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Split application of ureapolyacrylamide for enhancing nitrogen use efficiency in Rice–Maize system

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Research Article

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Posted Date: November 9th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11269065/v1

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Additional Declarations: No competing interests reported.

Split application of ureapolyacrylamide for enhancing nitrogen use efficiency in Rice–Maize system

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Abstract

An unreasonable application of nitrogen (N) fertiliser leads to increased agricultural greenhouse gas emissions and unbalancing the soil ecosystem. To solve this, synthesize a slow-release N fertilisers with urea (U) and polyacrylamide (PAM) through polymerisation under specific conditions is ureapolyacrylamide (UPAM). After polymerisation, UPAM can be designed into four grades with respective carbon (C) and N concentrations (UPAM-1: N-32 & C-35%; UPAM-2: N-27 & C-39%; UPAM-3: N-25 & C-41%; UPAM-4: N-23 & C-42%). In order to ascertain the impact of various grades UPAM on rice and maize growth, yield, nutrient uptake and nitrogen use efficiency (N-UE). A two-year field (2020-21 & 2021-22) experiment laid out in a randomized block design (RBD) with three replications and ten treatments consisting of the following T1-absolute control, T2-UPAM-1, T3-UPAM-2, T4-UPAM-3, T5-UPAM-4, T6-UPAM-1, T7-UPAM-2, T8-UPAM-3, T9-UPAM-4 and T10-neem coated urea (NCU), was conducted on an agricultural farm at the IAS, BHU, Varanasi, (middle Gangetic plains) India. The main of the study was to investigate the leverage of various grades of UPAM application on soil physico-chemical properties, yield, nutrient content, nutrient uptake, and economic analysis of rice and maize. Our research findings evidence for the positive impacts of UPAM on yield and, nutrient uptake and maximum values were observed in plots treated with UPAM-2 grade followed by UPAM-1 and NCU, with a significant impact on soil available N content at different phenological growth stages, and non-significant impact on soil properties of both crops. Comprehensive analysis showed that UPAM-2 is a sustainable N fertiliser that helps to enhance the N availability, and sustainability in crop production.

Keywords: Ureapolyacrylamide, slow-release N fertiliser, Neem coated urea, Nutrient uptake, Soil available N

Highlights

- Ureapolyacrylamide act as a source of N and C to the crop production
- Potent N fertilizer management is essential for crop production and environmental limits
- The practice of UAPM-2 grade have been proven to be beneficial for both crop yield & soil properties and economic factors.

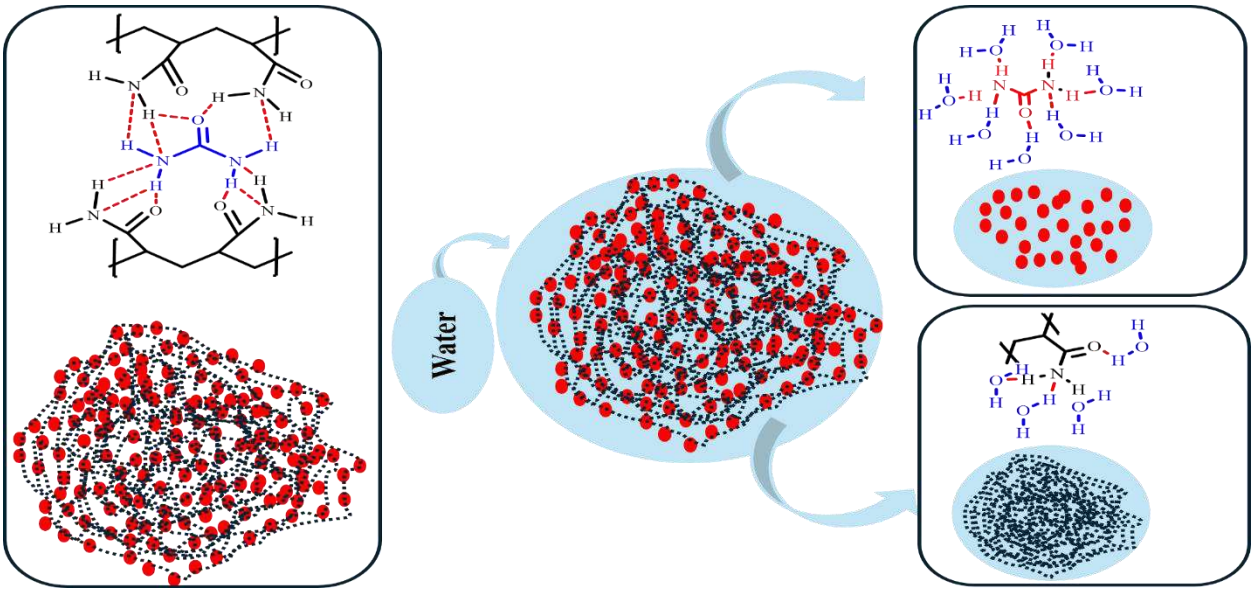
Introduction

Nitrogen is the most limiting nutrient in cereal-based cropping systems, and its deficiency in soils uniquely scarce in geological formations because it lacks a primary mineral reservoir in earth's crust relies on biological fixation and organic accumulation, necessitates external fertilisation [65]. N is a key factor in maintaining higher yields and the sustainable economic viability of agricultural systems [21,8,66]. Most conventional N fertilisers are sulfates (SO_4^{-2}), nitrates (NO_3^-), and amide (NH_2) are inefficient because they are readily water-soluble, yielding excessive of N concentrations in soil ecosystems that plants cannot takeup [18,31] among these, the most commonly used N fertiliser is urea, typically a solid granular fertiliser with N in amide (NH_2) form [71,58].

The global demand for N fertilisers has reached 132 million Mg $year^{-1}$ [12]. Urea accounts for over 50% of this amount, representing the most used fertiliser worldwide (IFASTAT 2024). The global popularity of urea fertiliser is explained by its high N content (46%), widespread availability, and low production cost [2]. Urea also is identified as a low-effective N source for crops because characterized by high constant N release kinetics [15,20]; thus causes harm to the ecosystem through processes like run-off loss via leaching (NO_3^-) [6], denitrification (N_2O & N_2) [13, 42], and volatilization (NH_3) [24], after being applied to soils, ultimately affecting the agricultural and ecological environment [7, 30, 68]. In general, low-value crops like cereals require a high amount of N fertiliser input [37,48,32,22] caused low N-UE, and increasing the frequency of topdressing applications incurs economically viable and environmentally N fertiliser.

UPAM (synthesis and characterization of UPAM is available in the following link: https://doi.org/10.1016/j.cej.2025.161215) is a slow-release N fertiliser, and productive blue print

to mitigate N losses. Further the common process for synthesis of UPAM is mixing of urea (U) with polyacrylamide (PAM) leads to the formation of adduct product UPAM, which are hydrogen (H) bonded (•) with one another via using H atom of -NH_2 functionality and oxygen (O) and the N atom of carbonyl (>C=O) and –NH_2 group respectively (Scheme-1). After polymerization of UPAM can be developed in to four various grades with respective N and C concentration (UPAM-1: C-35% & N-32%; UPAM-2: 27 & 39%; UPAM-3: 25 & 41; UPAM-4: 23 & 42). PAM matrices can modulate U dissolution, thereby extending N release and improving synchrony with crop demand. Therefore, the present study undertaken to evaluate the agronomic, soil, and economic assessment of various UPAM grades under rice-maize cropping system. Specifically, the objectives were: (i) to assess the effects of UPAM grades and split application schedules on yield, and N uptake; (ii) to examine their influence on soil properties and nutrient uptake; and (iii) to analyze the economic returns associated with different treatments. However, despite the availability of various s/cNf, limited comparative data exist on the agronomic performance of UPAM grades under rice–maize systems, particularly with respect to split application schedules. We hypothesized that UPAM-2, owing to its dissolution profile, would outperform neem coted urea and other UPAM grades by enhancing N uptake and profitability when applied in crop-specific split schedules.

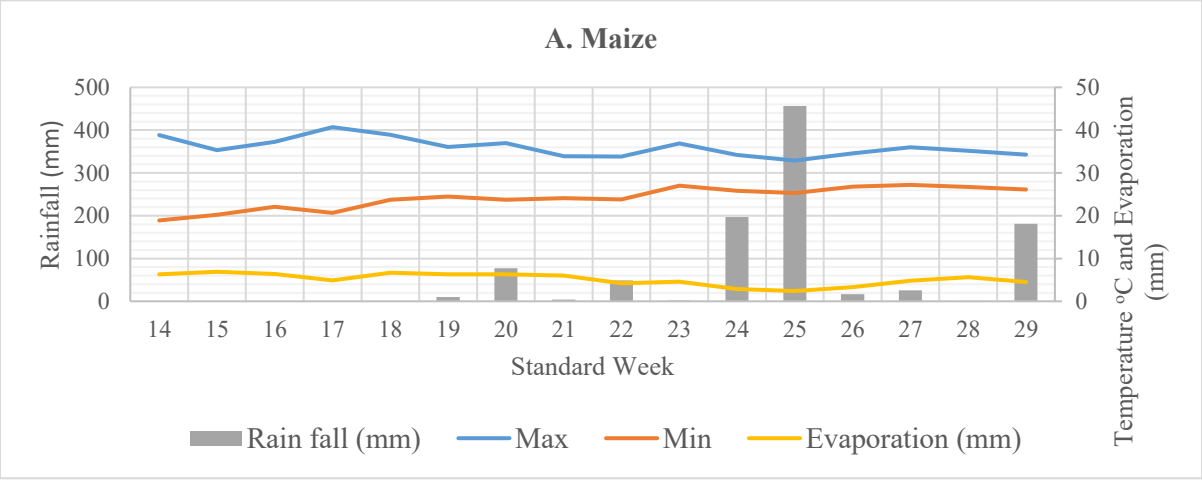


Scheme-1: Schematic representation of the structure and N release pattern from UPAM

Materials and methods

Study site: A field experiment was carried out during the year of 2020–2021 and 2021–2022 at the Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, situated between 25° 18′ North latitude, 83° 30′ East longitudes and at an altitude of 76.216 m from the mean sea level; representing the area under the middle Gangetic plains (IV agro-ecological region) of Uttar Pradesh in eastern India. A composite soil sample was analysed before crop establishment for texture, soil pH, electrical conductivity (EC) soil organic carbon (SOC), and soil available N, phosphorus (P), and potassium (K) following the standard protocols. Analysis report indicated that the soil was sandy clay loam, neutral to slightly alkaline (7.64 & 7.57) with low OC (4.30 & 4.52 g kg^{-1}), and available N (203 & 198 kg ha^{-1}), medium (21.01 & 18.75 kg ha^{-1}) and high (206 & 210 kg ha^{-1}) levels of available P, and K, respectively. After harvest of the each crop, we collect randomly 5 sites from each plot for post-harvest analysis. The USDA Soil Taxonomy classified this soil as a Typic Ustochrept (order Inceptisol) (https://www.nbsslup.in/soilresource-studies-srs.html). Varanasi is characterised by a semi-arid and sub-humid climate with an annual average rainfall of 1100 mm. Total rainfall of 1019.6 and 1036.7 mm was received during the experimentation cropping period of the maize and rice crops. The weekly mean maximum temperature (32.9 to 40.7°C and 26.7 to 34.9°C) and minimum temperature (18.9 to 27.2°C and 10.6 to 26.9°C) were recorded during both the crops of experimentation, respectively. Average sunshine hours and relative humidity (morning and evening) in both crops were 4.8 and 5.9 h, 76.15 & 56.61%, and 92.83 & 66.52% in maize and rice crops in the growth period. (Fig. 1 & 2)

Fig. 1 (A and B) Course of weekly weather conditions during the maize and rice growth period 2020-21



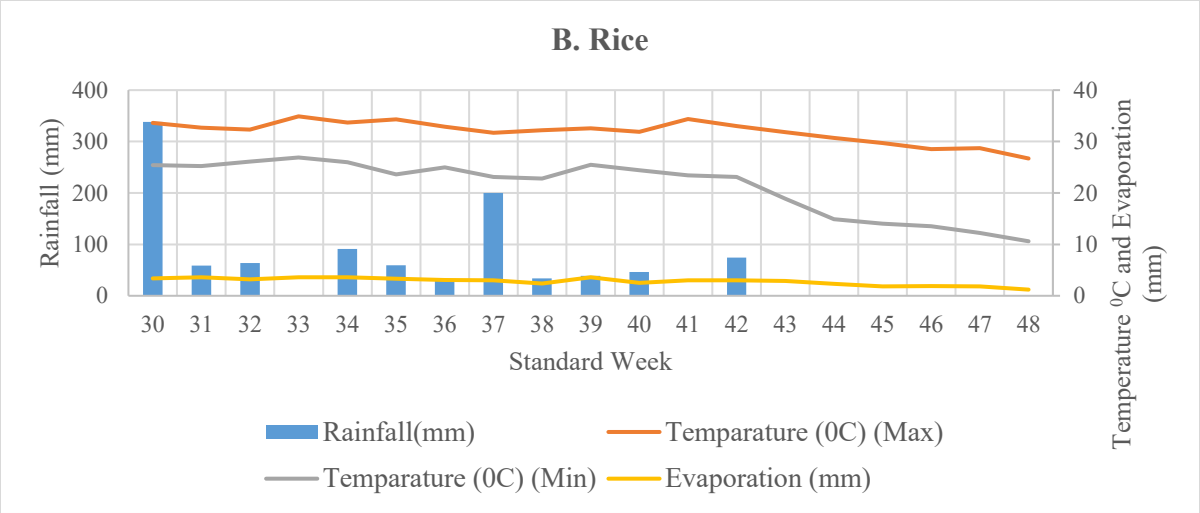
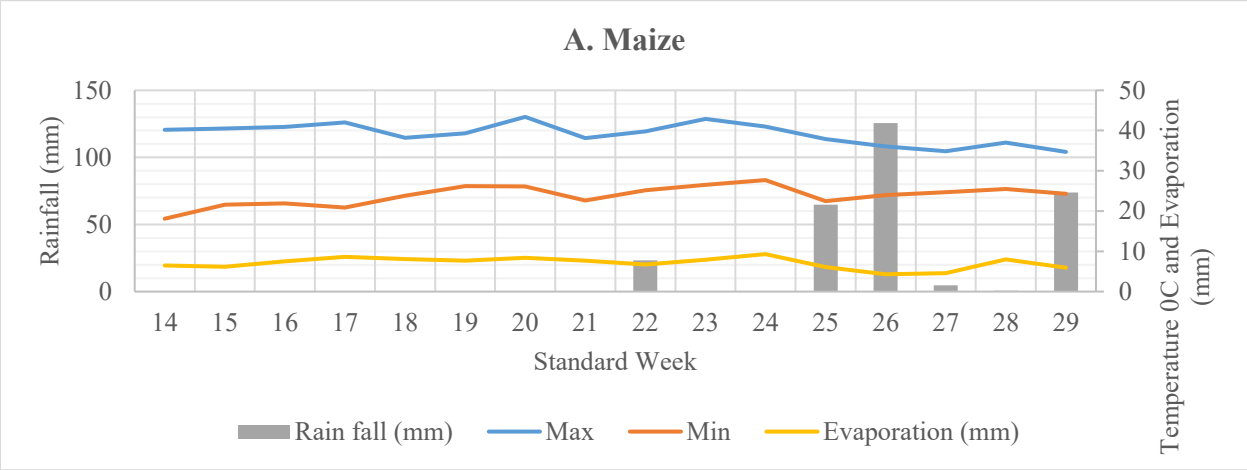
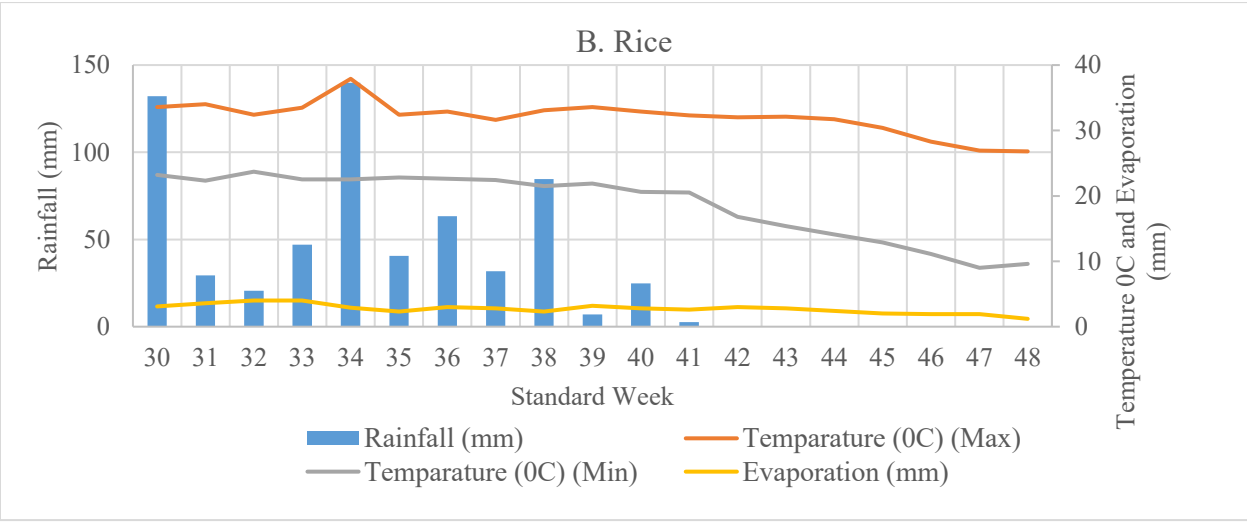


Fig. 2 (A and B) Course of weekly weather conditions during the maize growth period 2021-22





Experimental design and treatment details

The field experiment laid out in a randomized block design with three replication and ten treatments; combinations of various grades UPAM with respect to the number of applications and along with mineral fertilizers like SSP and MOP, including one neem coated urea (NCU) and absolute control consisting of the following T1-absolute control, T2-UPAM-1, T3-UPAM-2, T4-UPAM-3, T5-UPAM-4, T6-UPAM-1, T7-UPAM-2, T8-UPAM-3, T9-UPAM-4 and T10-NCU, here T2 to T5 two split applications and T6 to T10 three split applications. The recommended dose of fertiliser (RDF) was applied @ 180:60:60 kg ha^{-1} ($N:P_2O_5:K_2O$) through UPAM, NCU, single super phosphate (SSP), and muriate of potash (MOP), respectively, in both the crops. The full dose of SSP and MOP was applied at the time of sowing in both the crops. Here, the dose of N was given in two splits (1^{st} split: basal and 2^{nd} split: 40 DAS/T (DAS/T: days after sowing/transplanting); T2 to T5 treatments) and three splits (1^{st} split: basal, 2^{nd}: 30 DAS/T, and 3^{rd}: 60 DAS/T; T6 to T10 treatments), being administered accordingly.

Plant sampling and N, P, and K content determination

Three representative plant samples were obtained in each treatment at the physiological maturity stage. They were then dried at 80^0C in a forced-air oven to a constant weight and weighed separately. After weighing, the samples were grounded using a Willy mill with a fine mesh (0.5 mm). Leaf N content was determined by the Kjeldahl method; leaf P content was determined by the molybdenum antimony colorimetric method; leaf K content was determined by the flame photometric method [41,27]. The following parameters were calculated:

Plant N uptake (g $plant^{-1}$) = the plant N concentration × dry weight of the plant

Plant P uptake (g $plant^{-1}$) = the plant P concentration × dry weight of the plant

Plant K uptake (g $plant^{-1}$) = the plant K concentration × dry weight of the plant

B:C ratio = Net return (INR ₹ ha^{-1})/Total expenditure (INR ₹ ha^{-1})

Statistical analysis

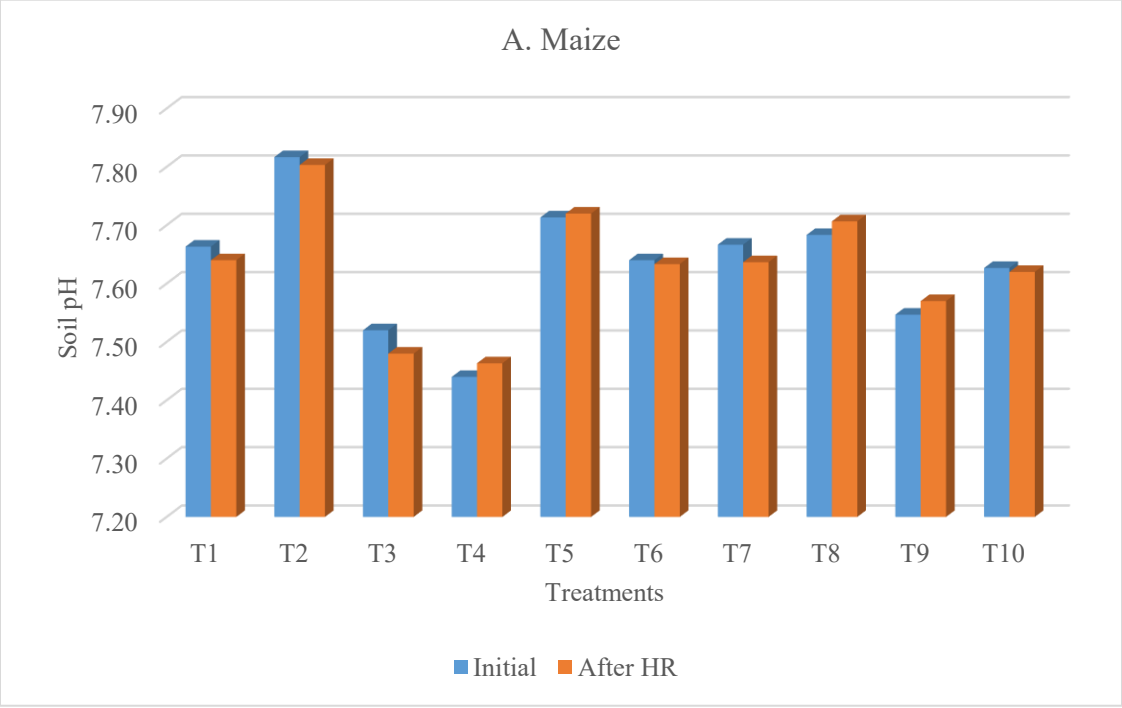
Statistical analysis was done by using "R" statistical software (R version 3.6.1). One-way analysis of variance (ANOVA) was performed to assess the significance of the differences in the parameters of the different treatments. Multiple-mean comparison or significance of the difference between treatments' means was analysed using critical difference (CD) and Duncan's multiple range test (DMRT). Lowercase letters in the table indicate statistically significant differences after the least significant difference (LSD) test at $P < 0.05$.

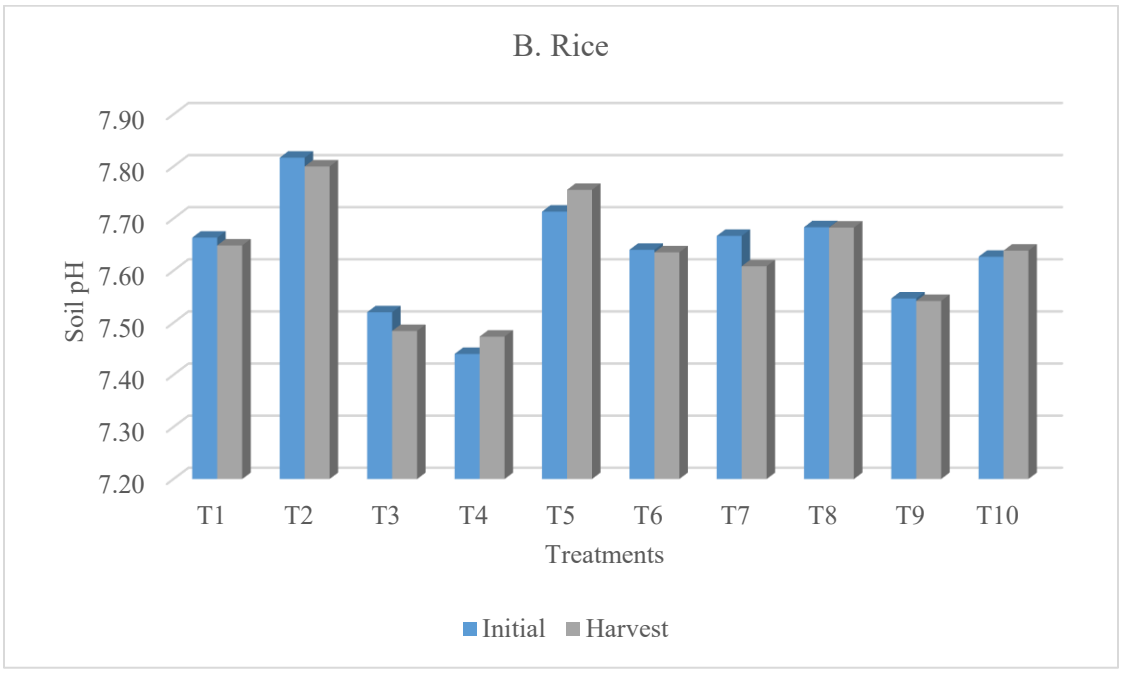
Results

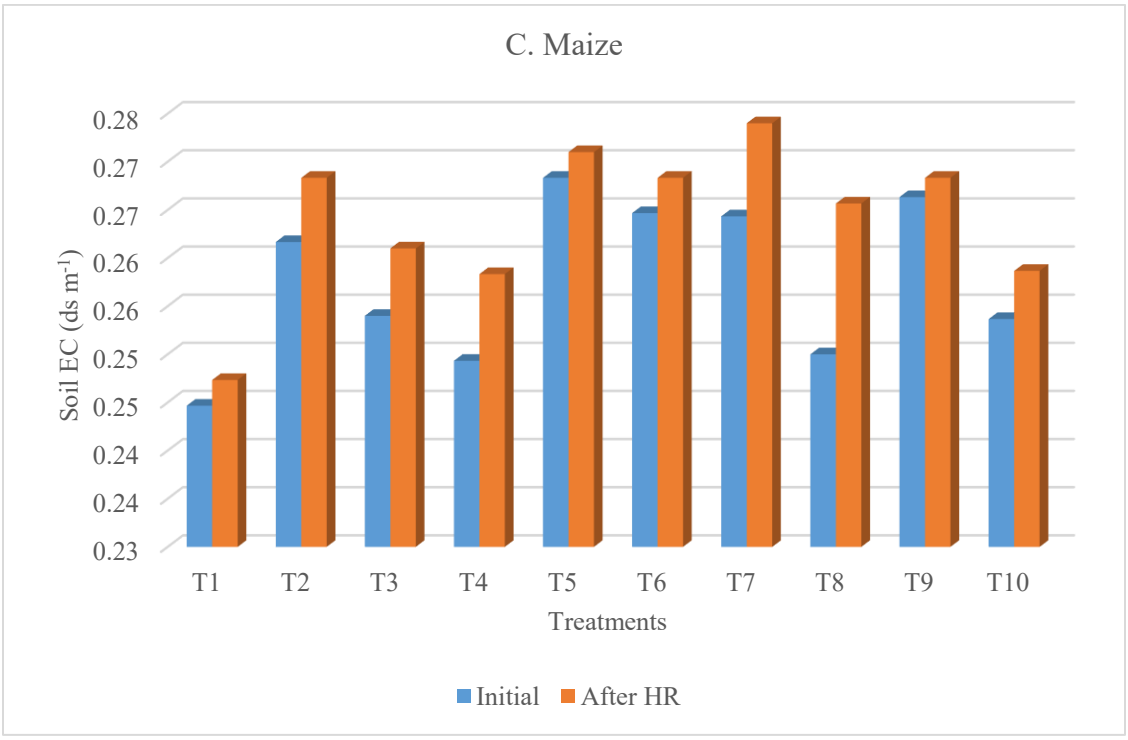
Assessment of UPAM application on soil pH, EC, and SOC, available N, P, and K content

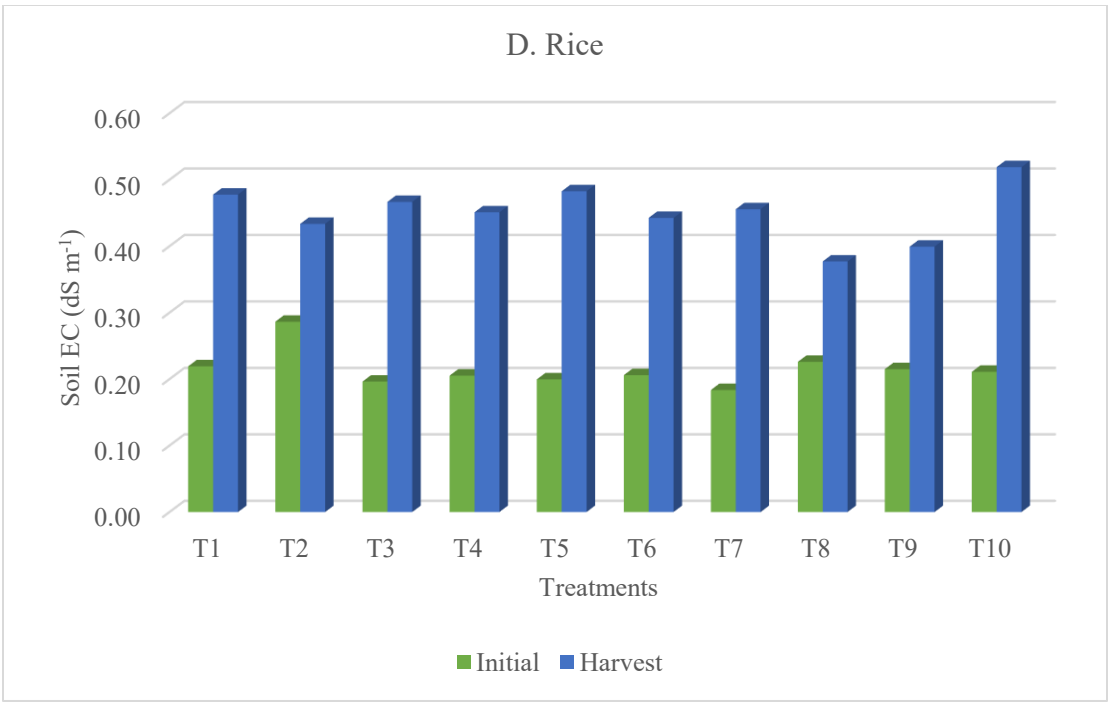
Soil pH, EC, and SOC are principal parameters of soil that control virtually all aspects of chemical and biological reactions occurring in soil. Data on the pH and EC of the soil as ramifications by various grades of UPAM, i.e., number of applications and non-significant changes between treatments at crop phenological growth stages, are presented in Fig. 3. The soil pH ranged between 7.44 to 7.82 and 7.42 to 7.90, respectively in maize and rice, with the maximum pH reported in T2 treatment where two split applications of UPAM-1 grade in maize and in rice T7 treatment where three split applications of UPAM-2 grade was made lowest in two split applications of UPAM-3 grade (T4) in maize and in rice T3 treatment where two split application of UPAM-2 grade. Further, following two and three split applications of UPAM-1 and UPAM-2 grade applications, SOC content increased, but the results are statistically non-significant when compared with the initial SOC content in both crops. The highest SOC was found in three split applications of UPAM-2 (T7; 4.82 g kg^{-1}) and three split applications of NCU (T10; 5.53 g kg^{-1}) in maize and rice crops, and the lowest was found in absolute control (T1) in both the crops.

Fig. 3 **(**A, B, C, D, E, F**)** Effect of various grades of UPAM application on soil pH, EC, and SOC (A to F) in maize and rice crop

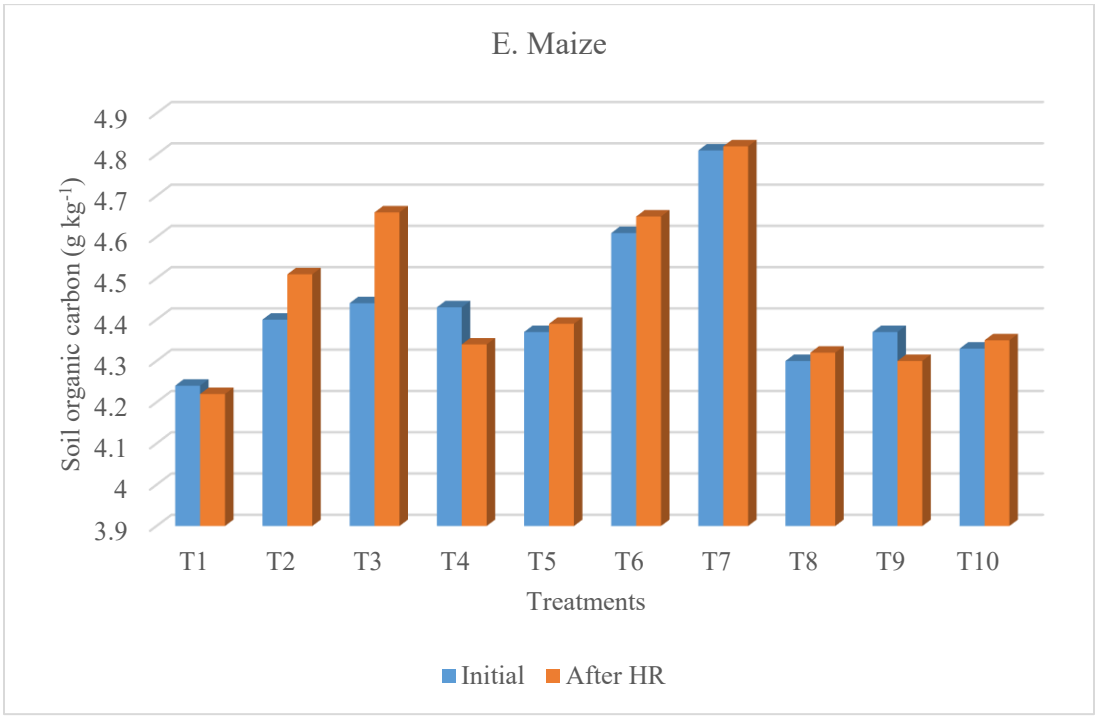



B. Rice
7.90
7.80
7.70
7.60
7.50
7.40
7.30
7.20
Soil pH
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
Treatments
Initial
Harvest

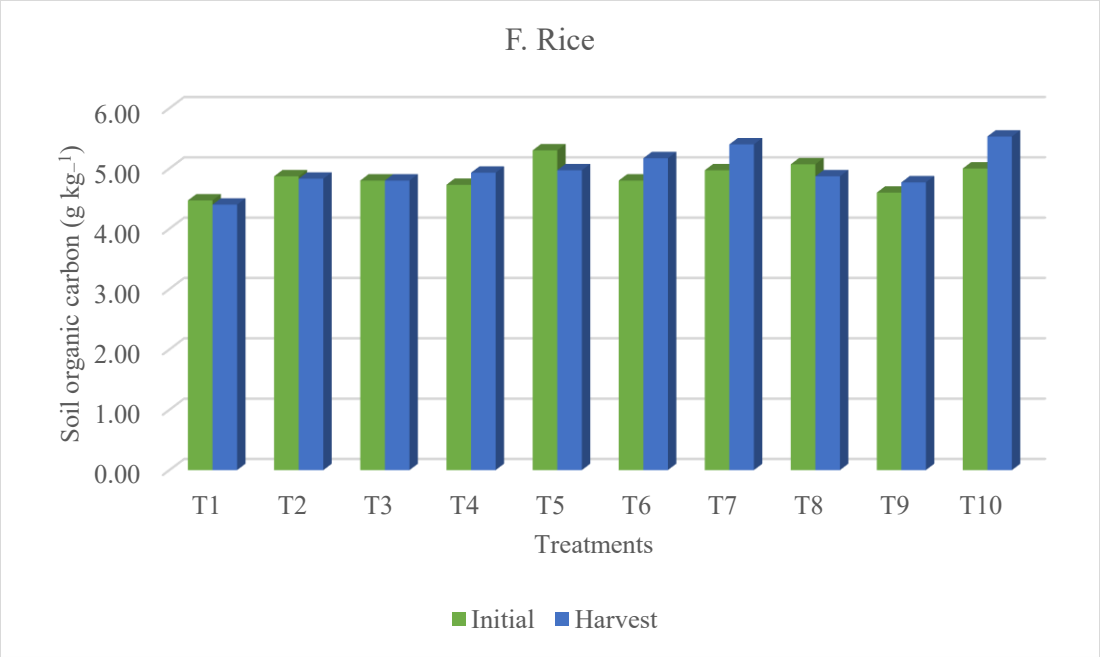

C. Maize
0.28
0.27
0.27
0.26
0.26
0.25
0.25
0.24
0.24
0.23
Soil EC (ds m-1)
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
Treatments
Initial
After HR


D. Rice
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Soil EC (dS m-1)
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
Treatments
Initial
Harvest

159


E. Maize
4.9
4.8
4.7
4.6
4.5
4.4
4.3
4.2
4.1
4
3.9
Soil organic carbon (g kg-1)
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
Treatments
Initial
After HR

160



T1-Absolute control, T2-UPAM-1, T3-UPAM-2, T4-UPAM-3, T5-UPAM-4, T6-UPAM-1, T7-UPAM-2, T8-UPAM-3, T9-UPAM-4, and T10-NCU. Here, T2 to T5 are two split applications; T6 to T10 are three split applications

Available N

In maize, various grades of UPAM, i.e., number of applications and significant changes between treatments at crop phenological growth stages, are presented in Table. 1, and the available N content of the soil significantly increased. The available N content ranged between 190 to 269 kg ha^{-1}. The highest available N was recorded in two splits of UPAM-2 (T3) at the grain filling (GF) stage, whereas the minimum was in T1 at harvest. Whereas at the knee height (KH) stage, a non-significant difference between treatments, thereafter till harvest significant difference between treatments. At the tasseling stage (TS) highest available N content was noticed in the T3 (252 kg ha^{-1}), followed by T2 (237 kg ha^{-1}) and T6 (234 kg ha^{-1}). At the GF and harvest stage (HR), the highest availability of N was found in T7 (269 and 237 kg ha^{-1}). Here, T3 and T7 are both the same grade polymeric N fertiliser but differ in number of applications At harvesting of the maize crop, the available N content in UPAM-2 grade treated plots by 11.35% and 13.79% respectively, in two (T3) and three (T7) splits, compared to the T1, where it registered a 6.84% decrease.

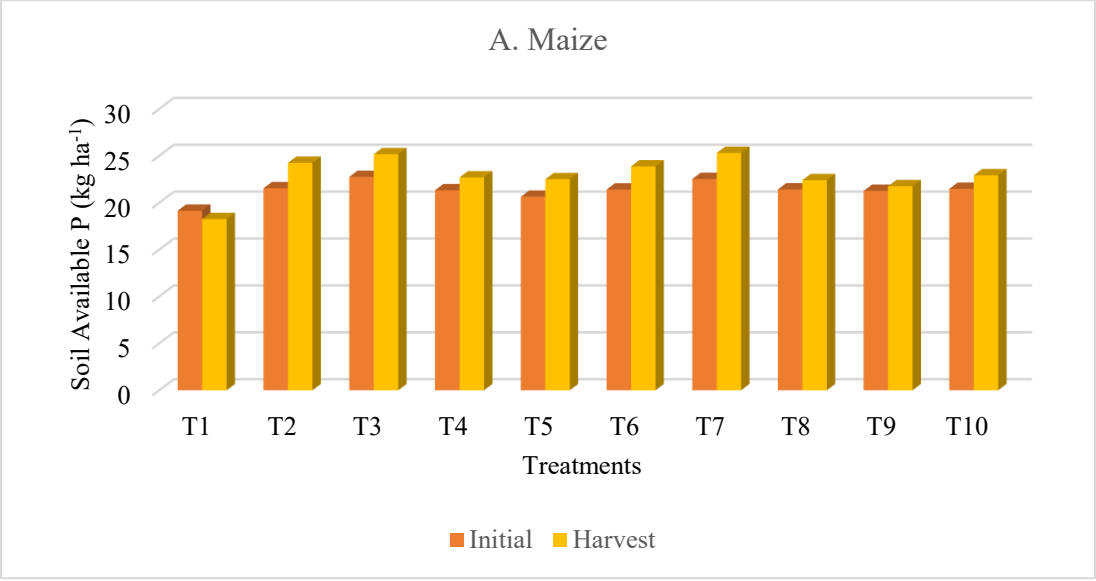
In rice, a significant difference was observed among all the treatments throughout the growth stages. Among fertilisation, at the active tillering (AT) stage, significantly higher available N was recorded under two split applications of UPAM-2 (T3; 233 kg ha^{-1}) followed by three split

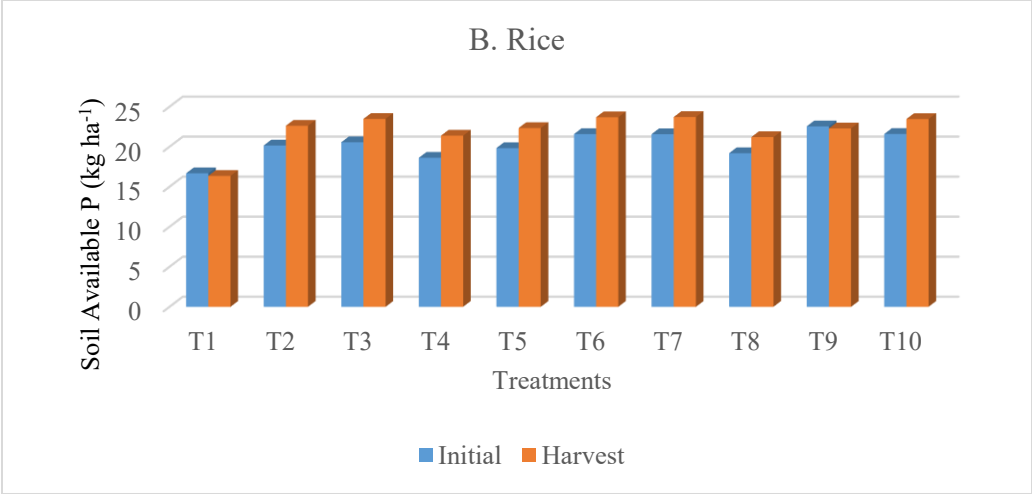
applications of the same grade (T7; 221 kg ha^{-1}). The highest soil available N was recorded at the PI stage in three split applications of UPAM-2 grade treated plot (T7; 248 kg ha^{-1}), at the heading (HE) and harvesting (HR) stage of three splits of UPAM-1 grade treated plot (214 and 209 kg ha^{-1}), and at all growth stages minimum value was registered in T1. Improvement in available N in three split applications of UPAM-1 and UPAM-2 grade treated plot over absolute control (T1) was 16.75 and 13.40%, respectively. However, the soil available N content in different treatments declined with time and reached a minimum at harvest.

Available P and K

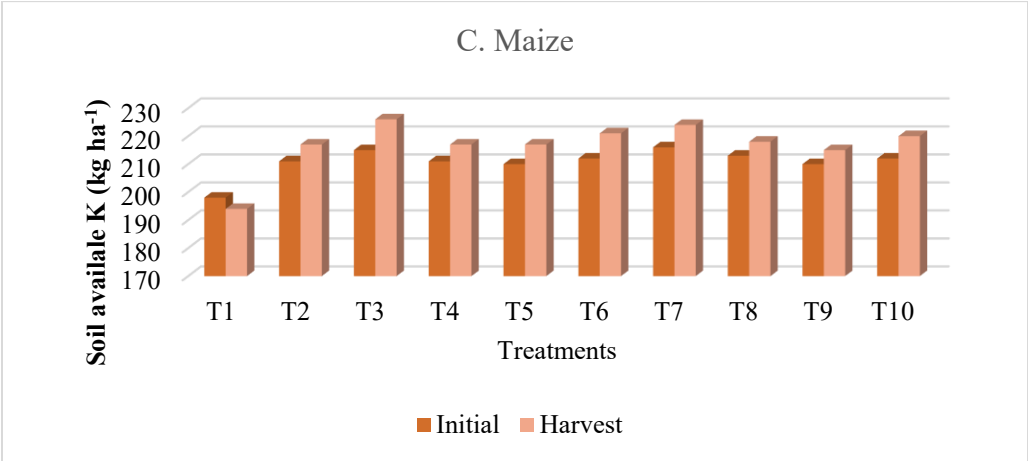
Fig. 4 showed a non-significant between the treatments, with applications of various grades of UPAM along with SSP and MOP as basal dose applications. The highest available P and K content was found in the UPAM-2 grade treated plot, followed by NCU and UPAM-1, and the lowest was found in the absolute control (T1). On average, from start to end of the experiment, 1.5 to 3.5% and 4.5 to 6.5% increase of available P & K was noted in all treatments except T1. In the T1 treatment, confronted with the initial available P and K content, 6.15 and 6.18% decreased after harvest. Results also suggested that various grades of UPAM had no negative impact on soil available P and K content and the synergistic effect between these nutrients (N, P, and K).

Fig. 4 (A, B, C, D) Effect of various grades of UPAM application on soil available P and K (kg ha^{-1}) in maize and rice crop

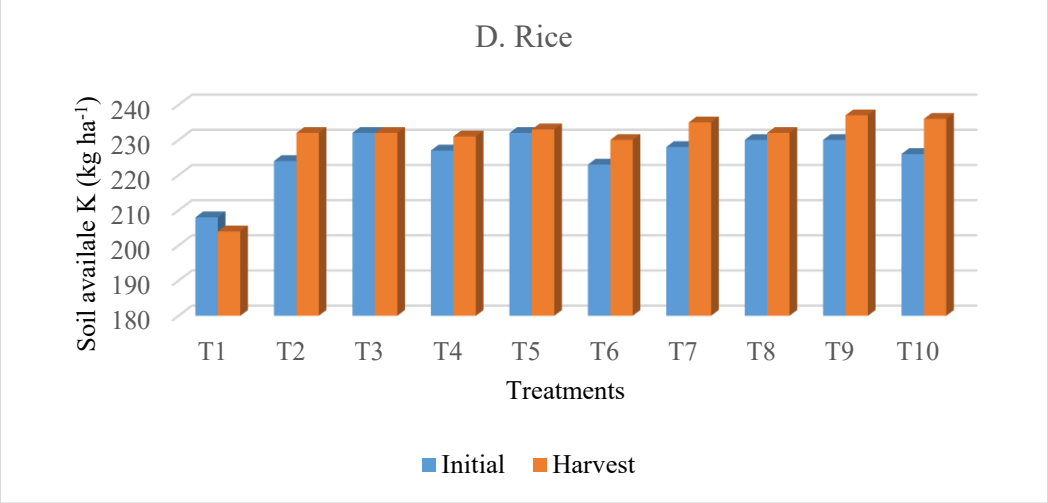




200



201



202

203 T1-Absolute control, T2-UPAM-1, T3-UPAM-2, T4-UPAM-3, T5-UPAM-4, T6-UPAM-1, T7-UPAM-2,
204 T8-UPAM-3, T9-UPAM-4, and T10-NCU. Here, T2 to T5 are two split applications; T6 to T10 are three
205 split applications

Assessment of UPAM application on yield and yield attributes of rice and maize crop

Response to various grades of UPAM in maize (Table. 2) was significant in yield and yield attributes. The highest economic yield (6.12 t ha^{-1}) was attained with two splits of UPAM-2 (T3), followed by three splits (5.75 t ha^{-1}) of the same grade, and the lowest was in T1 (2.94 t ha^{-1}). When the same grade UPAM but differ in number of applications, two splits of UPAM-1 and UPAM-2, recorded 6.91 & 18.70% higher economic than three splits, but in UPAM-3 and UPAM-4 three splits exhibited 9.10 & 10.13% higher economic yield than two splits. In comparison between three split applications of NCU (T10) with two and three split applications of UPAM-2, it was pertinent that two and three splits of UPAM-2 achieved 11.13 and 15.96 % higher biological yield (BY). Additionally, two and three splits of UPAM-2 achieved 108.29 and 95.64% higher economic yield (EY) compared with the absolute control. In contrast, among the various grades of UPAM, irrespective of number of applications, interestingly, three splits of UPAM-1 (5.19 t ha^{-1}) equivalent to three splits of NCU (5.19 t ha^{-1}) with different N concentrations.

In rice, (Table. 2) data indicated that various grades of UPAM, i.e., number of applications, exerted a significant effect on yield and yield attributes. The average number of productive panicles per m^2 in the experiment ranged from 86 to 175; the highest number of productive panicles and panicle length was recorded with three splits of UPAM-2 (T7). In contrast, the length of panicle in T2 treatment is statistically similar to three splits of NCU (T10). Most petite panicle lengths were found in T1. The highest economic yield was found in three splits of UPAM-2 (T7; 5.96 t ha^{-1}) followed by three splits of UPAM-1 (T6; 5.05 t ha^{-1}) and the lowest was noticed in T1. T7 treatment compared with T3 and T10, T7 treatment recorded 22.73 and 32.71% higher economic yield. Three split applications of UPAM-2 compared with three splits of UPAM-3 and UPAM-4 grade, 43.33 and 60.10% higher economic yield recorded in T7 treatment. It is interesting to note that the highest harvest index value was found in T1, followed by two splits of UPAM-4 (T5) treatment.

Assessment of various grades of UPAM application on nutrient content (N, P, K) in grain, straw and nutrient uptake in maize and rice crop

The nutrient (N, P, and K) content of grain and straw indicates nutrients absorbed by the crops (Table. 3). In maize grain N content significant but in straw non-significant with irrespective of the number of application of various grades of UPAM. The N content of grain was ranged from

1.21 to 1.42% and the highest N content in the two splits UPAM-2 (T3) treated plot. T3 is statistically superior to all treatments, compared with same grade three splits applications with 1.42% higher N content in grain. In straw, the highest N was also noticed in the T3 treatment, but compared with no fertilization treatment (T1), there was a 74% higher N content in T3. In Rice the N content of grain and straw increased significantly with successive N availability up to harvest. The N content in grain and straw oscillated between 1.13 to 1.20 and 0.47 to 0.62. It was noticed that the maximum N content of the grain and straw in UPAM-2 grade was followed by UPAM-1 and NCU and the lowest found in T1. The N content of UPAM-3 and UPAM-4 treated plots compared with UPAM-2 1.69 & 3.44% and 5.08 & 6.89 lower noticed in grain and straw. T7 treatment compared with T10 and T1 treatment resulted from 6.19 & 31.91% higher N content in grain and straw in T7.

In maize, P and K content of grain and straw are (Table. 3) showing that non-significant but in rice, noticed that the significant effect of P and non-significant of K content of grain and straw. P and K content of grain and straw were highest in T7 and was statistically superior to all treatments and identical to all treatments except T1 in grain P content. Although there was a non-significant in grain K content, the highest K content was found T6, and the lowest in T1. K content of straw, unlike N and P much higher than that of grain, and the highest K content is found where UPAM-1 and UPAM-2 grades, and the lowest is found in T1.

Nutrient uptake

The effectiveness of applied fertilisers is determined by the uptake of N, P, and K from soil, assimilation, and remobilization into grain and straw. N, P, and K uptake by maize and rice (Table. 4) noticed with two splits of UPAM-2 (T3) along with SSP, and MOP highest total N, P, and K (122.34, 19.63, 58.09 kg ha^{-1} and 113.02, 18.52, and 120.35 kg ha^{-1}) uptake was observed to be statistically superior to the treatments. Total N uptake of two splits of UPAM-2 compared with three splits of the same grade (T7) and NCU (T10), two splits of UPAM-2 registered 13.16 and 37.78% higher total N uptake recorded but treatment T3 and T7 are statistically at par with each other. Total P and K uptake were also found in two T3 followed by T7, T6, T3, and NCU, and the lowest were reported in T1 (44.93, 6.62, and 19.43 kg ha^{-1}). In rice T7 registered 34.25, 37.49, and 36.54% higher total uptake of N, P, and K with respective to NCU. Nutrient uptake is low in

UPAM-3 and UPAM-4 compared to UPAM-1 and UPAM-2 grades, seemingly the faster dissolution rate.

Table. 4 Assessment of various grades of UPAM on nutrient uptake (kg ha^{-1}) in maize and rice crop

Treatments	Maize			Rice		
	Total N uptake	Total P uptake	Total K uptake	Total N uptake	Total P uptake	Total K uptake
T1	44.93^{g}	6.62^{f}	19.43^{d}	31.07^{g}	4.70^{e}	31.96^{g}
T2	100.66^{bc}	15.73^{abc}	46.87^{abc}	83.36^{cd}	13.26^{bc}	89.90^{bcd}
T3	122.34^{a}	19.63^{a}	58.09^{a}	96.82^{b}	15.76^{ab}	107.16^{ab}
T4	73.36^{ef}	11.53^{de}	37.74^{c}	68.06ef	10.44^{cd}	72.62^{def}
T5	67.76^{f}	10.31^{ef}	35.58^{c}	59.24^{f}	9.41^{d}	60.40^{f}
T6	95.50^{bcd}	15.54^{abcd}	45.33^{abc}	94.51^{bc}	15.43^{ab}	100.47^{abc}
T7	108.11^{ab}	17.43^{ab}	54.39^{ab}	113.02^{a}	18.52^{a}	120.35^{a}
T8	83.28^{def}	12.92^{cde}	40.43^{c}	75.13^{de}	12.02^{cd}	79.28^{de}
T9	78.42^{ef}	12.31^{cde}	38.03^{c}	65.33^{ef}	10.50^{d}	67.27^{ef}
T10	88.79^{cde}	14.43^{bcd}	41.39^{bc}	84.18^{bcd}	13.47^{bc}	88.14^{cd}
SEm±	8.667	3.165	4.545	6.57	0.137	6.79
CD	18.983	5.49	10.618	19.70	2.408	18.34

T1-Absolute control, T2-UPAM-1, T3-UPAM-2, T4-UPAM-3, T5-UPAM-4, T6-UPAM-1, T7-UPAM-2, T8-UPAM-3, T9-UPAM-4, T10-NCU; Here, T2 to T5 are two split applications; T6 to T10 are three split applications. NCU-Neem coated urea. N-Nitrogen; P-Phosphorous; K-Potassium Mean values within the columns with different letter(s) indicate significant differences between treatments as per DMRT at P=0.05.

Economic analysis

An economic analysis (Table. 5) of fertiliser to the crop as assessed by gross return (GR), net return (NR), and B:C ratio. The cost of cultivation for the various grades of UPAM treated plots was higher than NCU treatment (T10). This is because the raw material is more expensive than the NCU. The NR of the UPAM-2 was higher than that of the 100% NCU treatment. The higher NR was attributed to the higher grain yield for these treatments. Maximum GR (1836.70 and 1889.64 \$ ha^{-1}) and NR (1150.42 and 1162.67 \$ ha^{-1}) UAPM-2 grade treatment followed by NCU in maize and rice crop. UPAM-2 grade also achieved the highest B:C (1.68 and 1.60) ratio and the lowest

returns were observed in T1. Our results showed that applying UPAM-2 along with SSP and MOP can be more profitable than NCU.

Table. 5 Economics of maize and rice crop production by various grades of UPAM fertilization

Treatments	Maize			Rice		
	GR ($ ha^{-1})	NR ($ ha^{-1})	B:C ratio	GR ($ ha^{-1})	NR ($ ha^{-1})	B:C ratio
T1	644.29	278.94	0.76	627.33	232.92	0.59
T2	1649.84	869.15	1.11	1559.42	749.66	0.93
T3	1836.70	1150.42	1.68	1813.77	1098.43	1.54
T4	1315.78	723.99	1.22	1371.01	750.16	1.21
T5	1228.41	651.24	1.13	1083.10	476.87	0.79
T6	1549.64	757.31	0.96	1616.13	794.74	0.97
T7	1732.12	1034.21	1.48	1889.64	1162.67	1.60
T8	1421.53	818.12	1.36	1376.49	744.01	1.18
T9	1339.87	758.05	1.29	1246.78	628.92	1.02
T10	1513.37	927.37	1.58	1530.07	915.01	1.49

T1-Absolute control, T2-UPAM-1, T3-UPAM-2, T4-UPAM-3, T5-UPAM-4, T6-UPAM-1, T7-UPAM-2, T8-UPAM-3, T9-UPAM-4, T10-NCU; Here T2 to T5, 2-two split applications, T6 to T10, 3-three split application. NCU-Neem coated urea, GR-Gross return, NR-Net return, B:C-Benefit cost ratio

Discussion

Today's agriculture focus on increasing crop yield with synchrony of essential nutrients with crop demand for achieving food and nutritional security [16,44]. Research on the application of slow/controlled release N fertilisers as an alternative to conventional N fertilizers with multiple application has been pursued internationally [55,39]. A comprehensive meta-analyses have quantified the effects s/cNf on N transformations, N-UE, and crop yields across diverse agro-ecosystems. For example, [52,57,64] demonstrated that slow-release nitrogen from CRU did not significantly alter soil NH_4^+-N and NO_3^--N content but reduced reactive N losses by 24.3–45.9 % and increased crop yield by 7.7 %. [70] Results indicated that enhanced crop yield and increase

SOC stock (yield by 3.4–7.7 %, SOC by 7.6–8.4 %), while reducing N_2O, CH_4, and CO_2 emissions (by 5.8 % to 26.9 %). [38] reported that the one-time application of slow-release N fertilizer can not only reduce the labour input, but also reduce the mechanical input cost, and has the characteristics of slow release and reduce volatilization loss. In some other studies combined use of slow release N with U with proper ration enhances the dry matter accumulation, nitrogen uptake and N-UE [19]. [28] noticed that the controlled release bulk blending fertilizers are regulating the C flow in the C & N metabolism to enhance rice quality and yield.

UPAM is a slowly degradable polymeric N fertilizer [1,60] when applied in soil irrespective of soil reaction, soil temperature, and soil texture and it is a good source of N when it starts to decompose increases the availability of N and C, similarly increase the soil microbial activity they promote the extracellular enzyme activity [50,54]. The results of soil pH and EC were non-significant under two ecological seasons of maize and rice crops. The results are in line with [53,4] and [29] reported that soil pH and EC did not significantly change with the application of the modified PAM. The results of SOC were also non-significant, but when compared with the initial SOC litter, higher SOC was found in UPAM-1 and UPAM-2 treatments. These results partially agree with [11] who reported that the C backbone chain of PAM could be broken down to form volatile fatty acids that function as C sources under aerobic and anaerobic conditions. [35] claim that the cultivated aerobic granules, consisting mainly of bacilli and filamentous bacteria, were able to use PAM both as the sole C and N source.

The results of soil available N, UPAM in combination with SSP and MOP had a positive effect on under UPAM-1 and UPAM-2 treated plots throughout the phenological growth stages of both crops and stabilized at harvest. This can be attributed to the addition of N through UPAM and root biomass, which enhanced microbial activity. The results are same line with the biodegradation of PAM involves microorganisms that utilize the amide group of the polymer as an N source and the C backbone as a C source [62,63,67]. Results are also in line with [59], and [47] work, which indicated that PAM might stimulate microbial activities in anaerobic and aerobic environments, and the amide group could serve as an N source for microorganisms. [69] also reported that optimum N rates are affected by many factors; conversely, improved N availability and use efficiency. The results of after harvest soil analysis indicated the little higher N in plots treated with UPAM-2 and UPAM-1 treated plots because of slow dissolution and degradation. These

results are align with [5] and [40] reported that anionic PAM their slow degradation can sustain appreciable amount of N and C released in the soil ecosystem.

The results of soil available P and K content increased at harvest with the addition of SSP and MOP fertiliser, indicating that fertilizer application, P-rich microbial activity and neutral to slightly alkaline nature of the soil was able to increase the effective P and K content in the soil [3,35]. The results are inline with [5,46,61] increased P and K availability with fertilizer addition under neutral condition. In this study, put in place that P addition could increase the available N content within a certain range, indicating that P addition promoted the mineralization of organic N and improved the N uptake. Results are the same line with [72] reported that combined N and P fertilisation shows responses to phosphatase activities that are interactive rather than additive to the effects of the single fertilisation treatments.

The results of economic and biological yield illustrated that the type of N fertiliser, and quantity are central factor [33,42,43]. The identical maize grain yield results were confirmed by [17] in the field, accounting for 20% higher yield in the controlled-release fertiliser compared to the traditional one at the same dose. [73] reported that compared to conventional urea, applying controlled-release fertiliser increased grain yield by 7.23% across all the studies in wheat, maize, and rice crops. [51] reported that slow/controlled release fertilisers and their quantity and time of application in maize crops, yielded 17.35-45.81% more grain yield than conventional urea practices in Nepal. In rice, the productive tillers were significantly higher in T7, where N availability in the soil led to increased cellular activities during panicle formation and development. These findings are closely in conformity with those of [25,34]. Panicle length increased with the increase in N availability because N takes part in panicle formation and elongation. Similar results were reported by [9,10]. The results are also in conformity with [36] who noticed that rice grain yield and higher N use efficiency could be achieved with optimum dose and time of application, thus reducing costs resulting from fertiliser inputs without compromising other environmental benefits. In both the crops, higher grain yield and test weight were observed with UPAM-2, which might be due to higher N availability, higher growth, leading to a higher photosynthetic rate, and in the end a positive impact on yield, along with efficient translocation of photosynthates from source to sink. This was in accordance with the findings of [45,49]. Nutrient uptake results are following [23] reported the greatest values of N uptake associated with time and

quantity of N fertilizer application, resulting in the higher nutrient uptake and N-UE in maize crop. Our findings were also consistent with those of these studies. [35] reported that rational fertilisation is the main resource to improve crop yield, nutrient uptake, and assimilation.

Eventually various grades of UPAM respond to the number of applications, the highest results are found with UPAM-2, this is due to the slow-release of N [60]. The increase in P and K content with an increase in N availability might be attributed to stimulating more vegetative growth and increased foraging capacity of roots that absorb more P and K from the soil. These results are also in agreement with the findings obtained by [56,35]. There is a non-significant difference between them due to the high availability of P and K in the soil. This result was consistent with [26] who reported a positive relation between the high availability of P, K with grain and straw P content.

Conclusion

s/cNf are critical for sustainable agriculture, providing a proven solution to the dual challenges of enhancing N-UE and mitigation environmental impacts. Over the past few decades, several s/cNf have been developed and commercialized to mitigate these losses. It is evident from the findings and discussion that UPAM-2 have the potential to improve the SOC, available N and yields of rice and maize crops, and enhancing the N-UE. In this context, UPAM-2 composites represent a promising alternative to conventional N fertilisers. However, despite these advancements, there is still a requirement for more intensive study to understand the effects of these compounds under different agro-climatic conditions.

Funding: The author(s) received no financial support for the research for authorship and article publication.

Clinical trial: No clinical trials were conducted as part of this research.

Declaration statement:

- Ethical approval-not applicable
- Consent to participate-not applicable
- Consent to publish-not applicable

Plant guidelines: The plant materials used in this study, namely rice (Oryza sativa L.) and maize (Zea mays L.), were collected and used in accordance with applicable institutional, and national guidelines. All plant materials were obtained from cultivated sources, and their collection and use

complied with the relevant regulations. No special permissions or licences were required for the collection and use of these plant materials.

Data availability statement: All original data included in the manuscript.

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637 Table. 1 Assessment of various grades of UPAM application on soil available N

Treat-ments	Maize				Rice			
	KH	TS	GF	HR	AT	PI	HE	HR
T1	198±4.58	193±2.89^{f}	190±1.53^{e}	190±3.51^{c}	191±8.74^{d}	189±13.05^{e}	187±3.79^{d}	179±5.57^{d}
T2	219±12.06	237±8.89^{bc}	255±5.69^{b}	229±6.43^{a}	217±12.66^{bc}	233±7.0^{ab}	215±8.96^{a}	204±7.37^{ab}
T3	221±7	252±8.02^{a}	262±11.93^{ab}	234±9.64^{a}	233±7^{a}	232±10.41^{bc}	208±3.06^{abc}	198±2.52^{abc}
T4	211±8.50	227±5.13^{cde}	236±4.0^{cd}	213±4.58^{b}	216±4.73^{bc}	219±7.09^{bcd}	198±11.93^{bcd}	190±5.69^{bcd}
T5	212±11.93	225±5.51^{cde}	233±5.77^{cd}	210±9^{b}	212±6.56^{bc}bc	217±5.77^{cd}	194±12.49^{cd}	187±3.61^{cd}
T6	213±2.89	234±5.86^{bcd}	254±10.69^{b}	231±4.73^{a}	215±8.50^{bc}	226±6.43^{bcd}	214±9.29^{a}	209±11.02^{a}
T7	219±3.61	241±8.08^{ab}	269±4.73^{a}	237±3.51^{a}	221±7.02^{ab}	248±14.29^{a}	212±6.03^{ab}	203±5.86^{ab}
T8	212±6.66	221±2.52^{de}	231±3.51^{cd}	214±7.77^{b}	212±10.21^{bc}	214±6.0^{d}	206±10.12^{abc}	198±14.57^{abc}
T9	213±8.08	219±10.26^{e}	226±12.42^{d}	212±6.66^{b}	205±12.29^{cd}	216±7.77^{cd}	203±14.47^{abc}	196±13.58^{abc}
T10	212±9.87	230±10^{bcde}	240±4.73^{c}	217±5.13^{b}	211±8.89^{bc}	219±10.60^{bcd}	204±6.51^{abc}	195±7.0^{abc}
SEm±	4.793	4.384	4.422	3.850	4.913	5.136	4.301	5.146
CD	14.241	13.027	13.139	11.441	14.598	15.260	12.780	15.289

T1-Absolute control, T2-UPAM-1, T3-UPAM-2, T4-UPAM-3, T5-UPAM-4, T6-UPAM-1, T7-UPAM-2, T8-UPAM-3, T9-UPAM-4, and T10-NCU. Here, T2 to T5 are two split applications; T6 to T10 are three split applications. KH-Knee height, TS-Tasseling stage, GF-Grain filling, HR-Harvest, AT-Active tillering, PI-Panicle initiation, HE-Heading. Mean values within the column with different letters(s) indicate significant differences among the treatments as per DMRT at P=0.05. Columns represent the mean values ± SD.

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639 Table. 3 Assessment of various grades of UPAM on nutrient content in grain and straw of maize and rice

Treatments	Maize						Rice					
	N content (%)		P content (%)		K content (%)		N content (%)		P content (%)		K content (%)	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
T1	1.21^{d}	0.27	0.18	0.043	0.25	0.35	1.13^{b}	0.47^{c}	0.18^{c}	0.06^{b}	0.53	1.10^{c}
T2	1.36^{abc}	0.42	0.21	0.063	0.30	0.49	1.20^{a}	0.61^{a}	0.21^{a}	0.08^{a}	0.61	1.25^{a}
T3	1.42^{a}	0.47	0.23	0.080	0.34	0.52	1.20^{a}	0.62^{a}	0.21^{a}	0.09^{a}	0.62	1.25^{a}
T4	1.28^{cd}	0.34	0.19	0.063	0.30	0.48	1.15^{a}	0.57^{ab}	0.20^{ab}	0.07^{b}	0.58	1.19^{b}
T5	1.26^{cd}	0.32	0.18	0.060	0.28	0.47	1.13^{ab}	0.55^{b}	0.20^{ab}	0.07^{b}	0.56	1.17^{b}
T6	1.34^{abc}	0.39	0.21	0.073	0.29	0.50	1.20^{a}	0.62^{a}	0.21^{a}	0.08^{a}	0.62	1.23^{ab}
T7	1.40^{ab}	0.42	0.21	0.077	0.32	0.53	1.20^{a}	0.62^{a}	0.21^{a}	0.09^{a}	0.61	1.25^{a}
T8	1.33^{abc}	0.37	0.19	0.070	0.30	0.48	1.18^{a}	0.59^{ab}	0.20^{ab}	0.08^{a}	0.58	1.21^{ab}
T9	1.30^{bcd}	0.34	0.19	0.067	0.29	0.47	1.16^{a}	0.58^{ab}	0.20^{ab}	0.08^{a}	0.56	1.19^{b}
T10	1.35^{abc}	0.37	0.20	0.073	0.30	0.48	1.20^{a}	0.60	0.21^{a}	0.08^{a}	0.59	1.22^{ab}
SEm±	0.040	0.039	0.018	0.011	0.020	0.02	0.033	0.021	0.006	0.003	0.028	0.02
CD	15.21	18.206	15.59	17.89	11.76	10.33	4.25	6.23	4.68	7.32	8.33	2.19

T1-Absolute control, T2-UPAM-1, T3-UPAM-2, T4-UPAM-3, T5-UPAM-4, T6-UPAM-1, T7-UPAM-2, T8-UPAM-3, T9-UPAM-4, and T10-NCU. Here, T2 to T5 are two split applications; T6 to T10 are three split applications. NCU-Neem coated urea. N-Nitrogen; P-Phosphorous; K-Potassium. Mean values within the columns with different letter(s) indicate significant differences between treatments as per DMRT at P=0.05.

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641 Table. 2 Pooled yield data (2020-21 and 2021-22) of maize and rice crop

	Maize					Rice				
Treatments	EY (t ha^{-1})	Straw yield (t ha^{-1})	BY (t ha^{-1})	Harvest index (%)	Seed index (grams)	EY (t ha^{-1})	Straw yield (t ha^{-1})	BY (t ha^{-1})	Harvest index (%)	Test weight (grams)
T1	2.94^{e}	3.18^{e}	6.12^{f}	0.48	22.22^{d}	2.02^{e}	1.76^{g}	3.79^{e}	0.53	20.67^{e}
T2	5.53^{ab}	6.34^{abc}	11.89^{abc}	0.47	36.00^{ab}	4.26^{bcd}	5.17^{bcd}	9.43^{bc}	0.48	22^{bcde}
T3	6.12^{a}	7.22^{a}	13.35^{a}	0.46	37.90^{a}	4.87^{b}	6.18^{ab}	11.05^{ab}	0.47	25^{ab}
T4	4.39^{cd}	5.17^{cd}	9.56^{de}	0.46	27.17^{bcd}	3.77^{cd}	4.14^{def}	7.92^{cd}	0.48	21^{e}
T5	4.08^{d}	4.87^{d}	8.95^{e}	0.46	24.22^{cd}	3.55^{d}	3.26^{f}	6.82^{d}	0.52	20.67^{e}
T6	5.19^{abc}	6.02^{abcd}	11.21^{bcd}	0.46	33.45^{abc}	5.05^{b}	5.56^{abc}	10.62^{b}	0.45	25^{abc}
T7	5.75^{ab}	6.88^{ab}	12.64^{ab}	0.46	34.83^{ab}	5.96^{a}	6.68^{a}	12.65^{a}	0.44	25.67^{a}
T8	4.78^{bcd}	5.45^{cd}	10.23^{cde}	0.47	27.27^{bcd}	4.16^{bcd}	4.43^{cdef}	8.59^{cd}	0.48	21.67^{de}
T9	4.54^{cd}	5.15^{cd}	9.69^{de}	0.47	24.02^{cd}	3.72^{cd}	3.81^{ef}	7.53^{d}	0.49	22^{cde}
T10	5.19^{abc}	5.51^{bcd}	10.70^{cde}	0.49	33.97^{ab}	4.49^{bc}	5.03^{bcde}	9.53^{bc}	0.47	24.67^{abcd}
SEm±	3.370	4.838	6.172		3.232	0.363	0.505	0.896		1.044
CV	12.015	15.013	10.241		18.594	12.489	15.804	3.255		7.886

T1-absolute control, T2-UPAM-1, T3-UPAM-2, T4-UPAM-3, T5-UPAM-4, T6-UPAM-1, T7-UPAM-2, T8-UPAM-3, T9-UPAM-4 and T10-NCU. NCU-Neem coated urea. Here T2 to T5, 2-two split applications, T6 to T10, 3-three split application. Mean values within the column with different letters indicate significant differences among the treatments as per DMRT at *P*=0.05.

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