.13040 (2022).

727 49. Wijeratne, S., Bakshi, A. & Talbert, J. Comparative analysis of NanoLuc luciferase and
728 alkaline phosphatase luminescence reporter systems for phage-based detection of bacteria.
729 *Bioengineering* 9, 479. https://doi.org/10.3390/bioengineering9090479 (2022).

730 50. Akhtar, K. et al. Changes in soil enzymes, soil properties, and maize crop productivity
731 under wheat straw mulching in Guanzhong, China. *Soil Tillage Res.* 182, 94–102.
732 https://doi.org/10.1016/j.still.2018.05.007 (2018).

733 51. Bamagoos, A. A. et al. Phosphate-solubilizing bacteria as a panacea to alleviate stress
734 effects of high soil CaCO3 content in *Phaseolus vulgaris* with special reference to P-releasing
735 enzymes. *Sustainability* 13, 7063. https://doi.org/10.3390/su13137063 (2021).

736 52. Duan, S., Declerck, S., Feng, G. & Zhang, L. Hyphosphere interactions between
737 *Rhizophagus irregularis* and *Rahnella aquatilis* promote carbon–phosphorus exchange at the
738 peri-arbuscular space in *Medicago truncatula*. *Environ. Microbiol.* 25, 867–879.
739 https://doi.org/10.1111/1462-2920.16333 (2023).

740 53. Latifmanesh, H. et al. How incorporation depth of corn straw affects straw decomposition
741 rate and C & N release in the wheat-corn cropping system. *Agric. Ecosyst. Environ.* **300**,
742 107000. https://doi.org/10.1016/j.agee.2020.107000 (2020).

743 54. Kajiura, M., Wagai, R. & Hayashi, K. Optimal thermolysis conditions for soil carbon
744 storage on plant residue burning: Modeling the trade-off between thermal decomposition and
745 subsequent biodegradation. *J. Environ. Qual.* **44**, 228–235.
746 https://doi.org/10.2134/jeq2014.06.0279 (2015).

747 55. Beyaert, R. & Voroney, R. P. Estimation of decay constants for crop residues measured
748 over 15 years in conventional and reduced tillage systems in a coarse-textured soil in southern
749 Ontario. *Can. J. Soil Sci.* **91**, 985–995. https://doi.org/10.4141/cjss2010-055 (2011).

750 56. Min, X. Y. et al. Effects of agronomic measures on decomposition characteristics of wheat
751 and maize straw in China. *Sustain. For.* **14**, 12199. https://doi.org/10.3390/su141912199
752 (2022).

753 57. Moretto, A. S., Distel, R. A. & Didone, N. G. Decomposition and nutrient dynamics of leaf
754 litter and roots from palatable and unpalatable grasses in a semi-arid grassland. *Appl. Soil Ecol.*
755 **18**, 31–37. https://doi.org/10.1016/S0929-1393(01)00151-2 (2001).

58. Rogers, C. W. et al. Barley residue biomass, nutrient content, and relationships with grain yield. *Crop Sci.* **64**, 2345–2367. https://doi.org/10.1002/csc2.21263 (2025).

59. Gupta, R. & Ladha, J. Placement effects on rice residue decomposition and nutrient dynamics on two soil types during wheat cropping in rice–wheat system in northwestern India. *Nutr. Cycl. Agroecosyst.* **88**, 471–480. https://doi.org/10.1007/s10705-010-9370-8 (2010).

60. Liu, K., Sollenberger, L. E., Silveira, M. L., Vendramini, J. M. B. & Newman, Y. C. Grazing intensity and nitrogen fertilization affect litter responses in 'Tifton 85' Bermudagrass pastures: II. Decomposition and nitrogen mineralization. *Agron. J.* **103**, 163–168. https://doi.org/10.2134/agronj2010.0320 (2011).

61. Ngwira, A., Johnsen, F. H., Aune, J. B., Mekuria, M. & Thierfelder, C. Adoption and extent of conservation agriculture practices among smallholder farmers in Malawi. *J. Soil Water Conserv.* **69**, 107–119. https://doi.org/10.2489/jswc.69.2.107 (2014).

62. Zhu, Z. K. et al. Microbial stoichiometric flexibility regulates rice straw mineralization and its priming effect in paddy soil. *Soil Biol. Biochem.* **121**, 67–76. https://doi.org/10.1016/j.soilbio.2018.03.003 (2018).

63. Saad, A. A. et al. Energy auditing of a maize–wheat–greengram cropping system under conventional and conservation agriculture in irrigated north-western Indo-Gangetic Plains. *Energy* **116**, 293–305. https://doi.org/10.1016/j.energy.2016.09.115 (2016).

64. Chaudhary, V. P. et al. Energy conservation and greenhouse gas mitigation under different production systems in rice cultivation. *Energy* **130**, 307–317. https://doi.org/10.1016/j.energy.2017.04.131 (2017).

65. Parihar, C. M. et al. Energy auditing of long-term conservation agriculture based irrigated intensive maize systems in semi-arid tropics of India. *Energy* **142**, 289–302. https://doi.org/10.1016/j.energy.2017.10.015 (2018).

66. Bhattacharyya, R. et al. Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice–wheat cropping system in the western Indo-Gangetic Plains. *Eur. J. Agron.* **70**, 11–21. https://doi.org/10.1016/j.eja.2015.06.006 (2015).

67. Parihar, C. M. et al. Long term effect of conservation agriculture in maize rotations on total organic carbon, physical and biological properties of a sandy loam soil in north-western Indo-Gangetic Plains. *Soil Tillage Res.* **161**, 116–128. https://doi.org/10.1016/j.still.2016.04.001 (2016).

68. Das, T. K. et al. Conservation Agriculture in rice-mustard cropping system for five years: Impacts on crop productivity, profitability, water-use efficiency, and soil properties. *Field Crops Res.* **250**, 107781. https://doi.org/10.1016/j.fcr.2020.107781 (2020).

69. Das, T. K. et al. Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize-wheat cropping system in the North-western Indo-Gangetic Plains. *Field Crops Res.* **215**, 222–231. https://doi.org/10.1016/j.fcr.2017.10.021 (2018).

70. Jat, S. L. et al. Energy auditing and carbon footprint under long-term conservation agriculture-based intensive maize systems with diverse inorganic nitrogen management options. *Sci. Total Environ.* **664**, 659–668. https://doi.org/10.1016/j.scitotenv.2019.01.425 (2019).

71. Singh, G. et al. Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo-Gangetic Plains. *Soil Tillage Res.* **184**, 291–300. https://doi.org/10.1016/j.still.2018.08.006 (2018).

72. Pathak, H., Bhatia, A., Jain, N. & Aggarwal, P. K. Greenhouse gas emission and mitigation in Indian agriculture—a review. *ING Bulletins on Regional Assessment of Reactive Nitrogen* **19**, 1–34 (2010).

73. Jain, N., Bhatia, A. & Pathak, H. Emission of air pollutants from crop residue burning in India. *Aerosol Air Qual. Res.* **14**, 422–430. https://doi.org/10.4209/aaqr.2013.01.0031 (2014).

74. Li, C. & Li, S. Energy budget and carbon footprint in a wheat and maize system under ridge furrow strategy in dry semi-humid areas. *Sci. Rep.* **11**, 9367. https://doi.org/10.1038/s41598-021-88717-3 (2021).

75. Jin, Z., Mu, Y., Li, Y. & Nie, L. Dry direct-seeded rice has higher energy and carbon production efficiencies without reducing economic benefits. *J. Sci. Food Agric.* **103**, 6044–6054. https://doi.org/10.1002/jsfa.12675 (2023).

76. Nakhjiri, E. S. et al. The effect of irrigation management and nitrogen fertilizer on grain yield and water-use efficiency of rice cultivars in northern Iran. *Gesunde Pflanzen* **73**, 359–366. https://doi.org/10.1007/s10343-021-00562-6 (2021).

77. Zhang, J. et al. Long-term straw incorporation increases rice yield stability under high fertilization level conditions in the rice–wheat system. *Crop J.* **9**, 1191–1197. https://doi.org/10.1016/j.cj.2020.11.007 (2021).

78. Lal, B. et al. Input–output energy analysis of rainfed rice-based cropping systems in Eastern India. *Agron. J.* **107**, 1750–1756. https://doi.org/10.2134/agronj14.0313 (2015)

79. Cui, S., Zhu, X. & Cao, G. Effects of years of rice straw return on soil nitrogen components from rice–wheat cropped fields. *Agronomy* **12**, 1247. https://doi.org/10.3390/agronomy12061247 (2022).

80. Wang, H. et al. Oilseed rape straw returning changes soil reducibility and affects the root and yield of rice in the rape-rice rotation field at Sichuan Basin area of China. *Agron. J.* **112**, 4681–4692. https://doi.org/10.1002/agj2.20408 (2020).

81. Qin, L. et al. Impact of incorporating wheat straw together with basal nitrogen ratio on panicle formation and grain yield in rice. *Sci. Rep.* **15**, 4093. https://doi.org/10.1038/s41598-025-88424-3 (2025).

82. Yang, S. et al. Improved crop yield and reduced nitrate nitrogen leaching with straw return in a rice-wheat rotation of Ningxia irrigation district. *Sci. Rep.* **8**, 9458. https://doi.org/10.1038/s41598-018-27776-5 (2018).

832 83. Wold, S., Sjöström, M. & Eriksson, L. PLS-regression: a basic tool of chemometrics. Chemometrics
833 and Intelligent Laboratory Systems 58, 109–130 (2001). https://doi.org/10.1016/S0169-
834 7439(01)00155-1.

835 84. Chong, I.-G. & Jun, C.-H. Performance of some variable selection methods when multicollinearity
836 is present. Chemometrics and Intelligent Laboratory Systems 78, 103–112 (2005).
837 https://doi.org/10.1016/j.chemolab.2004.12.011.

838 85. Mehmood, T., Liland, K. H., Snipen, L. & Sæbø, S. A review of variable selection methods in partial
839 least squares regression. Chemometrics and Intelligent Laboratory Systems 118, 62–69 (2012).
840 https://doi.org/10.1016/j.chemolab.2012.07.010.

841 86. Muñoz-Huerta, R. F. et al. A review of methods for sensing the nitrogen status in plants: advantages,
842 disadvantages and recent advances. Sensors 13, 10823–10843 (2013).
843 https://doi.org/10.3390/s130810823.

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Table 2 Available soil nitrogen (kg ha^{-1}) content at different intervals of maize as influenced by different paddy straw and nitrogen management options during both years and the pooled mean.

	15 DAS			30 DAS			45 DAS			60 DAS			Post-Harvest		
Trts	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean
Straw management options (F1)															
SB	225.7^{a}	222.1^{a}	223.9^{a}	203.7^{a}	199.3^{a}	201.5^{a}	193.5^{a}	187.1^{a}	190.3^{a}	182.8^{a}	178.0^{a}	180.4^{ab}	182.1^{a}	174.6^{a}	178.3^{ab}
SI	212.9^{a}	208.3^{a}	210.6^{b}	190.1^{a}	185.5^{a}	187.8^{b}	198.7^{a}	192.1^{a}	195.4^{a}	191.5^{a}	189.3^{a}	190.4^{a}	188.3^{a}	184.2^{a}	186.3^{a}
CR	217.8^{a}	214.5^{a}	216.1^{ab}	196.7^{a}	193.4^{a}	195.1^{ab}	187.2^{a}	180.1^{a}	183.7^{a}	179.0^{a}	173.6^{a}	176.3^{c}	176.0^{a}	171.5^{a}	173.8^{b}
Nitrogen management options (F2)															
T_1	223.9^{a}	221.1^{a}	222.5^{ab}	191.8^{a}	187.5^{a}	189.7^{bc}	200.8^{a}	193.5^{a}	197.2^{ab}	166.8^{b}	162.1^{b}	164.4^{d}	170.2^{a}	164.6^{a}	167.4^{c}
T_2	230.4^{a}	226.8^{a}	228.6^{a}	206.1^{a}	201.3^{a}	203.7^{ab}	185.5^{a}	177.8^{a}	181.6^{bc}	173.8^{ab}	169.4^{ab}	171.6^{cd}	176.4^{a}	171.0^{a}	173.7^{bc}
T_3	206.3^{a}	201.4^{a}	203.9^{c}	183.4^{a}	179.5^{a}	181.5^{c}	181.2^{a}	175.0^{a}	178.1^{bc}	179.9^{ab}	175.8^{ab}	177.9^{bcd}	180.6^{a}	174.6^{a}	177.6^{abc}
T_4	214.9^{a}	209.7^{a}	212.3^{bc}	189.9^{a}	187.1^{a}	188.5^{bc}	189.8^{a}	183.7^{a}	186.8^{abc}	185.6^{ab}	181.8^{ab}	183.7^{bc}	183.1^{a}	178.1^{a}	180 .6^{abc}
T_5	217.1^{a}	213.8^{a}	215.4^{abc}	199.0^{a}	194.8^{a}	196.9^{abc}	195.7^{a}	188.9^{a}	192.3^{abc}	194.2^{ab}	190.0^{ab}	192.1^{ab}	188.5^{a}	183.0^{a}	185.7^{ab}
T_6	220.2^{a}	216.8^{a}	218.5^{ab}	210.8^{a}	206.2^{a}	208.5^{a}	205.7^{a}	199.7^{a}	202.7 ^{a}	206.2^{a}	202.6^{a}	204.4^{a}	194.1^{a}	189.4^{a}	191.8^{a}

Trts = Treatments, B= Burning, I= Incorporation, CR= Cutting and removal, T1 = 100 % RDN (33.3 % at basal, 33.3% at 30 DAS and 33.3% at 60 DAS), T2 = 100% RDN (40 % at basal, 30% at 30 DAS, 30% at 60 DAS), T3 = 100% RDN (10% at basal, 30% at 15 DAS, 30% at 30 DAS and 30% at 60 DAS), T4 = 100% RDN (15% at basal, 30% at 15 DAS, 30% at 30 DAS and 25% at 60 DAS), T5 = 115% RDN (18 % at basal, 36% at 15 at DAS, 36% at 30 DAS and 25% at 60 DAS), T6 = 130% RDN (20% at basal, 42% at 15 DAS, 42% at 30 DAS and 26 % at 60 DAS). Means labelled by different letters are significant while same letters are non-significant at $p < 0.05$ using the Duncan's Multiple Range test.

Table 3 Ammonical nitrogen (kg ha^{-1}) content in soil at different intervals of maize as influenced by different paddy straw and nitrogen management options during both years and the pooled mean.

	15 DAS			30 DAS			45 DAS			60 DAS			Post-Harvest		
Trts	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean
Straw management options (F1)															
SB	102.97^{a}	101.34^{a}	102.16^{a}	92.95^{a}	91.02^{a}	91.98^{a}	88.30^{a}	85.40^{a}	86.85^{a}	83.12^{a}	80.63^{a}	81.88^{b}	79.06^{b}	79.47^{ab}	79.26^{b}
SI	90.48^{b}	88.56^{b}	89.52^{c}	76.70^{b}	79.02^{b}	77.86^{b}	87.41^{a}	81.54^{a}	84.47^{a}	91.28^{a}	84.84^{a}	88.06^{a}	90.04^{a}	88.44^{a}	89.24^{a}
CR	97.80^{ab}	96.33^{ab}	97.07^{b}	88.40^{ab}	87.15^{ab}	87.78^{b}	84.12^{a}	81.09^{a}	82.60^{a}	80.57^{a}	78.28^{a}	79.43^{b}	76.95^{b}	77.33^{b}	77.13^{b}
Nitrogen management options (F2)															
T_1	97.06^{a}	95.97^{a}	96.51^{a}	86.84^{ab}	85.01^{ab}	85.22^{b}	86.34^{ab}	82.53^{a}	85.15^{bc}	73.94^{c}	71.35^{b}	72.65^{d}	73.48^{b}	74.83^{a}	74.16^{c}
T_2	101.88^{a}	100.34^{a}	101.11^{a}	95.73^{a}	93.79^{a}	94.06^{a}	80.59^{b}	77.09^{a}	79.55^{bc}	77.87^{bc}	76.25^{b}	77.06^{cd}	77.03^{ab}	78.94^{a}	77.98^{bc}
T_3	89.54^{a}	87.26^{a}	88.40^{b}	77.99^{b}	76.37^{b}	76.48^{c}	80.45^{b}	74.59^{a}	78.24^{c}	82.17^{bc}	77.83^{ab}	80.00^{cd}	80.33^{ab}	79.17^{a}	79.75^{bc}
T_4	95.56^{a}	93.43^{a}	94.50^{ab}	81.53^{ab}	80.50^{ab}	80.32^{bc}	86.2^{ab}	80.30^{a}	83.97^{bc}	86.56^{abc}	82.27^{ab}	84.41^{bc}	83.33^{ab}	82.56^{a}	82.94^{ab}
T_5	97.68^{a}	96.22^{a}	96.95^{a}	87.35^{ab}	85.53^{ab}	85.74^{b}	88.99^{ab}	82.67^{a}	86.55^{b}	90.73^{ab}	86.22^{ab}	88.48^{ab}	86.60^{ab}	85.47^{a}	86.03^{ab}
T_6	100.79^{a}	99.26^{a}	100.03^{a}	95.06^{a}	93.18^{a}	93.42^{a}	97.10^{a}	90.26^{a}	94.40^{a}	98.67^{a}	93.60^{a}	96.13^{a}	91.34^{a}	89.50^{a}	90.42^{a}

Trts = Treatments, B= Burning, I= Incorporation, CR= Cutting and removal, T1 = 100 % RDN (33.3 % at basal, 33.3% at 30 DAS and 33.3% at 60 DAS), T2 = 100% RDN (40 % at basal, 30% at 30 DAS, 30% at 60 DAS), T3 = 100% RDN (10% at basal, 30% at 15 DAS, 30% at 30 DAS and 30% at 60 DAS), T4 = 100% RDN (15% at basal, 30% at 15 DAS, 30% at 30 DAS and 25% at 60 DAS), T5 = 115% RDN (18 % at basal, 36% at 15 at DAS, 36% at 30 DAS and 25% at 60 DAS), T6 = 130% RDN (20% at basal, 42% at 15 DAS, 42% at 30 DAS and 26 % at 60 DAS). Means labelled by different letters are significant while same letters are non-significant at $p < 0.05$ using the Duncan's Multiple Range test.

Table 4 Nitrate nitrogen (kg ha^{-1}) content in soil at different intervals of maize as influenced by different paddy straw and nitrogen management options during both years and the pooled mean.

	15 DAS			30 DAS			45 DAS			60 DAS			Post-Harvest		
Trts.	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean
Straw management options (F1)															
SB	90.06^{a}	88.75^{a}	89.41^{a}	83.55^{a}	81.69^{a}	82.62^{a}	73.01^{a}	74.78^{a}	73.89^{a}	71.92^{b}	69.39^{a}	70.65^{b}	68.12^{b}	70.41^{b}	69.08^{b}
SI	81.18^{b}	79.66^{b}	80.42^{b}	71.30^{b}	70.35^{b}	70.83^{b}	75.76^{a}	73.21^{a}	74.49^{a}	83.33^{a}	74.21^{a}	78.77^{a}	80.45^{a}	80.22^{a}	80.33^{a}
CR	84.26^{ab}	82.99^{ab}	83.63^{b}	77.00^{ab}	75.36^{ab}	76.18^{b}	72.14^{a}	69.76^{a}	70.95^{a}	67.64^{b}	67.35^{a}	67.49^{b}	66.18^{b}	71.99^{ab}	69.26^{b}
Nitrogen management options (F2)															
T_1	90.29^{ab}	89.16^{ab}	89.73^{ab}	76.70^{ab}	74.99^{ab}	75.85^{b}	71.76^{b}	70.74^{ab}	71.25^{bc}	63.19^{c}	59.17^{c}	61.18^{e}	62.74^{b}	65.68^{b}	64.21^{d}
T_2	94.31^{a}	93.00^{a}	93.65^{a}	85.59^{a}	84.37^{a}	84.98^{a}	68.29^{b}	66.78^{b}	67.53^{c}	67.99^{bc}	63.82^{bc}	65.90^{de}	66.94^{ab}	69.61^{ab}	68.27^{cd}
T_3	75.25^{c}	73.69^{c}	74.47^{e}	67.85^{b}	66.30^{b}	67.08^{c}	68.55^{b}	67.72^{b}	68.14^{c}	72.12^{bc}	68.22^{abc}	70.17^{cd}	70.40^{ab}	72.74^{ab}	71.57^{bc}
T_4	80.72^{bc}	78.79^{bc}	79.76^{de}	71.40^{ab}	70.06^{ab}	70.73^{bc}	73.02^{ab}	72.43^{ab}	72.73^{bc}	75.32^{abc}	71.64^{abc}	73.48^{bc}	72.46^{ab}	75.30^{ab}	73.88^{bc}
T_5	83.92^{abc}	82.71^{abc}	83.31^{cd}	77.22^{ab}	75.77^{ab}	76.49^{b}	77.00^{ab}	75.68^{ab}	76.34^{b}	80.60^{ab}	76.42^{ab}	78.51^{ab}	76.77^{ab}	79.25^{a}	78.01^{ab}
T_6	86.50^{ab}	85.47^{abc}	85.98^{bc}	84.93^{a}	83.31^{a}	84.12^{a}	83.21^{a}	82.16^{a}	82.68^{a}	86.56^{a}	82.61^{a}	84.58^{a}	80.19^{a}	82.65^{a}	81.42^{a}

Trts = Treatments, B= Burning, I= Incorporation, CR= Cutting and removal, T1 = 100 % RDN (33.3 % at basal, 33.3% at 30 DAS and 33.3% at 60 DAS), T2 = 100% RDN (40 % at basal, 30% at 30 DAS, 30% at 60 DAS), T3 = 100% RDN (10% at basal, 30% at 15 DAS, 30% at 30 DAS and 30% at 60 DAS), T4 = 100% RDN (15% at basal, 30% at 15 DAS, 30% at 30 DAS and 25% at 60 DAS), T5 = 115% RDN (18 % at basal, 36% at 15 DAS, 36% at 30 DAS and 25% at 60 DAS), T6 = 130% RDN (20% at basal, 42% at 15 DAS, 42% at 30 DAS and 26 % at 60 DAS). Means labelled by different letters are significant while same letters are non-significant at $p < 0.05$ using the Duncan's Multiple Range test.

Table 5 Effect of paddy straw and nitrogen management on bacterial population (× 10^5 cfu g^{-1} soil) in maize at different intervals during both years and the pooled mean.

	30 DAS			60 DAS			Post-Harvest		
Trts	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean
Straw management options (F1)									
SB	10.78^{c}	12.52^{c}	11.65^{c}	17.59^{b}	20.64^{b}	19.12^{c}	11.99^{c}	14.52^{c}	13.25^{c}
SI	14.55^{a}	16.73^{a}	15.64^{a}	20.90^{a}	23.48^{a}	22.19^{a}	15.51^{a}	17.78^{a}	16.65^{a}
CR	12.28^{b}	14.45^{b}	13.36^{b}	19.60^{a}	21.80^{b}	20.70^{b}	13.74^{b}	16.42^{b}	15.08^{b}
Nitrogen management options (F2)									
T_1	11.21^{b}	12.71^{b}	11.96^{c}	17.70^{b}	20.35^{c}	19.02^{d}	12.47^{b}	15.00^{b}	13.73^{d}
T_2	11.76^{ab}	13.70^{ab}	12.73^{bc}	18.52^{ab}	21.15^{bc}	19.84^{cd}	12.96^{ab}	15.51^{ab}	14.23^{cd}
T_3	12.40^{ab}	14.45^{ab}	13.42^{ab}	19.11^{ab}	21.36^{abc}	20.24^{bcd}	13.54^{ab}	15.70^{ab}	14.62^{cd}
T_4	12.85^{ab}	14.85^{ab}	13.85^{ab}	19.80^{ab}	22.07^{abc}	20.93^{abc}	13.89^{ab}	16.22^{ab}	15.06^{bc}
T_5	13.28^{ab}	15.55^{ab}	14.41^{a}	20.16^{ab}	23.01^{ab}	21.59^{ab}	14.57^{ab}	17.34^{a}	15.95^{ab}
T_6	13.71^{a}	16.15^{a}	14.93^{a}	20.88^{a}	23.90^{a}	22.39^{a}	15.06^{a}	17.70^{a}	16.38^{a}

Trts = Treatments, B= Burning, I= Incorporation, CR= Cutting and removal, T1 = 100 % RDN (33.3 % at basal, 33.3% at 30 DAS and 33.3% at 60 DAS), T2 = 100% RDN (40 % at basal, 30% at 30 DAS, 30% at 60 DAS), T3 = 100% RDN (10% at basal, 30% at 15 DAS, 30% at 30 DAS and 30% at 60 DAS), T4 = 100% RDN (15% at basal, 30% at 15 DAS, 30% at 30 DAS and 25% at 60 DAS), T5 = 115% RDN (18 % at basal, 36% at 15 at DAS, 36% at 30 DAS and 25% at 60 DAS), T6 = 130% RDN (20% at basal, 42% at 15 DAS, 42% at 30 DAS and 26 % at 60 DAS). Means labelled by different letters are significant while same letters are non-significant at $p < 0.05$ using the Duncan's Multiple Range test.

Table 6 Effect of paddy straw and nitrogen management on fungal population (× 10^3 cfu g^{-1} soil) in soil under maize at different intervals during both years and the pooled mean.

	30 DAS			60 DAS			Post-Harvest		
Trts	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean
Straw management options (F1)									
SB	23.90^{c}	25.15^{c}	24.52^{c}	34.56^{b}	35.92^{b}	35.24^{c}	27.85^{b}	29.05^{b}	28.45^{c}
SI	28.88^{a}	30.26^{a}	29.57^{a}	38.80^{a}	40.13^{a}	39.46^{a}	33.42^{a}	34.69^{a}	34.06^{a}
CR	26.40^{b}	27.85^{b}	27.13^{b}	36.79^{ab}	38.07^{ab}	37.43^{b}	31.61^{a}	32.95^{a}	32.28^{b}
Nitrogen management options (F2)									
T_1	24.77^{a}	26.05^{a}	25.41^{c}	34.26^{b}	35.64^{a}	34.95^{c}	28.46^{b}	29.40^{b}	28.93^{d}
T_2	25.49^{a}	26.75^{a}	26.12^{bc}	35.16^{ab}	36.42^{a}	35.79^{bc}	29.74^{ab}	31.00^{ab}	30.37^{cd}
T_3	26.08^{a}	27.56^{a}	26.82^{abc}	36.74^{ab}	37.89^{a}	37.32^{abc}	30.62^{ab}	31.77^{ab}	31.19^{bc}
T_4	26.67^{a}	28.00^{a}	27.34^{abc}	37.22^{ab}	38.55^{a}	37.88^{ab}	31.54^{ab}	32.87^{ab}	32.21^{abc}
T_5	27.35^{a}	28.62^{a}	27.99^{ab}	37.98^{ab}	39.25^{a}	38.61^{a}	32.30^{ab}	33.68^{ab}	32.99^{ab}
T_6	28.00^{a}	29.56^{a}	28.78^{a}	38.94^{a}	40.50^{a}	39.72^{a}	33.12^{a}	34.67^{a}	33.89^{a}

Trts = Treatments, B= Burning, I= Incorporation, CR= Cutting and removal, T1 = 100 % RDN (33.3 % at basal, 33.3% at 30 DAS and 33.3% at 60 DAS), T2 = 100% RDN (40 % at basal, 30% at 30 DAS, 30% at 60 DAS), T3 = 100% RDN (10% at basal, 30% at 15 DAS, 30% at 30 DAS and 30% at 60 DAS), T4 = 100% RDN (15% at basal, 30% at 15 DAS, 30% at 30 DAS and 25% at 60 DAS), T5 = 115% RDN (18 % at basal, 36% at 15 at DAS, 36% at 30 DAS and 25% at 60 DAS), T6 = 130% RDN (20% at basal, 42% at 15 DAS, 42% at 30 DAS and 26 % at 60 DAS). Means labelled by different letters are significant while same letters are non-significant at $p < 0.05$ using the Duncan's Multiple Range test.

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Table 7 Effect of paddy straw and nitrogen management options on actinomycetes population (× 10^4 cfu g^{-1} soil) in soil under maize at different intervals during both years and the pooled mean.

	30 DAS			60 DAS			Post-Harvest		
Trts	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean	2021-22	2022-23	Pooled mean
Straw management options (F1)									
SB	36.14^{b}	38.28^{b}	37.21^{c}	43.53^{b}	44.84^{b}	44.19^{c}	38.01^{a}	39.37^{b}	39.02^{b}
SI	40.43^{a}	42.54^{a}	41.48^{a}	48.77^{a}	50.09^{a}	49.43^{a}	40.77^{a}	43.38^{a}	42.41^{a}
CR	38.14^{ab}	40.26^{ab}	39.20^{b}	46.87^{a}	48.21^{a}	47.54^{b}	39.55^{a}	41.06^{ab}	40.67^{ab}
Nitrogen management options (F2)									
T_1	33.98^{d}	36.14^{c}	35.06^{e}	42.60^{c}	44.10^{c}	43.35^{d}	36.21^{c}	37.44^{b}	36.83^{c}
T_2	35.60^{cd}	37.86^{bc}	36.73^{de}	44.50^{bc}	45.66^{bc}	45.08^{cd}	38.30^{bc}	39.52^{ab}	38.91^{c}
T_3	37.61^{bcd}	39.55^{abc}	38.58^{cd}	46.22^{abc}	47.37^{abc}	46.79^{bc}	39.06^{abc}	39.99^{ab}	39.52^{bc}
T_4	39.39^{abc}	41.50^{ab}	40.45^{bc}	47.24^{ab}	48.57^{abc}	47.91^{b}	41.13^{abc}	42.42^{ab}	41.77^{ab}
T_5	40.49^{ab}	42.65^{ab}	41.57^{ab}	48.04^{ab}	49.42^{ab}	48.73^{ab}	42.15^{ab}	43.37^{a}	42.76^{a}
T_6	42.33^{a}	44.44^{a}	43.39^{a}	49.72^{a}	51.16^{a}	50.44^{a}	43.92^{a}	44.87^{a}	44.39^{a}

Trts = Treatments, B= Burning, I= Incorporation, CR= Cutting and removal, T1 = 100 % RDN (33.3 % at basal, 33.3% at 30 DAS and 33.3% at 60 DAS), T2 = 100% RDN (40 % at basal, 30% at 30 DAS, 30% at 60 DAS), T3 = 100% RDN (10% at basal, 30% at 15 DAS, 30% at 30 DAS and 30% at 60 DAS), T4 = 100% RDN (15% at basal, 30% at 15 DAS, 30% at 30 DAS and 25% at 60 DAS), T5 = 115% RDN (18 % at basal, 36% at 15 at DAS, 36% at 30 DAS and 25% at 60 DAS), T6 = 130% RDN (20% at basal, 42% at 15 DAS, 42% at 30 DAS and 26 % at 60 DAS). Means labelled by different letters are significant while same letters are non-significant at $p < 0.05$ using the Duncan's Multiple Range test.

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Table 8 Decomposition rate constants as influenced by different Nitrogen management options				
Treatments	**k**	**Regression equation (R^2)**	**$t_{0.5}$**	**$t_{0.95}$**
T_1	0.0031	y= -0.0031x-0.0775, R2= 0.9166	224	966
T_2	0.0031	y= -0.0031x-0.081, R2= 0.913	224	966
T_3	0.0032	y= -0.0032x-0.0835, R2= 0.8961	217	936
T_4	0.0033	y= -0.0033x-0.0889, R2= 0.8834	210	908
T_5	0.0034	y= -0.0034x-0.0921, R2= 0.8841	204	881
T_6	0.0034	y= -0.0034x-0.0926, R2= 0.8805	204	881
T1 = 100 % RDN (33.3 % at basal, 33.3% at 30 DAS and 33.3% at 60 DAS), T2 = 100% RDN (40 % at basal, 30% at 30 DAS, 30% at 60 DAS), T3 = 100% RDN (10% at basal, 30% at 15 DAS, 30% at 30 DAS and 30% at 60 DAS), T4 = 100% RDN (15% at basal, 30% at 15 DAS, 30% at 30 DAS and 25% at 60 DAS), T5 = 115% RDN (18 % at basal, 36% at 15 at DAS, 36% at 30 DAS and 25% at 60 DAS), T6 = 130% RDN (20% at basal, 42% at 15 DAS, 42% at 30 DAS and 26 % at 60 DAS).				

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Table 9 Energy indices as influenced by different paddy straw and nitrogen management options.

Treatments	Energy use efficiency	Energy productivity	Nutrient energy ratio	Specific energy ratio	Energy profitability	Human energy profitability	Total input	Total Output	Net Energy
Straw management options (F1)									
SB	9.40	0.31	0.48	3.23	8.40	175.29	26129	245143.60	219014.31
SI	9.36	0.31	0.49	3.27	8.36	191.57	27052	252941.19	225888.91
CR	8.46	0.28	0.45	3.56	7.46	155.60	27209	229805.75	202596.66
Nitrogen management options (F2)									
T_1	8.76	0.29	0.46	3.47	7.76	164.38	25679	224788	199108
T_2	9.12	0.30	0.48	3.35	8.12	171.13	25679	233925	208245
T_3	9.32	0.31	0.49	3.26	8.32	170.42	25719	239602	213882
T_4	9.61	0.32	0.51	3.16	8.61	175.67	25719	246967	221248
T_5	9.07	0.30	0.46	3.34	8.07	179.95	27900	252885	224985
T_6	8.57	0.28	0.42	3.53	7.57	183.35	30082	257612	227529

T1 = 100 % RDN (33.3 % at basal, 33.3% at 30 DAS and 33.3% at 60 DAS), T2 = 100% RDN (40 % at basal, 30% at 30 DAS, 30% at 60 DAS), T3 = 100% RDN (10% at basal, 30% at 15 DAS, 30% at 30 DAS and 30% at 60 DAS), T4 = 100% RDN (15% at basal, 30% at 15 DAS, 30% at 30 DAS and 25% at 60 DAS), T5 = 115% RDN (18 % at basal, 36% at 15 at DAS, 36% at 30 DAS and 25% at 60 DAS), T6 = 130% RDN (20% at basal, 42% at 15 DAS, 42% at 30 DAS and 26 % at 60 DAS).

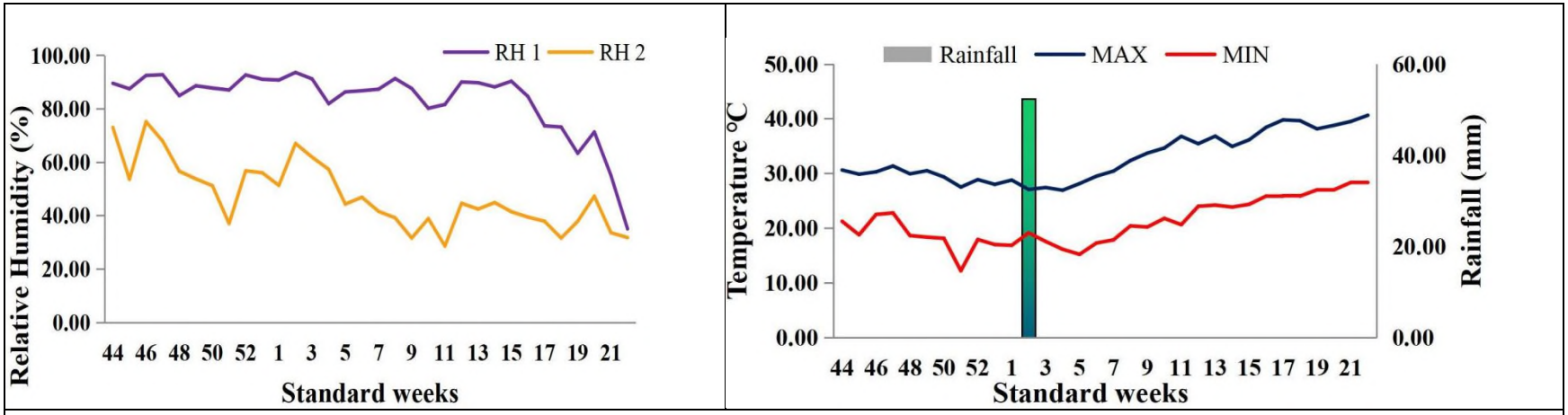


Fig. 1 Weekly mean meteorological data during the crop growth period *Rabi* 2021-22.

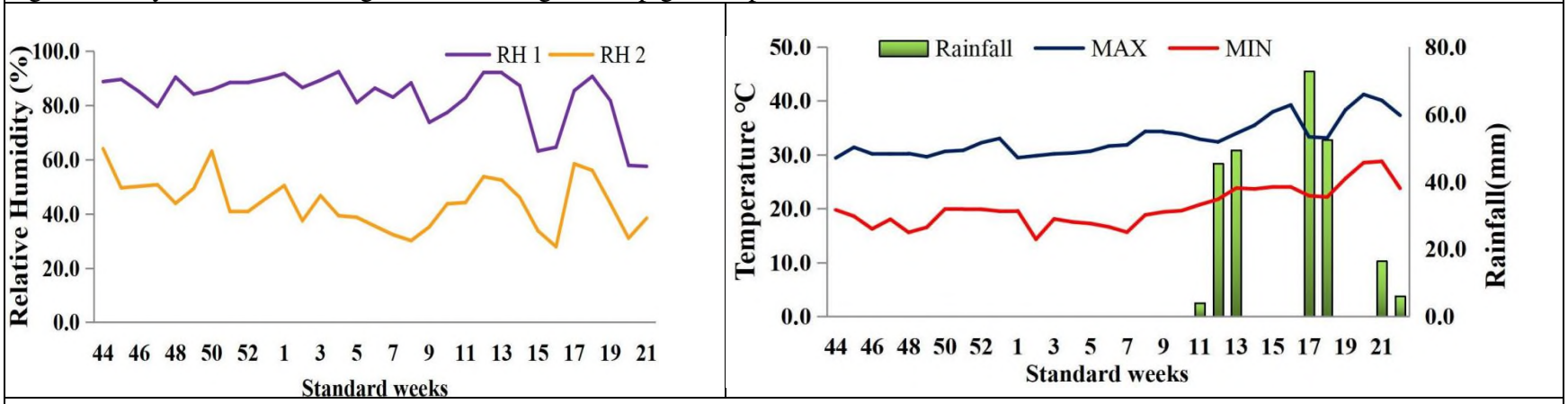


Fig. 2 Weekly mean meteorological data during the crop growth period *Rabi* 2022-23.

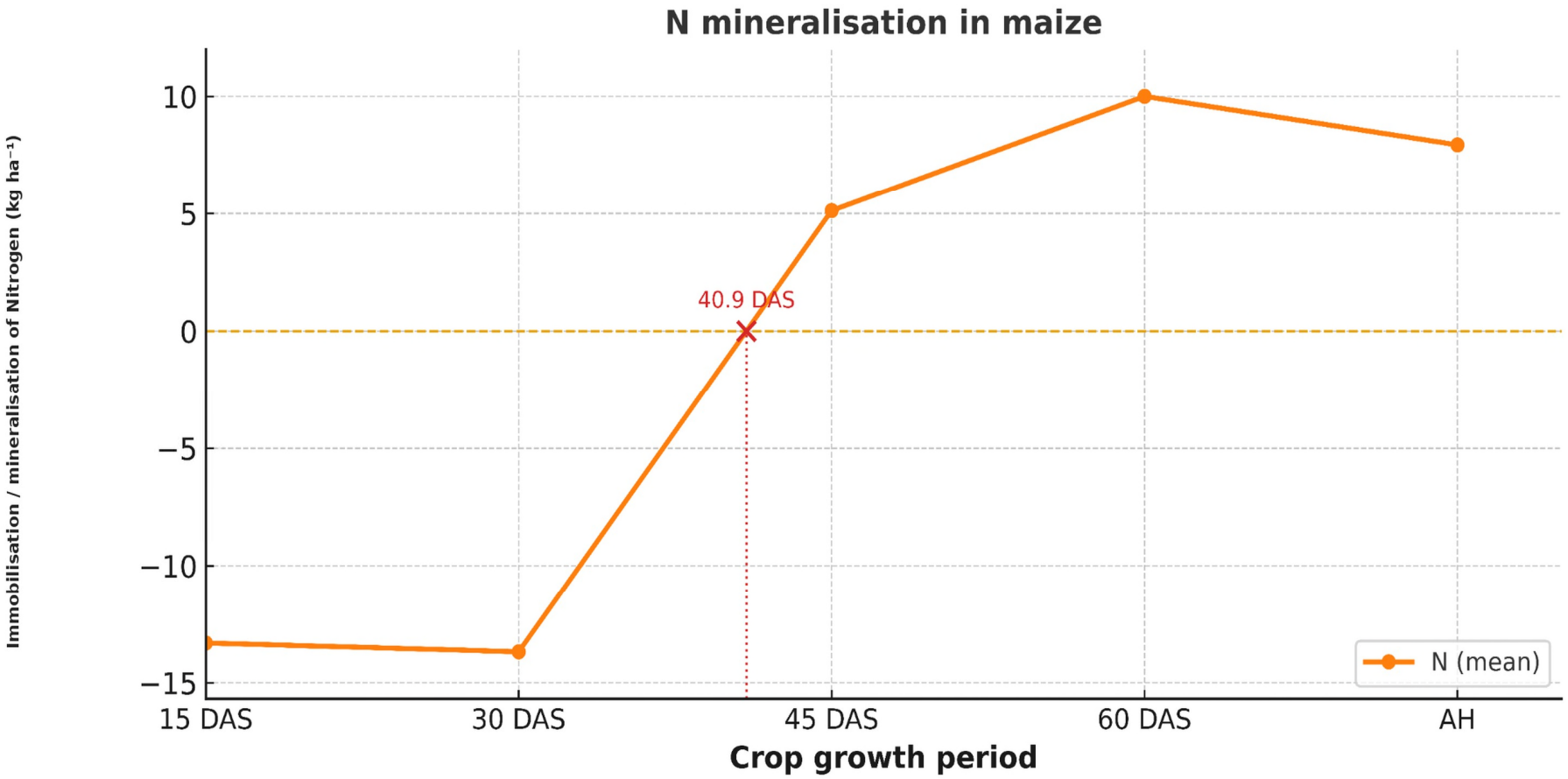


Fig. 3 Immobilisation/mineralisation of nitrogen (kg ha^{-1}) with paddy straw incorporation in Maize.

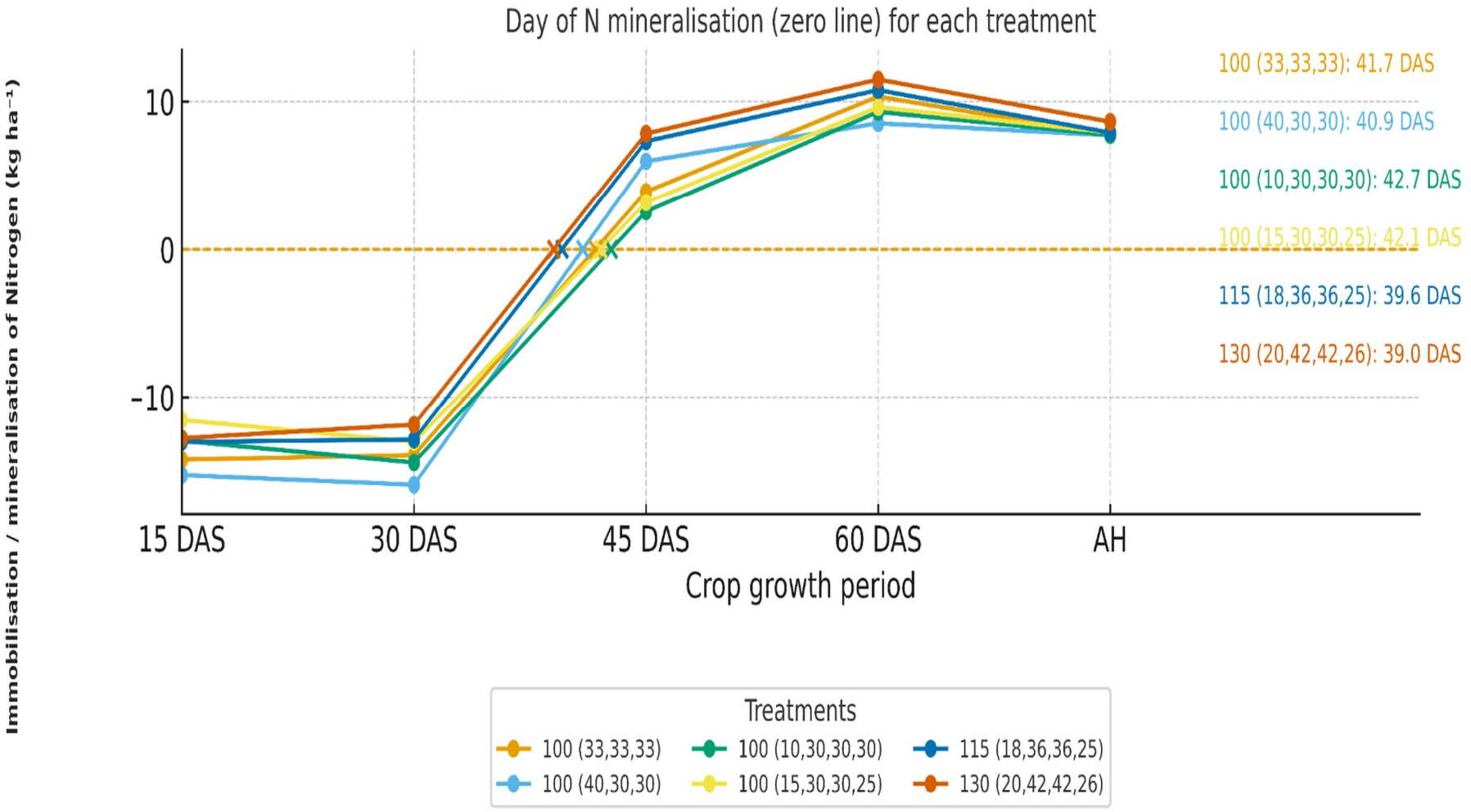


Fig.4 Immobilisation/mineralisation of nitrogen (kg ha^{-1}) among nitrogen management options in maize.

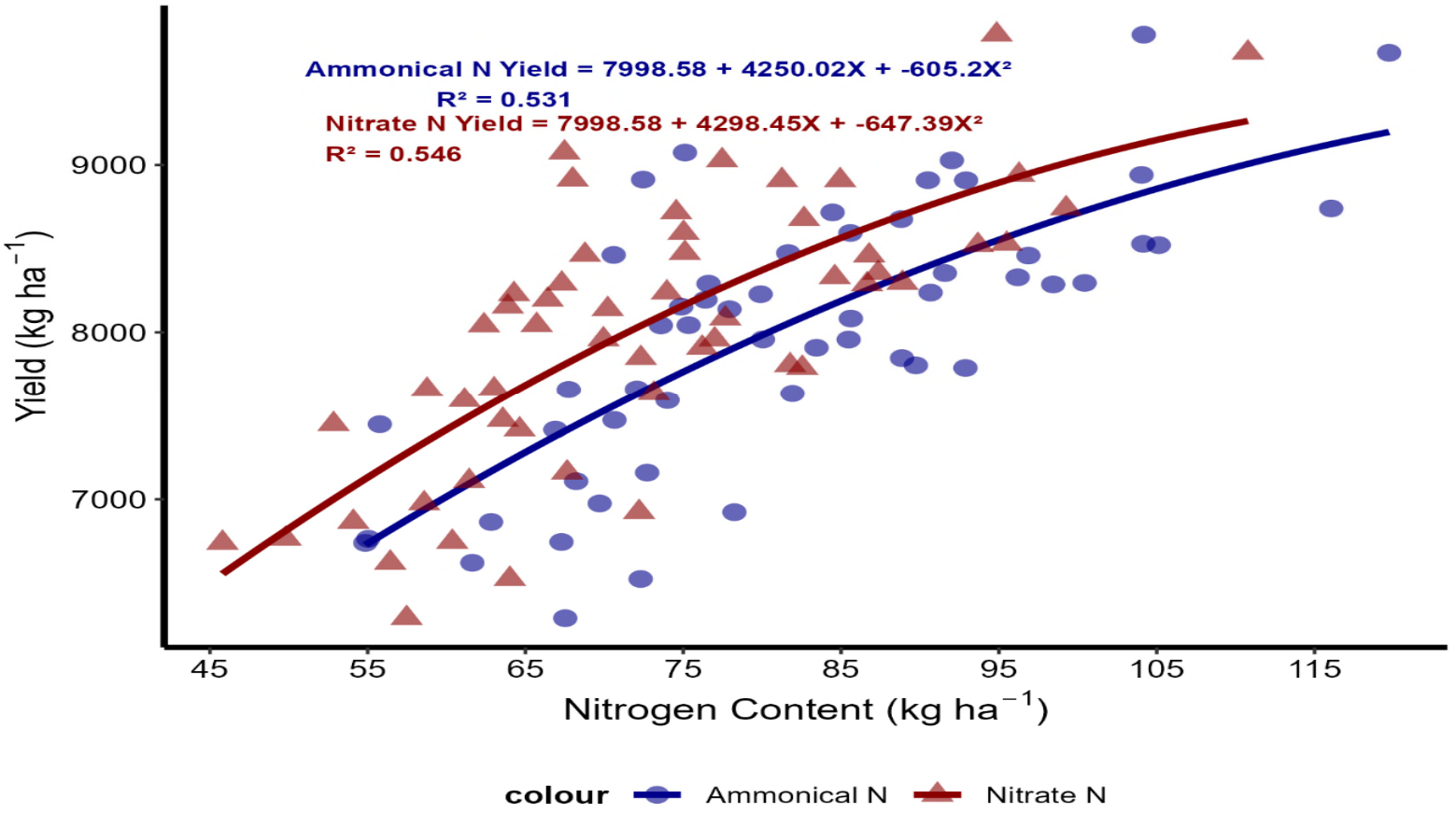


Fig. 5 Effect of Ammonical and Nitrate N content on maize yield using a polynomial regression model

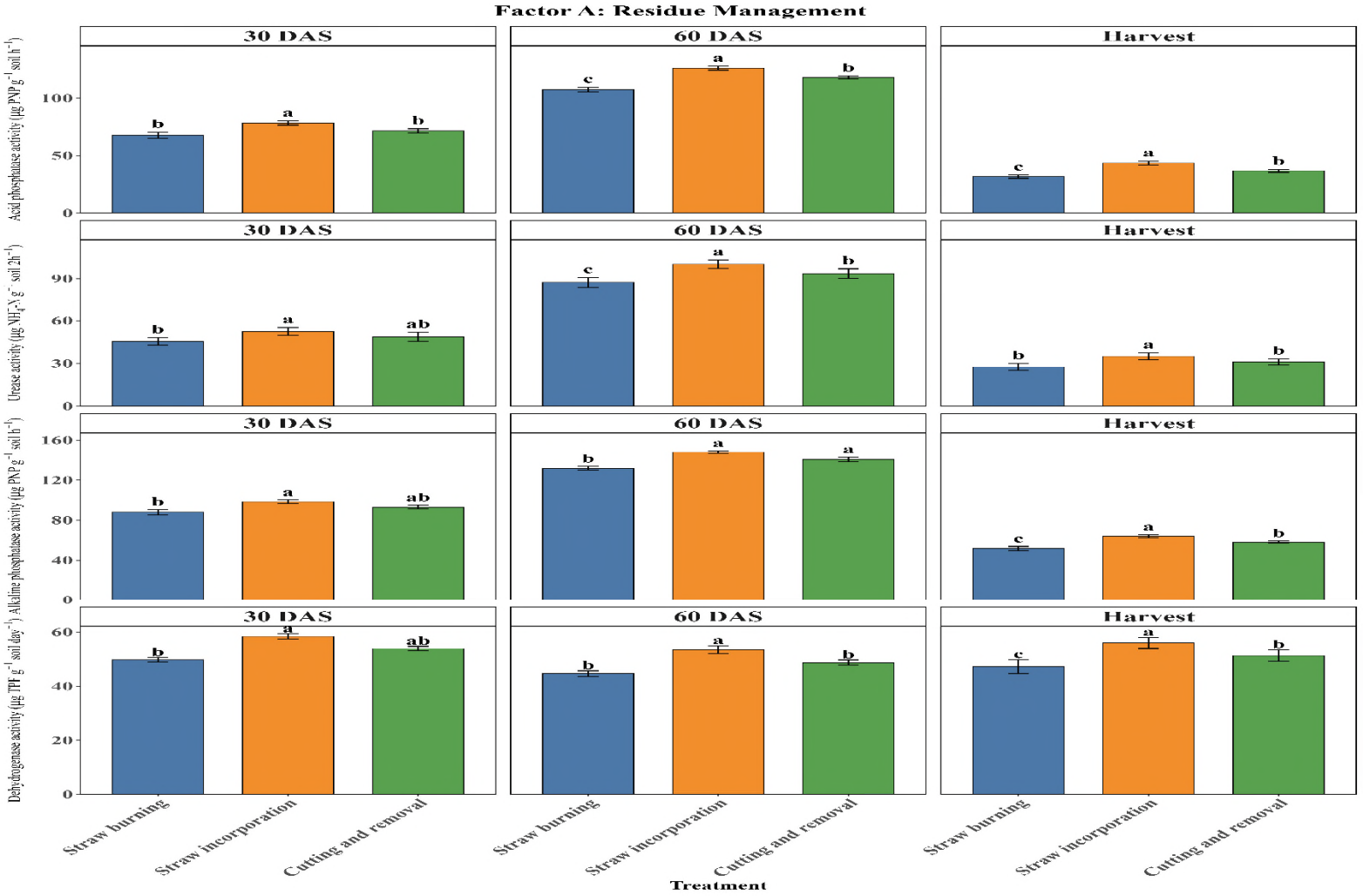


Fig. 6 Effects of Straw Burning, Straw Incorporation, and Cutting and Removal on Soil Enzymatic Activities at different growth Stages in rice-maize cropping system. Bars represent mean values ± standard error (SE). Different lowercase letters above bars indicate significant differences among nitrogen management treatments within the same growth stage and year according to DMRT test at $\boldsymbol{P} \leq 0.05$.

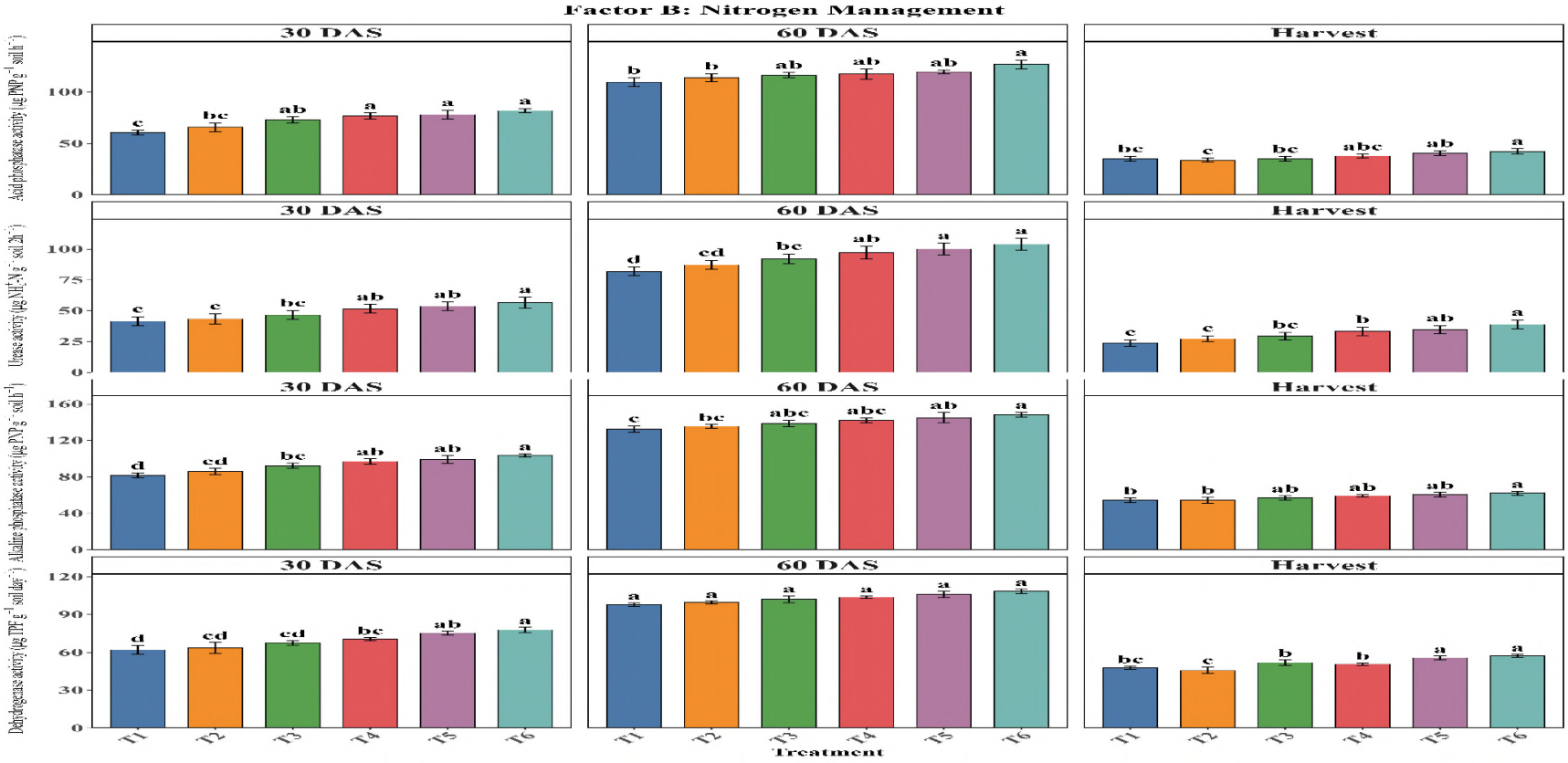


Fig. 7 Effect of Nitrogen management options (T1–T6) on soil Enzymatic activity at different growth stages in rice-maize cropping system Bars represent mean values ± standard error (SE). Different lowercase letters above bars indicate significant differences among nitrogen management treatments within the same growth stage and year according to DMRT test at $P \leq 0.05$.

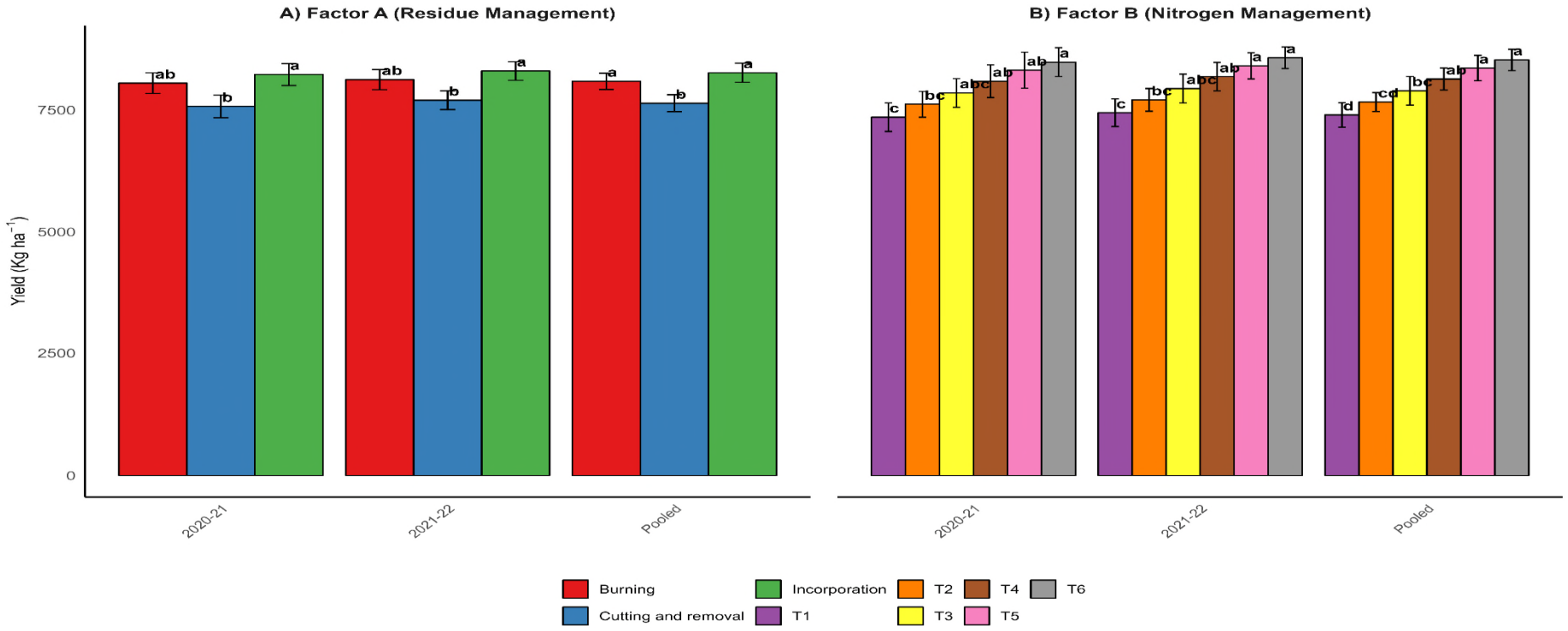


Fig. 8 Effect of Paddy straw management options—Straw burning, Cutting and removal, and Straw incorporation and different nitrogen management options (T1-T6) on the grain yield (kg ha^{-1}) in maize. Bars represent mean values ± standard error (SE). Different lowercase letters above bars indicate significant differences among nitrogen management treatments within the same growth stage and year according to DMRT test at $P \leq 0.05$.

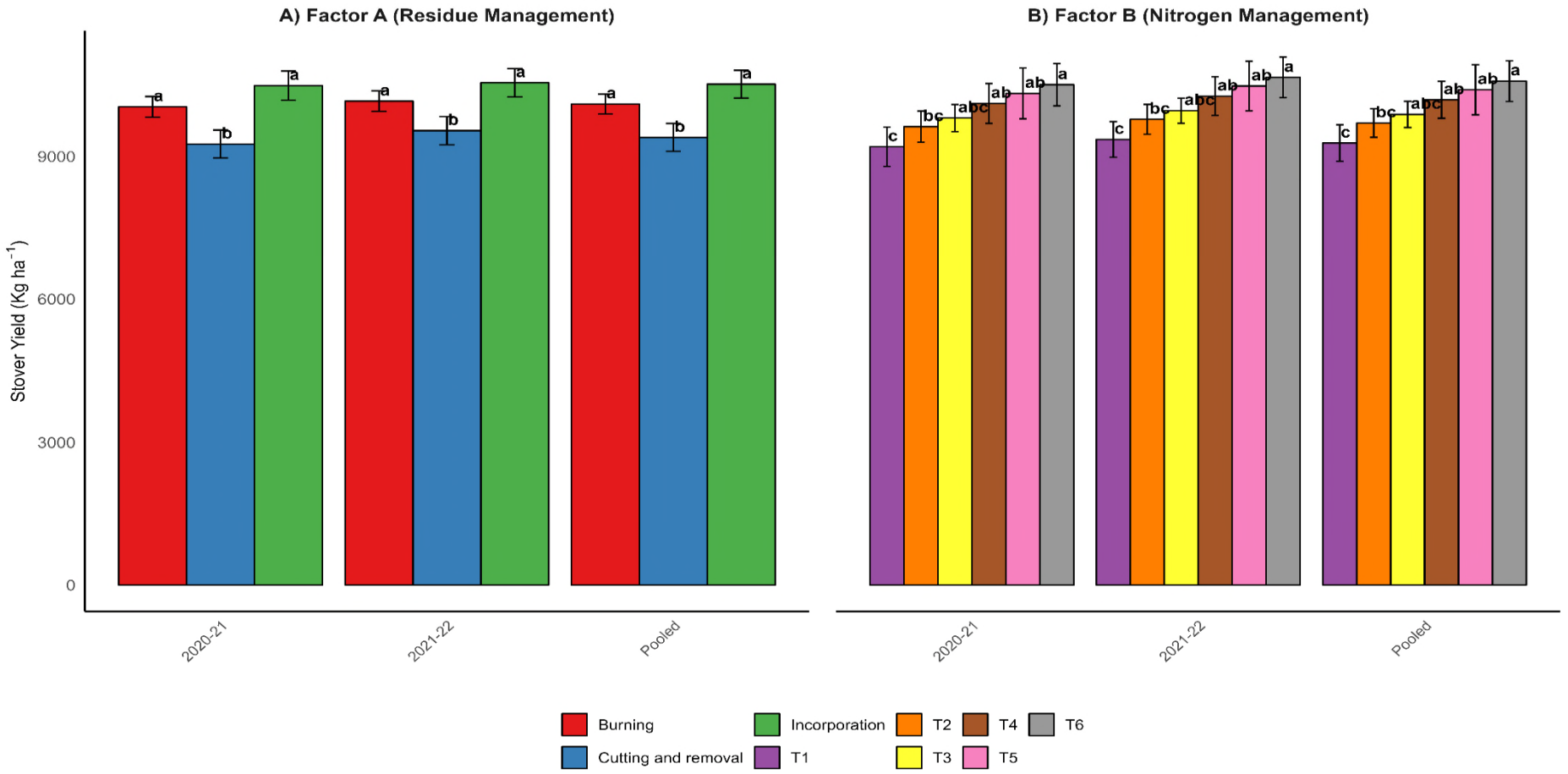


Fig. 9 Effect of Paddy straw management options—Straw burning, Cutting and removal, and Straw incorporation and different nitrogen management options (T1-T6) on the stover yield (kg ha^{-1}) in maize. Bars represent mean values ± standard error (SE). Different lowercase letters above bars indicate significant differences among nitrogen management treatments within the same growth stage and year according to DMRT test at $P \leq 0.05$.

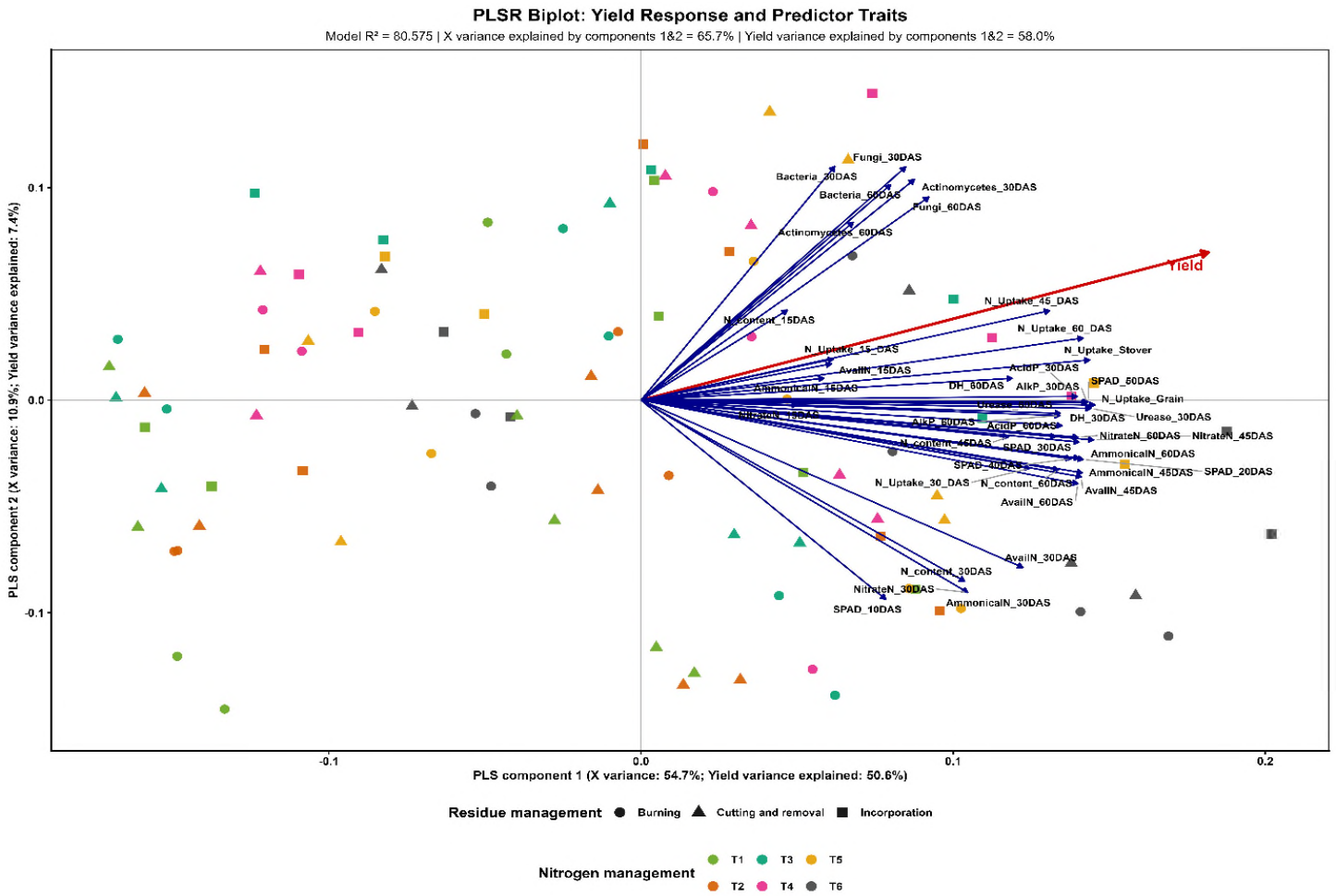


Figure 10. PLSR biplot illustrating the association of maize grain yield with soil nitrogen dynamics, nitrogen uptake, chlorophyll status, microbial populations and soil enzyme activities under rice straw and nitrogen management.

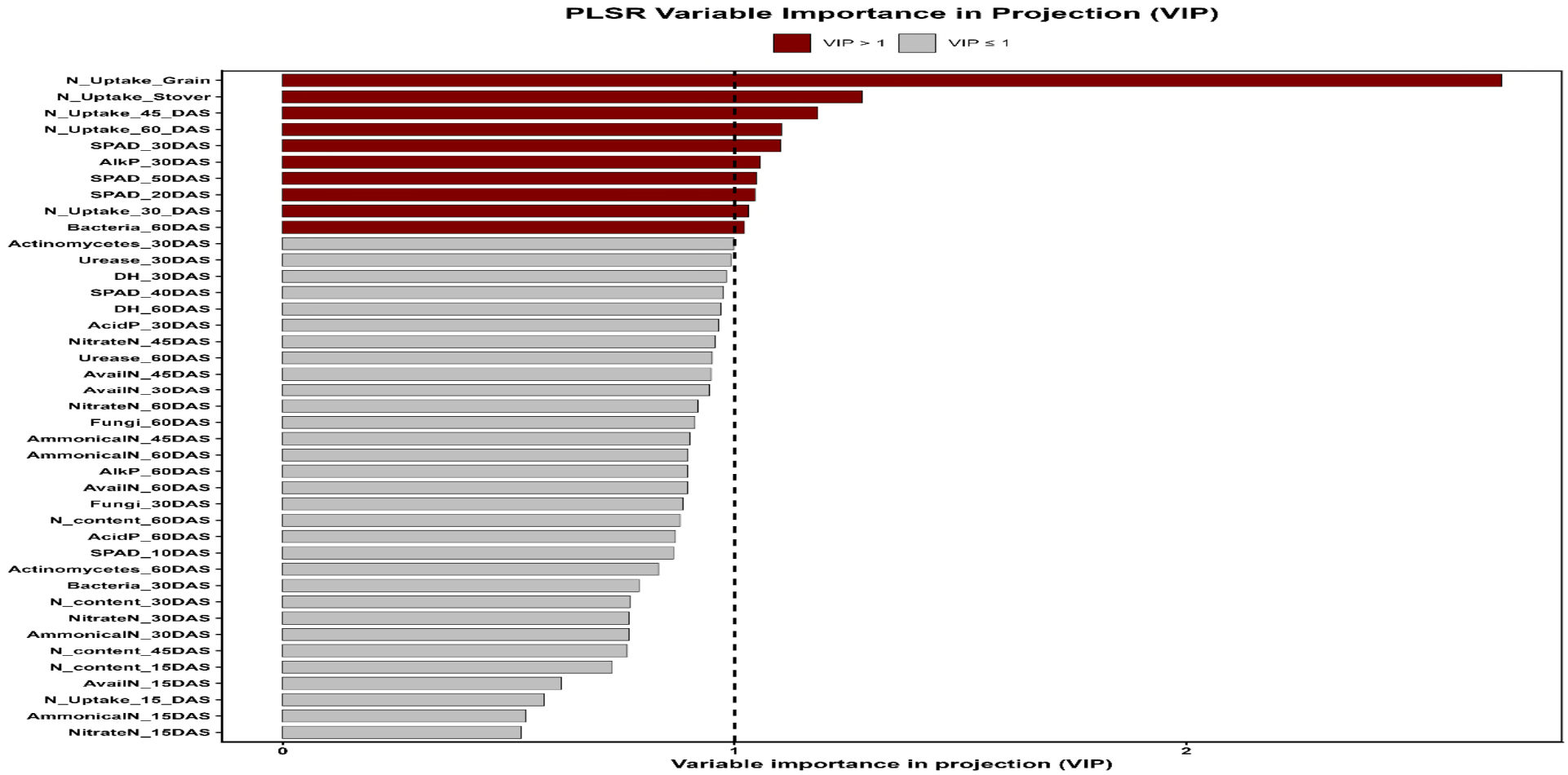


Figure 11. Variable importance in projection (VIP) scores of soil and plant attributes influencing the fitted PLSR model of maize grain yield.

Supplementary Files

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- Supplementarymaterial.docx