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NPK Release Patterns of Coated and Uncoated Slow-Release Fertilizers in Various Forms

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ABSTRACT

Excessive and inefficient use of nitrogen (N), phosphorus (P), and potassium (K) fertilizers remains a major issue in agricultural systems, often leading to low nutrient use efficiency and environmental losses. Slow-release fertilizers in different forms, such as tablets and granules, combined with coating technology, represent a potential strategy to regulate nutrient availability and improve release efficiency. This study aimed to evaluate the release patterns of N (including NH_4^+, NO_3^-, and total N), P, and K from coated and uncoated slow-release fertilizers in tablet and granule forms. The experiment, conducted at the Laboratory of Soil Chemistry and Plant Nutrition, Universitas Padjadjaran, used a Completely Randomized Design (CRD) with four treatments and five replications. The treatments included coated tablet fertilizer (A), uncoated tablet fertilizer (B), coated granule fertilizer (C), and uncoated granule fertilizer (D), incubated for 10 weeks under laboratory conditions. The key implication of these results is that uncoated tablet fertilizer (B) delivered the most balanced nutrient release, with total N, P, and K releases of 80.07%, 70.87%, and 88.22%, respectively, suggesting it may offer a practical solution for improving nutrient efficiency while minimizing losses. In contrast, coated tablet fertilizer (A) showed the slowest release, while uncoated granule fertilizer (D) had the fastest. These findings highlight that manipulating fertilizer form and coating application play a decisive role in optimizing nutrient release kinetics and improving synchronization in slow-release fertilizer systems, offering a targeted approach to address agricultural nutrient management challenges.

Keywords: granule fertilizer, macronutrients, nutrient release, slow-release fertilizer, tablet fertilizer

INTRODUCTION

Excessive application of nitrogen (N), phosphorus (P), and potassium (K) fertilizers beyond recommended rates remains a common practice among farmers and may decrease fertilizer efficiency while negatively affecting environmental sustainability. Siallagan *et al.* (2014) reported that many farmers still apply fertilizers in excessive amounts beyond the recommended dosage. Nitrogen is an essential macronutrient required for plant growth and development, playing an important role in the formation of chlorophyll, proteins, protoplasm, and nucleic acids (Wani *et al.* 2022). However, nitrogen in soil is highly susceptible to losses through leaching and volatilization. Similarly, phosphorus is also an essential nutrient that frequently limits plant growth and productivity. In soil, phosphorus availability is generally low because P is easily fixed by Al and Fe in acidic soils or by Ca in alkaline soils, resulting in the formation of insoluble compounds (Hardjowigeno 2015). Potassium is another essential macronutrient that plays a critical role in enzyme activation, osmotic regulation, and stomatal control, thereby influencing water use efficiency and plant stress tolerance (Imtiaz *et al.* 2023). However, K is also prone to losses through leaching, especially in sandy or low cation exchange capacity (CEC) soils (Yang *et al.* 2022). These challenges highlight the need for fertilizer technologies capable of gradually releasing nutrients according to plant requirements.

Slow-release fertilizer (SRF) technology has been increasingly developed to improve nutrient use efficiency and reduce nutrient losses in agricultural systems. Slow-release fertilizers are designed to release nutrients gradually over a certain period, matching the nutrient uptake pattern of plants (Hamzah *et al.* 2019). Several methods have been developed to produce SRF, such as increasing fertilizer particle size and applying coating materials to regulate nutrient release (Agency for the Assessment and Application of Technology 2010). Compared with conventional fertilizers, SRF provides nutrients more consistently and continuously over a longer period, thereby improving fertilization efficiency and reducing fertilizer application frequency (Purba *et al.* 2018). Currently, NPK slow-release fertilizers are commercially available in several forms, particularly tablets and granules. Differences in fertilizer form may influence nutrient release characteristics; for example, tablet fertilizers generally have a more compact structure and smaller surface area than granular fertilizers. In addition,

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coating treatments can further regulate nutrient dissolution and release rates. According to the Soil Research Institute (2018), nutrient release characteristics of slow-release fertilizers can be evaluated using soil incubation methods.

Previous studies have primarily focused on coating materials, nutrient efficiency, and the general performance of slow-release fertilizers (Almutari 2023). However, limited information is available on the combined effects of fertilizer form and coating treatment on the release patterns of N, P, and K under incubation conditions. Variations in fertilizer form and coating may influence nutrient release through differences in surface area and water–fertilizer interactions. Therefore, comparative studies on coated and uncoated slow-release fertilizers in tablet and granule forms are still required. This study evaluates the release patterns of N, P, and K from coated and uncoated NPK slow-release fertilizers during soil incubation to clarify the role of fertilizer form and coating in regulating nutrient release behavior.

METHODS

This study was conducted in 2024 at the Laboratory of Soil Chemistry and Plant Nutrition, Department of Soil Science and Land Resources, Faculty of Agriculture, Universitas Padjadjaran, West Java, Indonesia. It evaluated the nutrient release patterns of NPK slow-release fertilizers in different forms and coating treatments using paddy soil under flooded incubation conditions.

The fertilizers used in this study included four treatments: coated tablet fertilizer (A), uncoated tablet fertilizer (B), coated granule fertilizer (C), and uncoated granule fertilizer (D). The coated fertilizers were prepared using polyurethane coating with a thickness of 3–4%. Polyurethane was chosen for its hydrophobic properties, low permeability, and ability to regulate nutrient diffusion and release rates in slow-release systems (Bortoletto-Santos *et al.* 2020). The NPK slow-release fertilizer contained 15% N, 15% P_2O_5, and 15% K_2O. Each treatment received 9 g of fertilizer applied to 455 g of flooded paddy soil (Figure 1).

Before incubation, the initial soil characteristics, pH (6.9), organic C content (1.2%, low category), and silty clay loam texture were analyzed. Incubation lasted 10 weeks at 26°C under flooded conditions (about 1 cm water depth). The experiment used a Completely Randomized Design (CRD) with four treatments and five replications, resulting in 20 experimental units (Gomez & Gomez, 1984). Soil samples were collected every two weeks for nutrient release analysis. Soil pH was measured at each sampling using a pH meter. Nitrogen was analyzed in three forms, namely ammonium (NH_4^+), nitrate (NO_3^-), and total nitrogen (N-total) using the Kjeldahl method. Available P was analyzed with the Olsen method. Exchangeable K was measured using Atomic Absorption Spectrophotometry (AAS). Nutrient release percentage was calculated using: % NPK release = (Nutrient released from soil/initial nutrient in fertilizer) × 100. The obtained data were analyzed using analysis of variance (ANOVA) based on the Completely Randomized Design. When significant differences were observed, the data were further analyzed using Duncan's Multiple Range Test (DMRT) at a 5% significance level.

RESULTS AND DISCUSSION

Nitrogen Release Dynamics under Different Fertilizer Forms and Coating Treatments

Nitrogen release from the four fertilizer treatments was characterized by the release patterns of ammonium (NH_4^+), nitrate (NO_3^-), and total nitrogen over the 10-week incubation period. Overall, nitrogen transformation showed a gradual shift from ammonium dominance in the early stage toward increasing nitrate

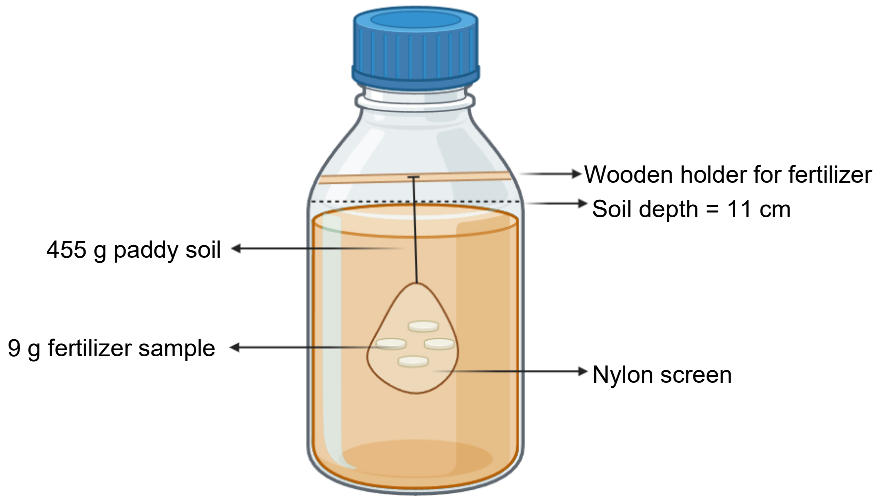

Figure 1 Illustration of slow-release tablet fertilizer incubation method in soil medium.

formation, reflecting coupled hydrolysis and nitrification processes under flooded soil conditions.

Ammonium (NH_4^+) release was highest during the early incubation phase, particularly in the second week, ranging from 6.79% to 14.20%, followed by a sharp decline to 1.00%–3.71% by the third week (Figure 2). This behavior reflects rapid hydrolysis of urea-based nitrogen compounds followed by progressive nitrification. These results are consistent with Lestari (2020), who reported a similar decline in ammonium release with increasing incubation time under soil conditions.

Nitrate (NO_3^-) release showed an opposite trend, increasing from 1.8%–3.2% in the second week to 12.1%–15.4% in later stages (Figure 3), indicating active nitrification of ammonium. Coated fertilizers (A: coated tablet fertilizer and C: coated granule fertilizer) exhibited a more gradual nitrate release than uncoated fertilizers (B: uncoated tablet fertilizer and D: uncoated granule fertilizer). This suggests that the polyurethane coating acted as a diffusion barrier that restricted water penetration and slowed nitrogen transformation kinetics, thereby regulating nutrient release behavior (Ghosh *et al.* 2023). In contrast, uncoated formulations (B: uncoated tablet fertilizer and D: uncoated granule fertilizer) showed faster nitrate release due to direct exposure to soil water, which enhanced dissolution and nitrogen transformation. Differences between tablet and granule forms also influenced release behavior. Granular fertilizers (C and D) exhibited slightly faster nitrogen release than tablet forms (A and B), particularly in the early incubation stage, due to their higher surface area and greater soil contact, which accelerated dissolution and diffusion processes (Lakhsani *et al.* 2023).

During the 10-week incubation period, all treatments showed a gradual increase in cumulative nitrogen (N-total) release over time, as illustrated in Figure 4. Nevertheless, distinct differences were observed among fertilizer formulations, particularly between coated and uncoated fertilizers as well as between tablet and granule forms. The cumulative nitrogen release after 10 weeks is presented in Table 1.

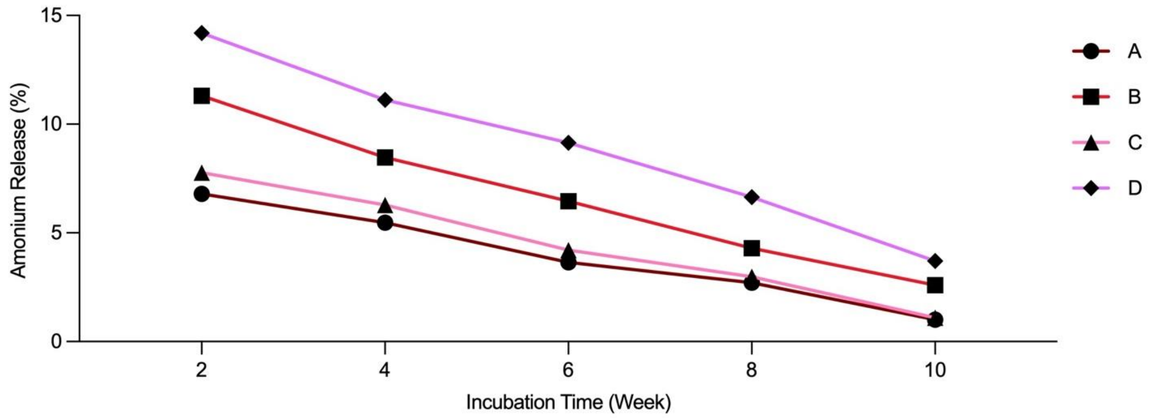

Figure 2 Graph of NH_4^+ (%) release from the four fertilizer treatments during 10 weeks incubation time. (A) = coating tablet fertilizer; (B) = tablet fertilizer without coating; (C) = granul coating fertilizer; (D) = granule fertilizer without coating.

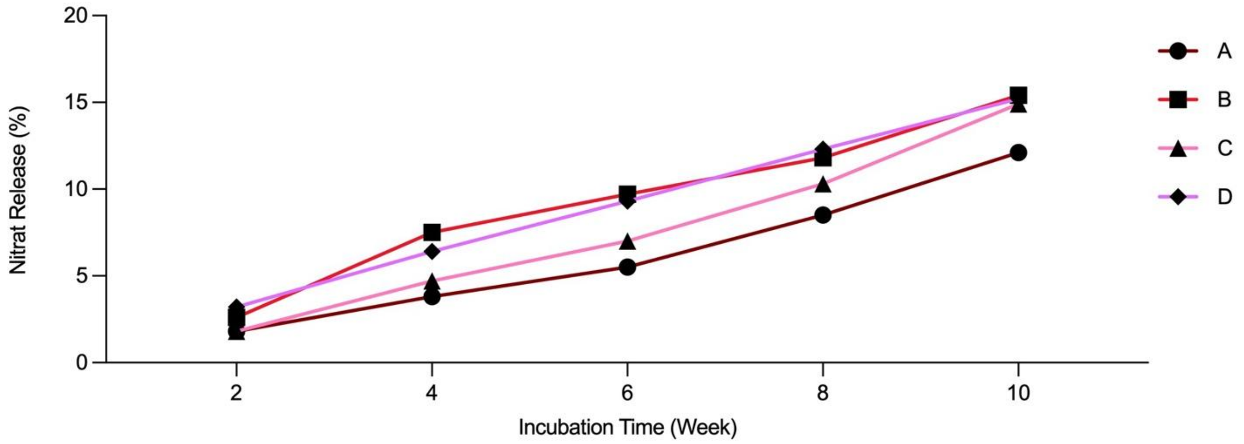

Figure 3 Trend of NO_3^- (%) release from the four fertilizer treatments during the course of a 10-week incubation. (A) = coating tablet fertilizer; (B) = tablet fertilizer without coating; (C) = granul coating fertilizer; (D) = granule fertilizer without coating.

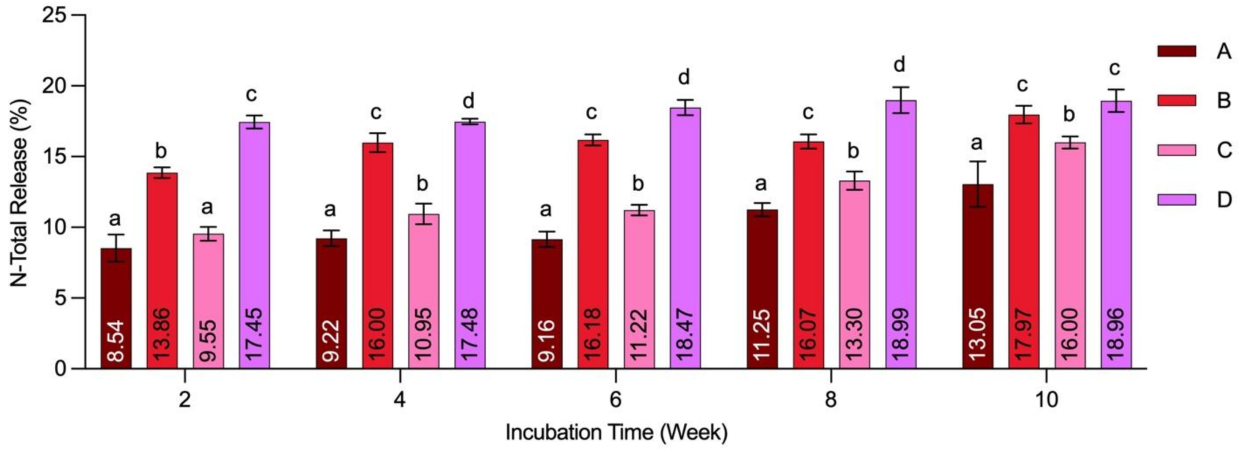

Figure 4 Graph of N-total release (%) of the four fertilizer treatments during 10 weeks of incubation time. (A) = coating tablet fertilizer; (B) = tablet fertilizer without coating; (C) = granul coating fertilizer; (D) = granule fertilizer without coating.

Table 1 Cumulative release percentage of total nitrogen (total-N), phosphorus (P), and potassium (K) during 10 weeks of incubation

Treatments	Total percentage of total-nitrogen released over 10 weeks incubation	Total percentage of phosprous released over 10 weeks incubation	Total percentage of potassium released over 10 weeks incubation
		(%)	
Coated tablet fertilizer	51.21	46.53	58.07
Uncoated tablet fertilizer	80.07	70.87	88.22
Coated granule fertilizer	61.01	55.77	69.07
Uncoated granule fertilizer	91.30	90.76	98.72

Treatment D (uncoated granule fertilizer) exhibited the highest nitrogen release, reaching 91.30%, followed by Treatment B (uncoated tablet fertilizer) with 80.07%. The rapid nitrogen release observed in both uncoated formulations indicates the absence of a physical barrier, which allowed faster water penetration and increased nitrogen dissolution and mineralization into the surrounding environment. In contrast, treatment A (coated tablet fertilizer) showed the lowest cumulative nitrogen release at 51.21%, followed by Treatment C (coated granule fertilizer) at 61.01%. These lower release values indicate that the polyurethane coating acted as an effective controlled-release barrier by limiting water ingress and reducing nitrogen diffusion, resulting in a slower and more sustained nutrient release pattern.

The physical form of the fertilizer also influenced nitrogen release behavior. Under uncoated conditions, granule-based fertilizers generally released nitrogen more rapidly than tablet forms, likely due to their larger surface area, which increased contact with water and microbial dynamics and consequently accelerated dissolution processes (Jariwala *et al.* 2022). In addition, the hydrophobic and low-permeability characteristics of polyurethane effectively reduced diffusion rates and delayed nitrogen loss (Ginting 2011).

Based on the cumulative nitrogen release results, Treatment B (uncoated tablet fertilizer) demonstrated the most favorable release performance among all formulations. According to the criteria proposed by Trenkel (2010), a slow-release fertilizer should release approximately 75% of its nutrients at the specified release time. Treatment B released 80.07% nitrogen after 10 weeks, showing a balanced and sustained nutrient supply throughout the incubation period. In comparison, treatments A (coated tablet fertilizer) and C (coated granule fertilizer) released less than 75% nitrogen, suggesting that the coating restricted nutrient diffusion excessively and limited nutrient availability during incubation. Meanwhile, Treatment D (uncoated granule fertilizer) released nitrogen too rapidly, reaching 91.30%, which may lead to faster nutrient depletion and increased nitrogen loss. Therefore, Treatment B provided the most balanced release pattern by maintaining sufficient nitrogen availability without causing excessively rapid nutrient release.

Under flooded soil conditions, limited oxygen availability affected nitrogen transformation by promoting ammonium persistence and suppressing nitrification during the early incubation stage (Yang *et al.* 2024). As incubation progressed, microbial oxidation gradually converted NH_4^+ into NO_3^-, causing an increase in nitrate concentration over time (Hartono *et al.* 2021). Overall, nitrogen release behavior was influenced by the interaction between coating-controlled diffusion, particle surface area, and microbial transformation processes in flooded soil conditions.

Soil pH Dynamics under Different Fertilizer Forms and Coating Treatments

Soil pH exhibited a consistent decline during the 10-week incubation across all treatments, indicating progressive nitrogen transformation processes under flooded anaerobic conditions (Figure 5). The decrease was more pronounced in uncoated fertilizers (B: uncoated tablet fertilizer and D: uncoated granule fertilizer) than in coated formulations (A: coated tablet fertilizer and C: coated granule fertilizer), highlighting the role of polyurethane coating as a diffusion barrier that regulates water penetration and nutrient release kinetics (Bortoletto-Santos *et al.* 2020). Under flooded conditions, limited oxygen availability promotes ammonium accumulation through hydrolysis and ammonification, contributing to H^+ generation and soil acidification.

Nitrogen transformations further intensified pH reduction via urea hydrolysis and ammonium dissociation reactions (Chang 2003), as described by $CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + HCO_3^-$ followed by $NH_4^+ \leftrightarrow NH_3 + H^+$, which directly increases H^+ concentration in the soil solution (Hidayatussittah 2018). Fertilizer physical form also significantly influenced pH dynamics. Granular fertilizers (C: coated granule fertilizer and D: uncoated granule fertilizer) exhibited faster dissolution due to higher surface area, resulting in accelerated ion release and stronger acidification compared with tablet formulations (A: coated tablet fertilizer and B: uncoated tablet fertilizer). This aligns with diffusion and surface-area-controlled dissolution kinetics, where increased contact area enhances nutrient release rates (Hardjowigeno 2015). Overall, pH dynamics were governed by the combined effects of coating-controlled diffusion, particle geometry, and flooded soil conditions.

Phosphorus Release Dynamics under Different Fertilizer Forms and Coating Treatments

Phosphorus (P) release from the four slow-release NPK fertilizer treatments increased continuously over the 10-week incubation period, with significant variation in both rate and magnitude among treatments (Figure 6). Table 1 presents the cumulative percentage of phosphorus released after 10 weeks: Treatment D (uncoated granule fertilizer) exhibited the highest release (90.76%), followed by Treatment B (uncoated tablet fertilizer) at 70.87%, Treatment C (coated granule fertilizer) at 55.77%, and Treatment A (coated tablet fertilizer) at 46.53%. These findings demonstrate that both fertilizer formulation and coating application substantially influenced phosphorus dissolution and diffusion under flooded soil conditions.

The observed differences between coated and uncoated fertilizers underscore the critical role of polyurethane coating in regulating nutrient release. Treatments A (coated tablet fertilizer) and C (coated granule fertilizer) exhibited slower and more gradual phosphorus release compared to their uncoated counterparts (B and D). This effect is attributed to the hydrophobic and low-permeability characteristics of polyurethane, which serve as a diffusion barrier by restricting water infiltration and slowing the release of dissolved phosphate ions from the fertilizer matrix (El Sayed 2023). Under flooded conditions, where water availability is high, but oxygen diffusion is limited, the coating further moderates nutrient exchange between fertilizer particles and the soil solution, resulting in a more controlled release profile.

In contrast, uncoated fertilizers released phosphorus more rapidly because of direct contact between fertilizer particles and the surrounding soil solution, which enhanced dissolution and diffusion processes. Among these, Treatment D exhibited the highest phosphorus release, indicating a rapid release pattern that could result in faster nutrient depletion and

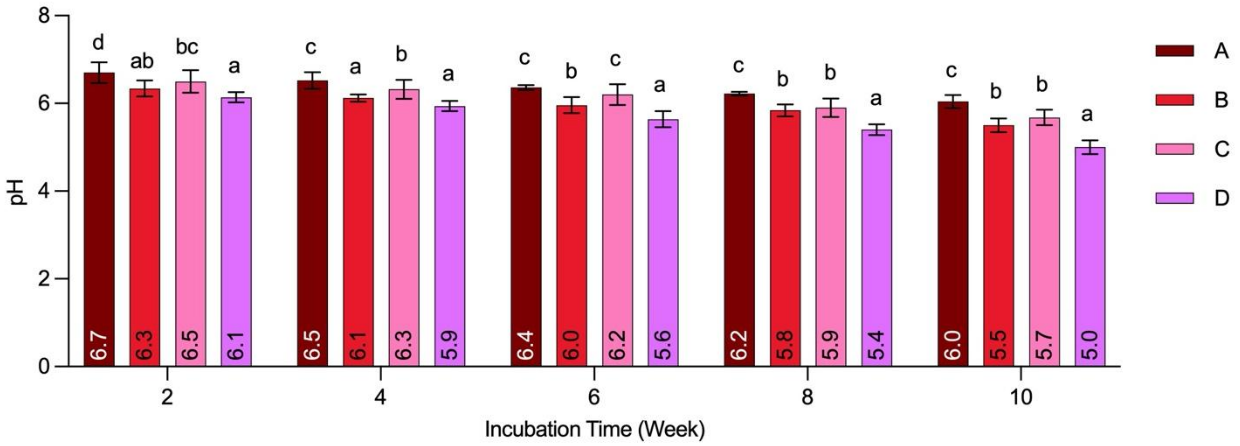

Figure 5 Graph of changes in ph of various forms of NPK slow release fertilizer during 10 weeks of incubation. (A) = coating tablet fertilizer; (B) = tablet fertilizer without coating; (C) = granul coating fertilizer; (D) = granule fertilizer without coating.

reduced nutrient use efficiency over time. Treatment B, however, demonstrated a more balanced release profile, reaching 70.87% afterThe physical form of the fertilizer further contributed to differences in phosphorus release. Granular fertilizers generally released phosphorus more rapidly than tablet formulations because their greater surface area increases contact with water and enhanced dissolution processes (Nugroho & Sembiring 2020). In contrast, tablet formulations reduced the exposed surface area, resulting in slower solubilization and a more prolonged release pattern.

According to the performance criteria proposed by Trenkel (2010), which specify that an ideal slow-release fertilizer should release approximately 75% of its nutrients at the designated release time, Treatment B (uncoated tablet fertilizer) demonstrated the most favorable behavior among all treatments. With a cumulative phosphorus release of 70.87% after 10 weeks, Treatment B was closest to the expected release threshold, indicating relatively balanced nutrient availability without excessive delay or overly rapid depletion. In contrast, Treatments A and C released phosphorus below this threshold, suggesting restricted nutrient availability due to coating effects, while Treatment D exceeded the controlled-release range, indicating excessively rapid nutrient release.

The release behavior was further governed by diffusion-controlled kinetics, in which nutrient movement from fertilizer particles into the soil solution occurred gradually and depended on concentration gradients, coating resistance, and water penetration. Cruz *et al.* (2017) reported that coating degradation progresses gradually during incubation, allowing nutrients to be released continuously rather than instantaneously. This mechanism accounts for the sustained increase in phosphorus release over time, particularly in coated fertilizers where diffusion pathways remain restricted.

Overall, phosphorus release dynamics were influenced by the interaction among fertilizer form (tablet versus granule), coating presence, and flooded soil conditions. These factors collectively determined the balance between rapid dissolution in uncoated fertilizers and diffusion-limited release in coated formulations, resulting in distinct phosphorus release patterns throughout the incubation period. Treatment B exhibited the most optimal and balanced performance relative to the slow-release criterion.

Potassium Release Dynamics under Different Fertilizer Forms and Coating Treatments

Potassium (K) release from the four slow-release NPK fertilizer treatments exhibited a consistent upward trend over the 10-week incubation period, with distinct differences in both the rate and extent of release among treatments (Figure 7). According to Table 1, Treatment D (uncoated granule fertilizer) achieved the highest cumulative K release (98.72%), followed by Treatment B (uncoated tablet fertilizer) at 88.22%, Treatment C (coated granule fertilizer) at 69.07%, and Treatment A (coated tablet fertilizer) at 58.07%. These results demonstrate that potassium mobility was significantly influenced by both the formulation type and the presence of a coating layer under flooded soil conditions.

The differing release patterns between coated and uncoated fertilizers highlight the regulatory role of polyurethane in controlling nutrient movement. Treatments A (coated tablet fertilizer) and C (coated granule fertilizer) demonstrated more restrained potassium release compared to their uncoated counterparts (B and D). This outcome is attributed to the hydrophobic and semi-permeable properties of the polyurethane coating, which restrict water infiltration into the fertilizer core and decrease the rate of K^+ diffusion into the soil solution (Yang *et al.* 2016; Saleem *et al.* 2021). Under continuously flooded conditions, where dissolution processes are typically enhanced, the effect of the coating in moderating nutrient release dynamics becomes even more significant.

In contrast, the uncoated treatments permitted direct and unrestricted contact between fertilizer particles and floodwater, resulting in accelerated potassium dissolution. Treatment D exhibited nearly complete nutrient release (98.72%), indicating a rapid depletion pattern that could decrease nutrient retention efficiency within the soil system. Treatment B also showed high K release (88.22%), although its release pattern was slightly less rapid than that of the uncoated granular formulation.

Fertilizer geometry also influenced potassium release dynamics. Granular formulations released potassium more rapidly than tablet forms, especially during the initial stages of incubation, due to their larger exposed surface area, which increases interaction with water and accelerates dissolution processes (Lasindrang 2018). In contrast, tablet formulations possess a more compact structure with reduced surface exposure, resulting in slower solubilization and a more gradual nutrient release profile.

According to the classification proposed by Trenkel, which states that slow-release fertilizers generally release approximately 75% of their nutrients within the designated release period, the results in Table 1 reveal two distinct behaviors. Treatments B and D surpassed this threshold (88.22% and 98.72%), indicating rapid nutrient availability and a tendency toward fast-release behavior. In contrast, Treatments A and C remained below the 75% benchmark, demonstrating more restricted and gradual potassium release during the incubation period.

In summary, potassium release patterns were determined by the combined effects of coating presence, fertilizer physical form, and flooded soil conditions. These interacting factors influenced whether nutrient release occurred rapidly in uncoated systems or was moderated by diffusion resistance in coated formulations, as demonstrated by the variations presented in Table 1.

CONCLUSION

Over the 10-week incubation under flooded soil conditions, nitrogen dynamics exhibited a distinct transformation pattern. Ammonium (NH_4^+) concentrations decreased over time, while nitrate (NO_3^-) and total nitrogen increased across all treatments, indicating progressive nitrification. In contrast, phosphorus and potassium displayed continuously increasing release trends, with the magnitude of release varying significantly among fertilizer formulations.

Fertilizer form and coating application were major factors influencing nutrient release behavior. Coated fertilizers (Treatments A and C) consistently exhibited slower nutrient release due to the diffusion-limiting effect of the polyurethane coating. In contrast, the uncoated granule fertilizer (Treatment D) demonstrated the most rapid release, particularly for potassium, indicating lower nutrient retention potential.

The uncoated tablet fertilizer (Treatment B) demonstrated the most balanced nutrient release pattern among all treatments, with relatively high cumulative release of nitrogen (80.07%), phosphorus (70.87%), and potassium (88.22%). This result suggests more synchronized nutrient availability compared to other formulations, where nutrient release was either excessively restricted (coated treatments) or too rapid (uncoated granules). In conclusion, Treatment B provides the most favorable compromise between nutrient availability and release control under flooded soil conditions, indicating its potential effectiveness for improving nutrient use efficiency in paddy soil systems.

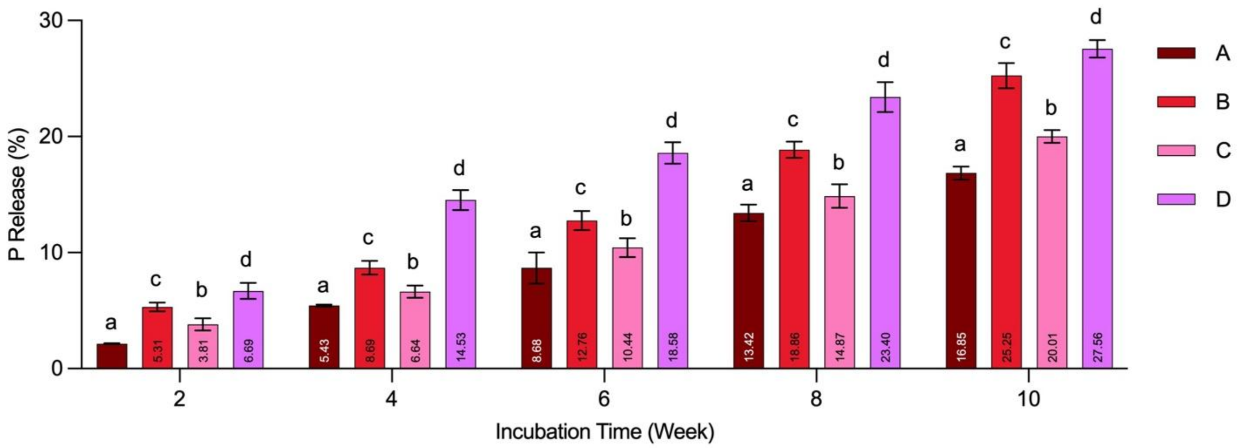

Figure 6 Graph of phosphorus release (%) from various forms of NPK slow released fertilizer for 10 weeks incubation time in soil media. (A) = coating tablet fertilizer; (B) = tablet fertilizer without coating; (C) = granul coating fertilizer; (D) = granule fertilizer without coating.

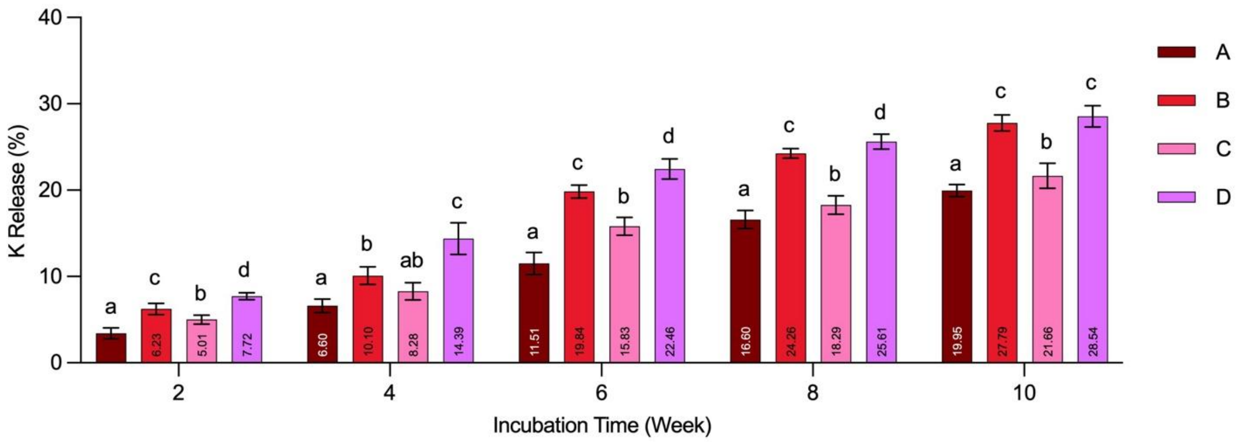

Figure 7 Graph of potassium release (%) from various forms of NPK slow release fertilizer for 10 weeks incubation time. (A) = coating tablet fertilizer; (B) = tablet fertilizer without coating; (C) = granul coating fertilizer; (D) = granule fertilizer without coating.

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