

Original Research Article

Biopolymer Urea Composite for Enhancing Nitrogen Use Efficiency in Coastal Sandy Soils of Kerala, India

ABSTRACT

Aim: To formulate biopolymer urea composites in pellet form and to test their efficacy on the release and leaching of nitrogen in northern coastal sandy soils of Kerala.

Place and duration of study: Department of Agronomy, College of Agriculture, Padannakkad, Kasaragod, Kerala agricultural University, between May 2023 and March 2024.

Methodology: Pellets of biopolymer urea composites (BUCs) were formulated by mixing prilled urea with coconut shell charcoal (C₁), gypsum (C₂), rice husk biochar (C₃), and zeolite (C₄) as coating materials and potato starch (S₁) and tapioca starch (S₂) as binding materials. The experiment was laid out in a Factorial Completely Randomised Design. Castor oil was uniformly sprayed on the composites after formulation. These composites were tested against urea for their nitrogen content and pH. Release behavior of nitrogen in soil and distilled water and leaching behavior in the soil were studied using CRD as the experimental design. The treatments were: T₁: Urea, T₂: BUC 1, T₃: BUC 2, T₄: BUC 3, T₅: BUC 4, T₆: BUC 5, T₇: BUC 6, T₈: BUC 7, T₉: BUC 8 and T₁₀: Control (Soil).

Results: Total nitrogen content was not significantly varied across different treatments, but the increase in pH was significant for the treatment, C₄. Release of nitrogen in distilled water revealed marked differences among the treatments. Urea exhibited significantly elevated nitrogen release on first day compared to other treatments, whereas T₉ and T₄ initially showed substantially lower values, which gradually increased, reaching significantly higher levels by day 30. The soil incubation study demonstrated that urea exhibited significantly higher values of ammoniacal and nitrate nitrogen release on the 7th day, reaching their maximum on 14th day and then decreased gradually till 30 days. All other treatments showed significantly lower release of ammonia into the soil, followed by a gradual increase, reaching a maximum at 90 days. Leaching of ammoniacal and nitrate nitrogen was maximum for T₁ on day 8. Significantly lower nitrate nitrogen leaching values were recorded by T₉ towards the end of the experiment.

Conclusion: T₉ showed initial release of nitrogen at significantly lower rates. Furthermore, it had a significantly higher pH compared to other treatments, rendering its suitability for acidic soil.

Key words: *Biopolymer; urea; nitrogen; coconut shell charcoal; rice husk biochar; gypsum; zeolite*

1. INTRODUCTION

Urea, containing 46% nitrogen (N), is the most widely used nitrogenous fertilizer globally due to its high nutrient concentration and affordability, with India alone consuming 35 million tonnes annually

(FI, 2023). The N use efficiency of urea is between 30 and 50%, with 2-20% loss through volatilization, 15-25% reacting with organic matter in the soil, and 2-10% leaching into water sources (Versino *et al.*, 2019). These N losses lead to reduced yield, economic setbacks and environmental risks. The rapid N release from conventional urea can be addressed through controlled and slow-release mechanisms, which ensure a steady nutrient supply to crops, improving efficiency and promoting healthy crop growth. This is achieved by coating urea with materials that reduce its solubility in water, slowing its release into the soil. These coatings physically form a barrier during dissolution and control the N release rate (Guo *et al.*, 2005; Rehman *et al.*, 2021). Use of nanotechnology for slow release nanofertilizers seems an attractive alternative in changing climate and can also help decrease nitrogen losses through leaching,

emissions and long-term soil absorption (Hossain *et al.*, 2020). Nano clay polymer composite based N fertilizers are one of the possible options to minimize the N losses and enhancing N use efficiency (Rakshitha *et al.*, 2023)

Various processes and procedures have been used to coat fertilisers to make them available to crops for a longer period. The coating materials can be split into two major types: inorganic mineral and organic polymer (Zou *et al.*, 2009). Most of these polymers are not immediately biodegradable following total nutrient release, which provides a new source of soil contamination by causing an undesired accumulation of plastic residues up to 50 kg/ha/year (Trenkel, 1997). Biopolymers are a sustainable alternative to synthetic polymers for encapsulating agrochemicals (Fertahi *et al.*, 2021).

Many coatings have properties between hydrophobic and hydrophilic, allowing water to penetrate and release N gradually while preventing rapid nutrient loss due to their water-repellent nature (Meisen and Choi, 1997; Chen *et al.*, 2010). The characteristics of the gradual release of nitrogen contents can be physically imparted to the urea by coating its granules with various materials which delay its dissolution rate (Mustafa *et al.*, 2022). The physical properties of coating materials play a key role in regulating nutrient release (Babadi *et al.*, 2014).

A fertilizer containing a mixture of biochar and urea had the hydrophobic surfaces of the biochar, which prevented the movement of water in part and delayed the rate of N release (Zhong *et al.*, 2017). When zeolite coated urea was applied to spodosol and alfisol soils, a decrease in NH₃ volatilisation was observed by 47% and 32%, respectively, as compared to urea fertiliser (Ahmad *et al.*, 2021). The dissolving rate of fluidized bed coating with phosphogypsum results revealed that coating reduces the dissolution rate, which is directly connected to N use efficiency, resulting in coated urea with a high moisture holding capacity (Vashishtha *et al.*, 2010). Polyurethane based on castor oil had better wetting characteristics on the urea surface and therefore longer release time (Bortoletto-Santos *et al.*, 2020). Considering these aspects, this experiment was carried out to develop an effective bio-polymer urea composite for northern coastal sandy soils of Kerala. The materials used, methodologies followed, findings gained, and future studies are described here.

2. MATERIALS AND METHODS

2.1 Soil

The soil sample (0-15 cm) for the present study was collected from the experimental field of College of Agriculture, Padannakkad, Kasaragod, Kerala which was sandy belonging to the soil order, Entisol. The soil sample was air dried in shade, ground to pass through a 2 mm sieve and stored in plastic bags at room temperature for incubation study.

2.2 Experimental Design

The experimental design was factorial CRD with two factors: four coating materials (C) and two binding materials (B). The respective treatments were coconut shell charcoal (C₁), gypsum (C₂), rice husk biochar (C₃), zeolite (C₄) as coating materials and potato starch (S₁) and tapioca starch (S₂) as binding materials. The treatment combinations, T₁: C₁S₁, T₂: C₁S₂, T₃: C₂S₁, T₄: C₂S₂, T₅: C₃S₁, T₆: C₃S₂, T₇: C₄S₁, and T₈: C₄S₂, were replicated thrice. The experimental design for nutrient release and leaching studies was CRD.

2.3 Formulation of Biopolymer Urea Composites

Biopolymer urea composites (BUCs) were formulated in pellet form. The coating and binding materials were available from commercial sources. Different ratios by weight of coating and binding materials were tried out as trial and error to find the consistency of the pellets. The ratio of 75% coating material and 25% starch was the best in pelleting and all other ratios exhibited challenges in pelleting due to their higher stickiness, which was resulted in malformed pellets. Hence, this ratio was used for each mixture for coating on prilled urea in 1:1 ratio. After formulation, castor oil was sprayed uniformly on the compound. The physical composition of the formulations is described in Table 1. Total N content and pH of the formulations were analysed using standard procedures.

Table 1. The physical composition of biopolymer urea composites

Biopolymer urea composite (BUC) (1:1 urea: coating mixture)	Coating material (C) (75% w/w coating mixture)	Binding material/ Starch (S) (25% w/w coating mixture)
BUC 1 (C ₁ S ₁)	Coconut shell charcoal	Potato starch
BUC 2 (C ₁ S ₂)	Coconut shell charcoal	Tapioca starch
BUC 3 (C ₂ S ₁)	Gypsum	Potato starch
BUC 4 (C ₂ S ₂)	Gypsum	Tapioca starch
BUC 5 (C ₃ S ₁)	Rice husk biochar	Potato starch
BUC 6 (C ₃ S ₂)	Rice husk biochar	Tapioca starch
BUC 7 (C ₄ S ₁)	Zeolite	Potato starch
BUC 8 (C ₄ S ₂)	Zeolite	Tapioca starch

2.3 Release Behaviour of N from BUCs in Soil

An incubation study was conducted under laboratory conditions for 90 days to test the nutrient release pattern of different BUCs. The experiment was laid out in CRD with ten treatments. The treatments were T₁: Urea (control), T₂ to T₉: the eight urea composites respectively from BUC 1 to BUC 8 and

T₁₀: blank (soil without fertilizer). Three replications were carried out for each treatment. Each pot was filled with 5 kg soil. Urea and its composites were added at the rate of 200 mg N kg⁻¹ of soil per pot at a depth of 10 cm and incubated for 90 days at room temperature and field capacity moisture level. Soil samples were drawn 7, 14, 30, 45, 60, 75, and 90 days after incubation and analysed for the availability of nitrate and ammoniacal nitrogen with the Kjeldahl distillation in the presence of Devarda alloy.

2.4 Release Behavior of N from BUCs in Distilled Water

200 mg of N containing fertilizer samples were accurately weighed, transferred into cotton bags, and placed in plastic bottles containing 250 mL distilled water. The nine treatments for this experiment included T₁: Urea (control) and the eight urea composites (BUC 1 to BUC 8), respectively from T₂ to T₉. Three replications were carried out for each treatment. Total N content (%) in aqueous solution was determined following Kjeldahl method at 1, 7, 10, 14 and 30 days after the addition of fertilisers, from which the N release curve for different composites including conventional prilled urea (control) were obtained.

2.5 Leaching Behaviour of BUCs in Soil Column

The leaching studies were carried out using PVC tubes of 50 cm length and 6 cm diameter and filled with 1200 g soil up to 30 cm height. One end of the column was sealed by a cotton cloth so that all drained water could come out through it. The tube was connected to a flexible plastic bottle of 10 cm length. The ten treatments for this experiment included T₁: Urea (control), the eight urea composites (BUC 1 to BUC 8) respectively from T₂ to T₉ and T₁₀: blank (soil without fertilizer). Three replications were carried out for each treatment. Fertiliser was applied at the rate of 200 mg N kg⁻¹ soil. The columns were covered using a steel cap. The soil columns were fixed vertically on a wall. 100 ml of water was poured into the column periodically and leachate was collected at 8, 15, 22, and 29 days for ammoniacal-N and Nitrate -N estimation.

2.6 Statistical Analysis

The statistical analysis was done as per standard ANOVA for simple and factorial CRD. The values of ammoniacal N (NH₄⁺ - N) and nitrate N (NO₃⁻ - N) of blank treatments were deducted from the corresponding values of BUCs and control treatments for soil column and incubation studies.

3. RESULTS AND DISCUSSION

3.1. Total Nitrogen (%) and pH of BUCs

Neither the coating material, the binding material nor their interaction could make any significant variation in total N content (%) of BUCs as shown in Table 2.

The treatments had significant effect on the pH of urea composites (Table 2) with C₄ recorded the highest pH (9.698), followed by C₃ (8.738), while C₁ (8.182) and C₂ (7.905) showed lower pH values. In contrast, the type of binding material (starch) did not have a significant effect on pH. The interaction of binding material and coating material had no significant effect on the pH. These results imply that

while the binding material has little effect on changing the pH, the coating material is crucial for affecting pH. The pH of rice husk biochar is typically alkaline, ranging from 7.1 to 10.5 while the zeolite aqueous solution is found to be in the alkaline area (10.0–10.5) (Khaleque *et al.*, 2020). Numerous studies have evaluated the pH of gypsum solutions, which frequently range from neutral to slightly acidic.

3.2 Release Pattern of Nitrogen from BUCs in Distilled Water

The data on the release pattern of N from BUCs in distilled water given in Table 3 revealed varying N content (in ppm) across different treatments over time. Treatment T₁ exhibited the highest N release on the first day itself. The treatment T₉ began with 149.33 ppm on day 1 and gradually increased to 636.67 ppm by day 30, demonstrating a steady and consistent release of N over the entire period. This slow and sustained release profile makes T₉ particularly suitable as a slow-release fertilizer. In comparison, treatment T₁, although releasing the highest N content (644.67 ppm) by day 30, showed a faster release pattern, which might not be ideal for long-term nutrient supply. Treatments such as T₂, T₃, and T₄ showed moderate N release, but T₉'s gradual increase in N content from 149.33 ppm to 636.67 ppm over 30 days suggests a more controlled and sustained release. Other treatments like T₅, T₆, T₇, and T₈ displayed varying release patterns, but none matched the slow, steady release observed in T₉ (Fig. 1). For crops with long development periods or those that need a balanced nutrient availability to prevent peaks and deficits, this slow-release profile is perfect for sustaining a steady nutrient supply throughout the period. The slow, constant release seen in T₉ was not matched by other treatments such as T₅, T₆, T₇, or T₈, which showed different release patterns. Mu *et al.* (2024) reported that when compared to normal urea, which releases 50.3% of its nutrients in 15 hours, coated fertilisers have better water retention qualities. Studies have shown that slow-release fertilisers only lose 48% of their weight over 13 days, with nearly full release occurring in the aqueous phase over 25 hours.

3.3 Release Pattern of NH₄⁺-N (mg/kg) from BUCs in Soil

The data presented in Table 4 shows the release pattern of ammoniacal N (NH₄⁺-N) from BUCs in soil over 90 days. Treatment T₁ exhibited the highest NH₄⁺-N content at all time points, starting with 42.34 mg/kg on day 7, peaking at 56.97 mg/kg on day 14, and then gradually decreasing to 12.84 mg/kg by day 90. This suggests a rapid initial release of ammoniacal N followed by a steady decline over time. Treatments T₂, T₆, and T₇ displayed lower initial release, with T₂ starting at 13.57 mg/kg and reaching 36.11 mg/kg by day 90, indicating a slower release pattern compared to T₁. Treatment T₆ started with 16.34 mg/kg on day 7, gradually declining to 36.64 mg/kg by day 90, while T₇ exhibited a similar trend, starting at 16.90 mg/kg and reaching 35.31 mg/kg by day 90. Treatment T₃ and T₄ showed moderate levels of NH₄⁺-N release. T₃ started at 25.52 mg/kg on day 7 and peaked at 44.31 mg/kg by day 90, while T₄ began with 25.97 mg/kg and ended with 45.87 mg/kg, indicating a steady release of N throughout the period of 90 days. Treatments T₅, T₈, and T₉ showed relatively lower initial releases, with T₅ starting at 11.00 mg/kg and T₉ starting at 8.67 mg/kg, both increasing gradually and maintaining a moderate level of NH₄⁺-N over time. Treatment T₈ had a slightly higher initial release,

starting at 12.37 mg/kg, and maintained a steady release, reaching 42.01 mg/kg by day 90. T₁ showed the fastest release with a peak at day 14, while treatments like T₂, T₅, and T₇ had slower release patterns. Treatments T₃, T₄, T₈, and T₉ demonstrated more balanced, sustained release over the 90 days, with T₃ and T₄ showing the highest levels of NH₄⁺-N at the end of the study (Fig. 2). These treatments may be less successful for crops with longer nutrient demands but more appropriate for crops with intermediate nutrient uptake times. Zeolite is a good choice for slow-release fertilisers because of its special qualities, which include porosity and cation exchange capacity, which improve its potential to regulate nitrogen release. Zeolite's porosity and cation exchange ability improve nutrient retention, resulting in longer nutrient release and less leaching (Soltys *et al.*, 2020).

3.4 Release Pattern of NO₃⁻ - N (mg/kg) from BUCs in Soil

The result presented in Table 5 shows the release pattern of nitrate N (NO₃⁻-N) from BUCs in soil over 90 days. Treatment T₁ exhibited the highest initial NO₃⁻-N release, with 19.90 mg/kg on day 7, reaching a peak of 31.74 mg/kg on day 14, before gradually decreasing to 3.80 mg/kg by day 90. This indicates a rapid release of NO₃⁻-N at the beginning, followed by a steady decline over time. Such a release profile may result in early nutrient surpluses, followed by deficiencies in later growth stages, making it less suitable for crops with extended nutrient requirements. Treatments T₂, T₃, and T₅ demonstrated relatively consistent release patterns, with T₂ starting at 9.33 mg/kg on day 7, peaking at 34.67 mg/kg on day 45, and then decreasing to 26.77 mg/kg by day 90. T₃ followed a similar trend, starting at 2.73 mg/kg on day 7, peaking at 41.07 mg/kg on day 75, and ending at 36.34 mg/kg on day 90. T₅ showed a moderate release pattern, with 7.73 mg/kg on day 7, peaking at 34.90 mg/kg on day 75, and ending at 34.97 mg/kg by day 90. Treatment T₄ showed the lowest initial release at 0.97 mg/kg on day 7, with a peak at 23.43 mg/kg on day 45, and a decrease to 31.24 mg/kg by day 90, indicating a slower and more steady release of NO₃⁻-N. Treatments T₆, T₇, and T₈ had varied release profiles, with T₆ starting at 11.50 mg/kg and increasing to 39.00 mg/kg by day 75, and T₇ starting low at 1.67 mg/kg, peaking at 32.47 mg/kg on day 75. Treatment T₈ showed a relatively moderate release, starting at 10.10 mg/kg on day 7 and reaching 31.74 mg/kg by day 90. Treatment T₉ showed a low initial release of 1.10 mg/kg on day 7, peaking at 39.14 mg/kg on day 75, and ending at 33.84 mg/kg on day 90 (Fig. 3). When compared to uncoated urea, zeolite-coated urea with acrylic polymer binder displayed a N release control of 54.7% over 30 days, notably lowering N leaching by 65% (Dubey and Mailapalli, 2019).

3.5 Leaching Pattern of NH₄⁺ - N (mg/L) from BUCs in Soil Column

The leaching pattern of ammoniacal N (NH₄⁺-N) from BUCs in the soil column varied across treatments and time (Table 6). On day 8, T₁ showed the highest leaching (26.71 mg/L), indicating rapid release, while T₈ had the lowest (1.34 mg/L), suggesting strong retention. By day 15, T₂, T₃, T₅, and T₇ exhibited peak leaching values between 28.27 and 29.59 mg/L, whereas T₁ and T₄ showed more controlled release. On day 22, T₉ recorded the highest leaching (33.04 mg/L), reflecting its peak release phase, while T₁ and T₅ had the lowest leaching (14.21 and 14.82 mg/L, respectively). By day 29, T₉ maintained the highest leaching (28.93 mg/L), indicating sustained release, while T₁ exhibited

minimal loss (2.77 mg/L). Overall, T₉ demonstrated an effective slow-release profile, balancing early retention with sustained nutrient availability, making it the most promising treatment for controlled N release (Fig. 4). The delayed peak in N leaching indicates the effectiveness of the coating in regulating the release rate, reducing the risk of early nutrient losses through leaching. According to the study, BUCs exhibit a noticeably reduced early N release and a progressive nutritional release when compared to urea. Guo *et al.* (2005) and Rehman *et al.* (2021) obtained similar results with superabsorbent and slow-release urea formaldehyde and neem coated urea respectively.

3.6 Leaching Pattern of NO₃⁻ - N (mg/L) from BUCs in Soil Column

The leaching pattern of nitrate N (NO₃⁻-N) from BUCs in the soil column exhibited significant variation across the treatments and sampling days (Table 7). On day 8, T₁ showed the highest leaching (4.40 mg/L), indicating faster nitrate release, while T₉ demonstrated the lowest (0.63 mg/L), reflecting effective nitrate retention. By day 15, T₁ continued to have the highest leaching (4.18 mg/L), whereas T₂, T₃, and T₉ displayed minimal values (0.09–0.43 mg/L). On day 22, T₂ peaked at 7.16 mg/L, highlighting a delayed release, while T₉ maintained a controlled release at 2.86 mg/L. By day 29, T₇ recorded the highest leaching (6.71 mg/L), indicating a prolonged release phase, whereas T₉ remained the most controlled with only 2.61 mg/L. Overall, T₉ consistently exhibited the lowest nitrate leaching across all time points, making it the most effective treatment for minimizing nitrate loss through leaching. The low leaching levels highlight the potential of T₉ to mitigate environmental risks such as groundwater contamination and eutrophication. In contrast, urea treatment (T₁) showed relatively high nitrate N leaching levels initially, peaking at 4.40 mg/L on day 8 and maintaining higher levels through day 29 (Fig. 5). This rapid release may lead to significant nitrogen losses early in the crop cycle, reducing long-term nutrient availability and increasing environmental risks. In a soil column leaching investigation, urea combined with clinoptilolite zeolite reduces leaching losses and exhibits better control over NH₄⁺ and nitrate (NO₃⁻) release than normal urea (Omar *et al.*, 2015).

4. CONCLUSION

To improve crop yield and lessen the associated nitrogen losses and their effects on the environment, coating of urea with organic and synthetic materials is seen to be a crucial strategy. Even though the synthetic polymers can contribute well for the controlled release of N from urea, it is questionable whether any of these materials is environmentally friendly. Four different organic coating materials and two different natural starch polymers were mixed with urea to test the efficacy of the formulations (Fig. 6) on release and leaching of nitrogen. Statistical analysis of data proved that the treatment, T₉ (Zeolite as the coating material and Tapioca starch as the binding material) demonstrated an initial release of significantly lower values, gradually attaining a maximum in both distilled water and soil. Furthermore, it had a significantly higher pH compared to other treatments, rendering its suitability in coastal saline acid soil of Kerala.

COMPETING INTERESTS

We, the authors declare that no competing interests exist.

AUTHORS' CONTRIBUTIONS:

Mohammed Midlaj, C. P.: Conduct of experiment, data collection, analysis and preparation of manuscript

Jinsy, V. S.: Idea conception, implementation of the research

Sumesh, K. V., N. Manikandan, Sajitha Rani T. and Nideesh P. : Reviewing and editing of Manuscript

Table 2. Effect of treatments and their interaction on total nitrogen content (%) and pH of biopolymer urea composites

Treatments	N%	pH
Coating material (C)		
C1	14.155	8.182 ^c
C2	14.123	7.905 ^d
C3	14.307	8.738 ^b
C4	14.417	9.698 ^a
SEm (\pm)	0.40	0.04
CD ($P=0.05$)	NS	0.117
Binding material/ Starch (S)		
S1	14.248	8.653
S2	14.253	8.608
SEm (\pm)	0.28	0.03
CD ($P=0.05$)	NS	NS
Interaction (C x S)		
C1S1	14.310	8.183
C1S2	14.000	8.180
C2S1	14.100	7.957
C2S2	14.147	7.853
C3S1	14.147	8.760
C3S2	14.467	8.717
C4S1	14.433	9.713

C4S2	14.400	9.68
SEm (\pm)	0.56	0.05
CD ($P=0.05$)	NS	NS

Table 3. Effect of treatments on release pattern of N from BUCs in distilled water (total N (ppm) in aqueous solution)

Treatment	Day 1	Day 7	Day 10	Day 14	Day 30
T1 (Urea)	492.667 ^a	565.67 ^a	614.67 ^a	630.67 ^a	644.67 ^a
T2 (BUC 1)	204.00 ^c	276.33 ^c	376.33 ^{bcd}	460.33 ^{bcd}	582.00 ^{abc}
T3 (BUC 2)	156.33 ^{cd}	201.00 ^d	336.67 ^{cd}	420.00 ^{cde}	487.00 ^d
T4 (BUC 3)	179.33 ^{cd}	208.33 ^d	294.00 ^d	364.00 ^e	582.00 ^{abc}
T5 (BUC 4)	135.33 ^d	176.00 ^d	349.67 ^{bcd}	508.67 ^b	538.67 ^{bcd}
T6 (BUC 5)	328.33 ^b	391.00 ^b	411.67 ^{bc}	481.67 ^{bcd}	518.00 ^{cd}
T7 (BUC 6)	374.67 ^b	406.00 ^b	424.33 ^b	494.33 ^b	601.67 ^{ab}
T8 (BUC 7)	195.67 ^c	224.00 ^{cd}	327.00 ^d	487.67 ^{bc}	599.00 ^{ab}
T9 (BUC 8)	149.33 ^{cd}	176.00 ^d	318.33 ^d	416.33 ^{de}	636.67 ^a
SEm (\pm)	19.25	22.73	28.28	22.88	25.99
CD ($P=0.05$)	57.196	67.545	84.036	67.966	77.213

Table 4. Effect of treatments on release pattern of NH₄⁺ - N (mg/kg) from BUCs in soil

Treatment	Day 7	Day 14	Day 30	Day 45	Day 60	Day 75	Day 90
T1 (Urea)	42.3374 ^a	56.97 ^a	45.10 ^a	33.90 ^a	32.80 ^{ab}	23.71 ^c	12.84 ^d
T2 (BUC 1)	13.57 ^{cde}	16.30 ^b	11.27 ^{cde}	20.77 ^d	35.23 ^a	33.67 ^b	36.11 ^c
T3 (BUC 2)	25.517 ^b	16.18 ^b	12.47 ^{cde}	23.34 ^{bcd}	28.70 ^{cd}	41.24 ^a	44.31 ^a
T4 (BUC 3)	25.97 ^b	14.13 ^b	13.07 ^{cd}	23.34 ^{bcd}	28.97 ^{cd}	42.51 ^a	45.87 ^a

T5 (BUC 4)	11.00 ^{de}	15.17 ^b	10.47 ^{cde}	23.40 ^{bcd}	27.30 ^{de}	41.27 ^a	42.71 ^a
T6 (BUC 5)	16.34 ^{cd}	8.23 ^c	8.93 ^e	21.94 ^{cd}	24.10 ^e	33.14 ^b	36.64 ^{bc}
T7 (BUC 6)	16.90 ^c	4.77 ^d	9.07 ^{de}	21.34 ^{cd}	26.47 ^{de}	33.34 ^b	35.31 ^c
T8 (BUC 7)	12.37 ^{cde}	7.80 ^c	17.60 ^b	27.27 ^b	31.33 ^{bc}	41.64 ^a	42.01 ^a
T9 (BUC 8)	8.67 ^e	8.37 ^c	13.97 ^{bc}	25.34 ^{bc}	31.67 ^{bc}	41.81 ^a	41.94 ^{ab}
SEm (±)	1.83	0.84	1.36	1.48	1.18	1.63	1.79
CD (P=0.05)	5.427	2.506	4.054	4.404	3.513	4.842	5.313

Table 5. Effect of treatments on release pattern of NO₃⁻ - N (mg/kg) from BUCs in soil

Treatment	Day 7	Day 14	Day 30	Day 45	Day 60	Day 75	Day 90
T1 (Urea)	19.90 ^a	31.74 ^a	18.57 ^a	16.50 ^{cd}	10.94 ^c	7.30 ^e	3.80 ^e
T2 (BUC 1)	9.33 ^{bc}	18.54 ^b	18.51 ^a	34.67 ^a	21.84 ^b	31.70 ^{cd}	26.77 ^d
T3 (BUC 2)	2.73 ^d	13.41 ^c	13.91 ^b	24.53 ^b	22.34 ^b	41.07 ^a	36.34 ^{ab}
T4 (BUC 3)	0.97 ^d	8.24 ^d	12.74 ^b	23.43 ^b	19.27 ^b	29.34 ^d	31.24 ^c
T5 (BUC 4)	7.73 ^c	11.24 ^{cd}	14.64 ^b	25.70 ^b	21.30 ^b	34.90 ^{bc}	34.97 ^{abc}
T6 (BUC 5)	11.50 ^b	0.47 ^e	14.07 ^b	23.63 ^b	29.27 ^a	39.00 ^{ab}	38.94 ^a

Treatment	Day 8	Day 15	Day 22	Day 29
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T7 (BUC 6)	1.67 ^d	0.47 ^e	6.07 ^c	18.80 ^c	21.90 ^b	32.47 ^{cd}	34.17 ^{bc}
T8 (BUC 7)	10.10 ^{bc}	7.61 ^d	6.34 ^c	14.50 ^d	18.00 ^b	30.57 ^{cd}	31.74 ^c
T9 (BUC 8)	1.10 ^d	7.77 ^d	11.67 ^b	23.40 ^b	29.14 ^a	39.14 ^{ab}	33.84 ^{bc}
SEm (±)	1.20	1.56	1.08	1.36	1.65	1.57	1.37
CD (P=0.05)	3.557	4.621	3.195	4.031	4.897	4.664	4.059

T1 (Urea)	26.71 ^a	12.34 ^d	14.21 ^e	2.77 ^e
T2 (BUC 1)	9.58 ^b	28.27 ^a	20.84 ^c	25.82 ^{abc}
T3 (BUC 2)	2.51 ^d	28.64 ^a	24.87 ^b	22.33 ^{cd}
T4 (BUC 3)	5.14 ^c	13.00 ^d	24.91 ^b	21.93 ^d
T5 (BUC 4)	6.04 ^c	29.50 ^a	14.82 ^e	26.43 ^{ab}
T6 (BUC 5)	5.41 ^c	23.17 ^b	19.93 ^{cd}	21.37 ^d
T7 (BUC 6)	2.26 ^{de}	29.59 ^a	17.34 ^{de}	24.90 ^{bcd}
T8 (BUC 7)	1.34 ^e	16.47 ^c	16.74 ^e	24.13 ^{bcd}
T9 (BUC 8)	2.13 ^{de}	21.17 ^b	33.04 ^a	28.93 ^a
SEm (\pm)	0.37	0.99	1.07	1.23
CD ($P=0.05$)	1.086	2.95	3.178	3.654

Table 6. Effect of treatments on leaching pattern of NH_4^+ - N (mg/L) from BUCs in soil column

Treatment	Day 8	Day 15	Day 22	Day 29
T1 (Urea)	4.40 ^a	4.18 ^a	4.19 ^{bc}	2.71 ^c
T2 (BUC 1)	3.70 ^{ab}	0.09 ^e	7.16 ^a	5.57 ^{ab}
T3 (BUC 2)	2.63 ^c	0.32 ^e	3.99 ^{bc}	5.00 ^{ab}
T4 (BUC 3)	1.77 ^d	3.02 ^b	4.94 ^b	4.33 ^{bc}
T5 (BUC 4)	3.40 ^b	0.95 ^{cd}	4.06 ^{bc}	3.89 ^{bc}
T6 (BUC 5)	3.67 ^{ab}	1.48 ^c	2.13 ^d	4.52 ^{bc}
T7 (BUC 6)	1.47 ^d	0.29 ^e	3.39 ^{bcd}	6.71 ^a
T8 (BUC 7)	1.50 ^d	1.12 ^c	3.61 ^{bcd}	5.51 ^{ab}
T9 (BUC 8)	0.63 ^e	0.43 ^{de}	2.86 ^{cd}	2.61 ^c
SEm (\pm)	0.26	0.19	0.55	0.73
CD ($P=0.05$)	0.757	0.574	1.63	2.165

Table 7. Effect of treatments on leaching pattern of NO_3^- - N (mg/L) from BUCs in soil column

DER PEER REVIEW

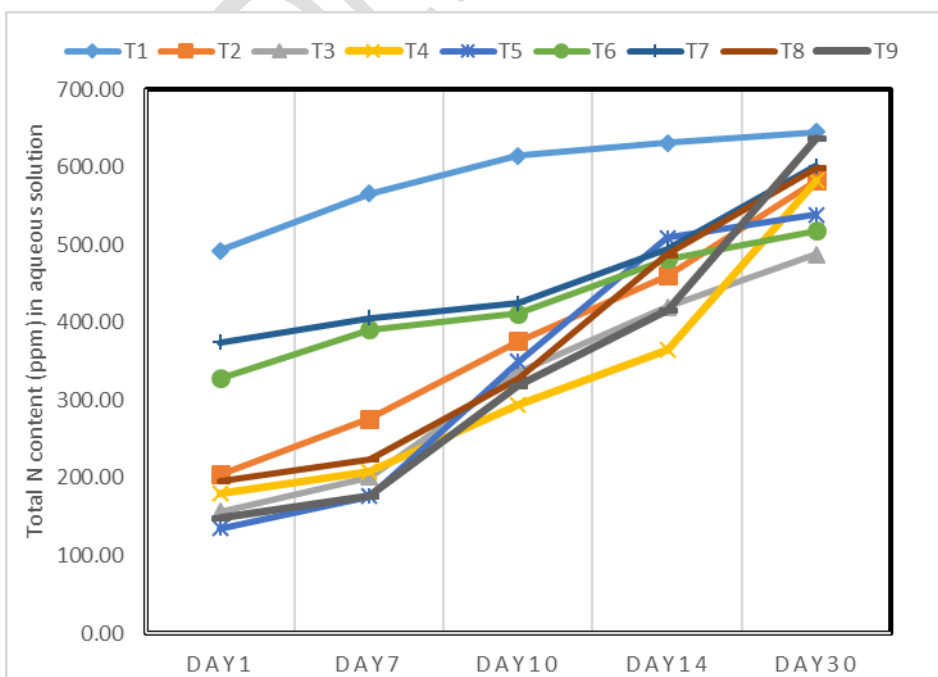


Fig. 1 Total N content (ppm) in aqueous solution

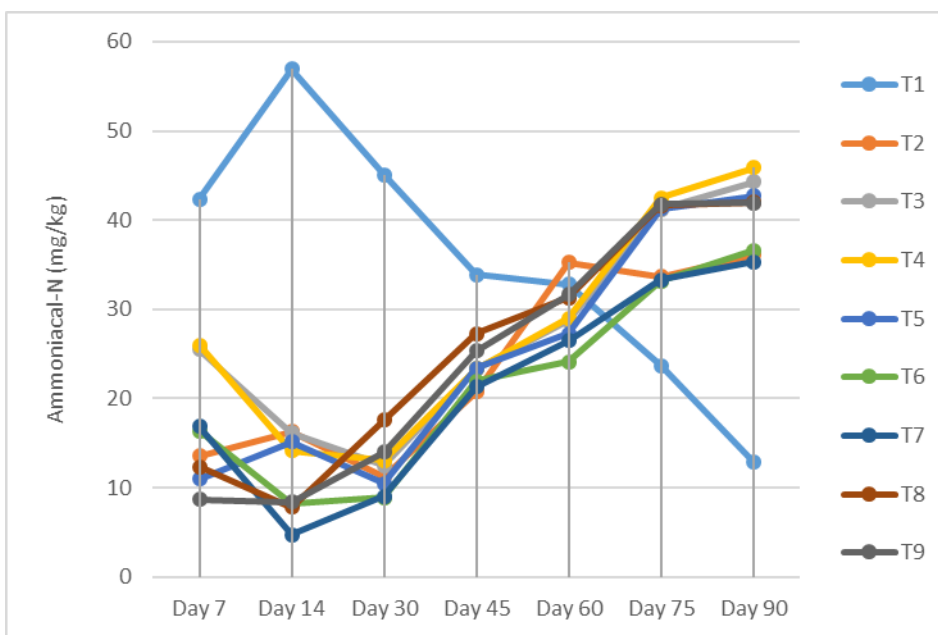


Fig. 2 Release pattern of NH_4^+ - N (mg/kg) from BUCs in soil

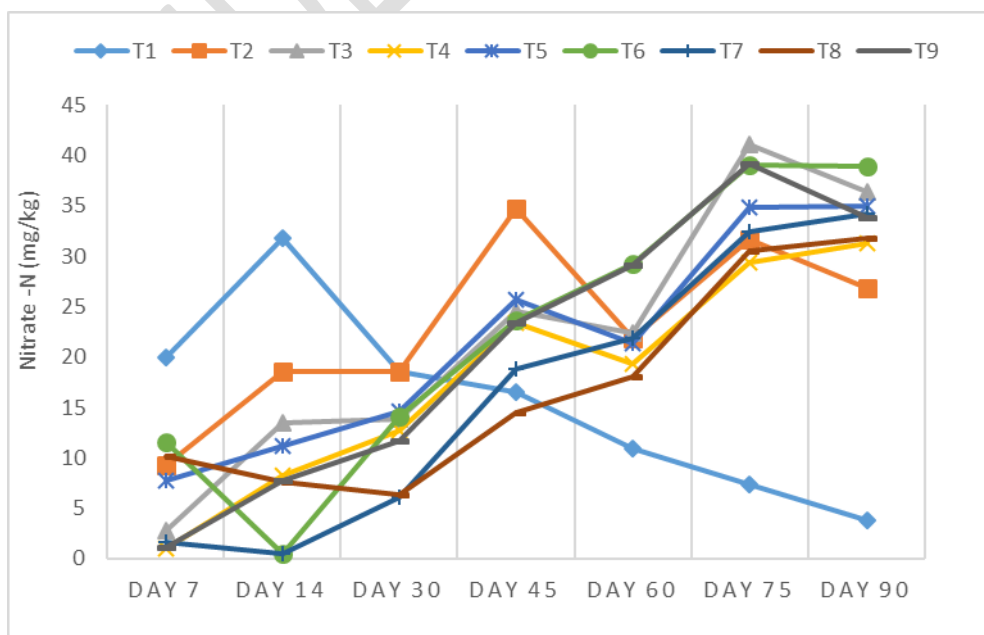


Fig. 3 Release pattern of $\text{NO}_3^- - \text{N}$ from BUCs in soil

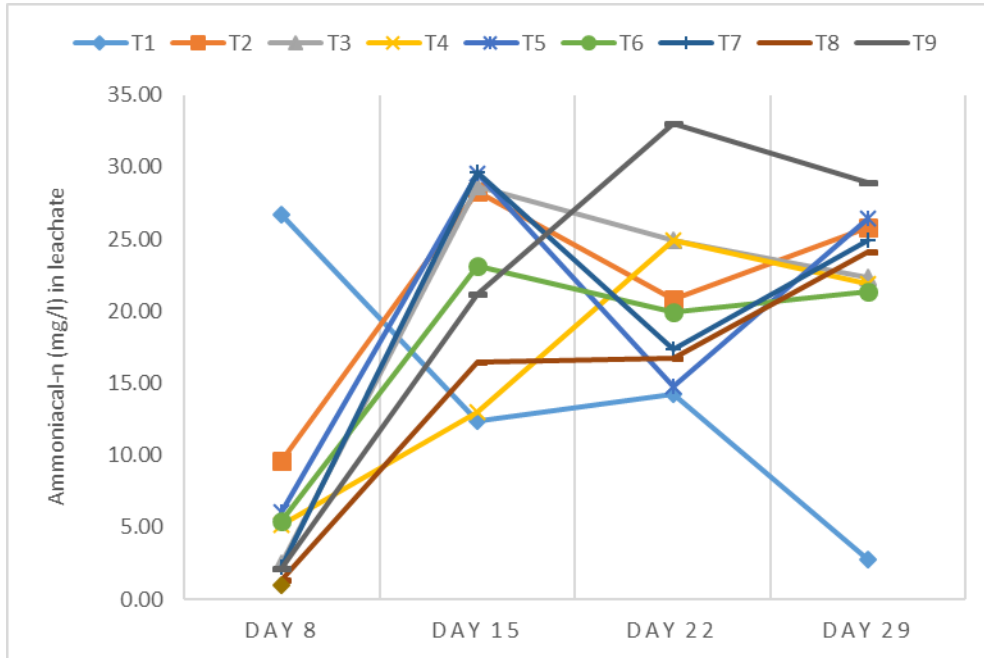


Fig. 4 Leaching pattern of $\text{NH}_4^+ - \text{N}$ (mg/L) from BUCs in soil column

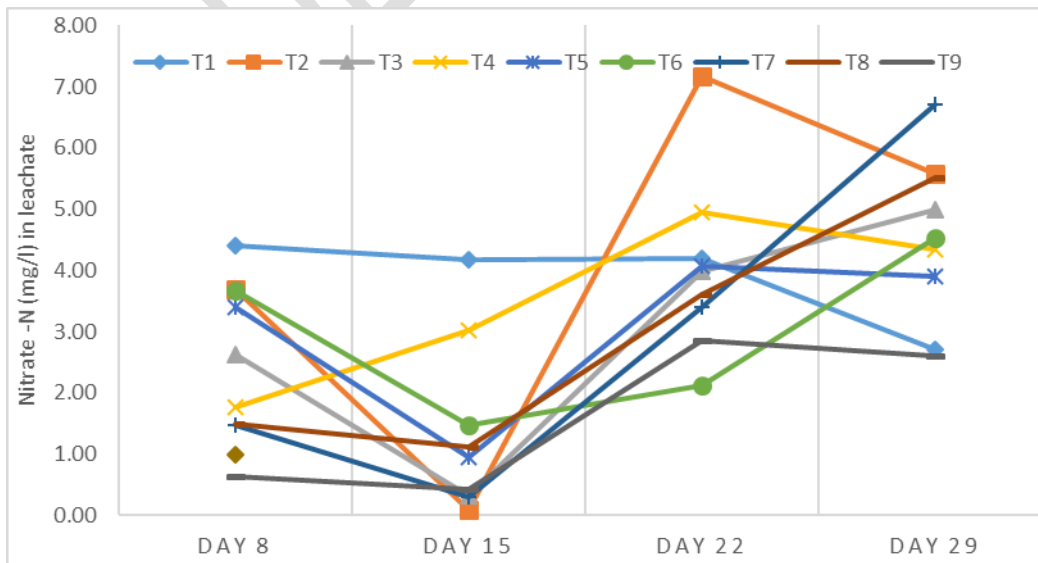


Fig. 5 Leaching pattern of NO_3^- - N (mg/L) from BUCs in soil column



Fig. 6 Biopolymer urea composites

Disclaimer (Artificial intelligence)

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

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