ISSN: 2621-4709 E-ISSN: 2621-2528
Journal of Applied Agricultural Science and Technology
Vol. 10 No. 4 (2026): 789-802

NPK Release and Residue from Coated and Shape-Adjusted Tablet Fertilizers under Controlled Soil and Water Incubation

Stefina Liana Sari [a,*], Muhamad Rahman Djuwansah [b], Emma Trinurani Sofyan [c], Rahmat Budiarto [d], Astri Nur Istyami [e], Rizky Maulana Ramadhan [f], Zainal Abidin Muhammad [f]

[a] Agrotechnopreneur Study Program, Universitas Padjadjaran, Bandung, Indonesia
[b] Research Center for Geological Resources, National Research and Innovation Agency (BRIN), Bandung, Indonesia
[c] Department of Soil Science, Faculty of Agriculture, Universitas Padjadjaran, Sumedang,
[d] Department of Agronomy, Faculty of Agriculture, Universitas Padjadjaran, Sumedang, Indonesia
[e] Department of Bioenergy Engineering and Chemurgy, Institut Teknologi Bandung, Bandung, Indonesia
[f] Faculty of Agriculture, Universitas Padjadjaran, Bandung, Indonesia

Abstract. *Fertilization efficiency remains a major challenge in modern agriculture because large fractions of applied nitrogen (N), phosphorus (P), and potassium (K) are lost after application. This study quantified how surface coating and shape adjustment affect the cumulative release and residual N, P, and K of tablet fertilizers under controlled soil and water incubation. A factorial completely randomized design combined two factors: incubation medium (soil, water) and fertilizer modification (uncoated, coated, shape-adjusted). The shape-adjusted tablet was largely coated and exposed a single, model-derived release zone. Each of the six treatment combinations was replicated five times, and media were sampled every two weeks for eight weeks. Release differed significantly with medium, modification, and their interaction ($p < 0.001$). Uncoated tablets released nutrients almost completely and abruptly (N 99.97% and P 99.43% in water), indicating a high potential for nutrient loss. Coated tablets released more slowly but left large undissolved fractions in soil, particularly K (40.49% residual). The shape-adjusted tablet showed the smallest deviation from a literature-derived rice nutrient-uptake reference curve: in soil it released N (91.91%), P (88.65%), and K (98.10%) gradually with the lowest residues, while in water its residual N (1.29%) and P (1.35%) remained low. Combining surface coating with shape adjustment therefore produced the most gradual and reference-consistent release under incubation. Because nutrient uptake and field performance were not measured, agronomic benefits require further validation under plant-growth and field conditions.*

Keywords: *controlled-release fertilizer; nutrient release; nutrient residue; incubation; shape adjusted tablet fertilizer.*

Type of the Paper: Regular Article.

1. Introduction

Fertilizers are essential components of agricultural systems because they supply the nitrogen (N), phosphorus (P), and potassium (K) that crops require for growth. In practice, however, a large share of applied nutrients is lost before uptake, and each nutrient follows a different loss pathway: nitrogen is lost mainly through leaching and volatilization, with up to 60 % of applied N lost by these routes [1]. Phosphorus is readily fixed into sparingly soluble forms and can be transported to water bodies; and potassium is prone to leaching, particularly in coarse-textured or wet soils.

https://doi.org/10.55043/jaast.v10i4.605
Received June 14, 2026; Received in revised form September 01, 2026; Accepted September 12, 2026; Published November 23, 2026
* Corresponding author
Email: stefina.liana@mail.unpad.ac.id
© 2026 The Authors. Published by Green Engineering Society on Journal of Applied Agricultural Science and Technology
This is an open access article under the CC BY-SA 4.0 license https://creativecommons.org/licenses/by-sa/4.0

These losses reduce fertilization efficiency, raise costs for farmers, and represent a potential source of environmental harm; this has driven the development of fertilizer technologies aimed at improving nutrient-use efficiency.

Tablet fertilizers represent promising innovation, designed to release nutrients more gradually and consistently than conventional formulations. Unlike powders or prills, which dissolve rapidly and inconsistently, tablet fertilizers have been reported to provide a steadier nutrient supply while reducing leaching losses. Adlim et al. [2] demonstrated that tablet fertilizers can minimise nitrogen, phosphorus [3], and potassium leaching [4]. Trenkel [5] and Lee et al. [6] reported reductions in soil and water nutrient residues of up to 30 % relative to conventional fertilizers; and Soti et al. [7] and Lawrencia et al. [8] found that controlled-release formulations reduce nutrient leaching by 20–30 %. However, most of these studies have focused on optimising coating chemistry rather than tablet geometry, leaving the specific contribution of fertilizer shape to release behaviour comparatively unexplored.

Tablet fertilizers have also been investigated for their capacity to retain nutrients after application and to sustain a more controlled release. Legese et al. [9] observed that zeolite-based tablet fertilizers can increase soil nutrient levels and prolong nutrient availability to plants. However, Sharma and Singh [10] noted that the release pattern of slow-release tablets is often inefficient, because peak release occurs during the first two weeks—when the tablet exposes its largest dissolving surface area—and then declines sharply. In contrast, coated tablets tend to release nutrients only after the coating has degraded. Consequently, the release pattern of tablet fertilizers still requires considerable optimisation.

Two strategies have been proposed to address these limitations. The first involves geometric modification: adjusting tablet shape and the fertilizer–medium contact area to distribute nutrient release more evenly over time [8,11]. The second relies on coating technology. Cui et al. [12] and Xu and Guo [13] showed that polyacrylic-acid (PAA)-based coatings slow nutrient release and thereby improve fertilizer efficiency, while Balashanmugavel et al. [14] demonstrated that stearin- and paraffin-based coatings can effectively control release. Zeolite has also been used as a coating owing to its high cation-exchange capacity, which supports more consistent nutrient delivery [9,15]. However, few studies have examined these two strategies in combination or isolated the specific effect of tablet geometry on release behaviour.

Given the complementary shortcomings identified above—rapid, poorly timed release from uncoated tablets and incomplete release from coated tablets—this study compared three tablet formulations under controlled soil and water incubation: uncoated, coated, and shape-adjusted tablets. The specific objectives were to (i) quantify cumulative N, P, and K release and residual fractions, (ii) evaluate how coating and shape adjustment alter release patterns relative to a

literature-derived nutrient-uptake reference, and (iii) assess the extent to which combining surface coating with shape adjustment improves release consistency.

2. Materials and Methods

2.1 Fertilizer Materials and Preparation

The three tablet types evaluated in this study (Fig.1) were prepared from a single base fertilizer blend to ensure that any observed differences in nutrient release could be attributed solely to tablet modification rather than composition. The nutrient source was standard granular NPK (16-16-16) compound fertilizer, which was milled to a fine powder and compacted into cylindrical tablets using a stainless-steel die and a hydraulic press, following approach of Adlim et al. [2]. To ensure replication, several fabrication parameters were kept constant across all tablets: powder mass per tablet (9 g), die diameter (21 mm), and applied uniaxial load (18 kN, corresponding to approximately 52 MPa) producing tablets of 25 mm height and a bulk density of 1.04 g cm^{-3}.

Three distinct tablet types were then produced (Fig.1). The first was (a) an uncoated tablet, whose entire surface is exposed; (b) a coated tablet, whose whole surface received a uniform resin-based polymer coating to slow diffusion; and (c) a shape-adjusted tablet, in which almost the entire surface was coated leaving only a single, geometrically defined zone (marked by the red-circle in Fig.1c) uncoated; this design ensures that dissolution begins at the open zone and advances directionally through the tablet body. Because compaction mass, die diameter, and load were identical across all treatments, the tablets differed only in their surface coating and in the area and position of the exposed release zone.

2.2 Shape-Adjustment Modelling

The geometry of the shape-adjusted tablet was derived by mathematical modelling of a rice nutrient-uptake curve. The uptake data were taken from a companion field study of lowland rice (*Oryza sativa* L.) [11], in which weekly N, P, and K uptake was measured throughout the growing period. The weekly values were expressed as a cumulative-uptake curve and fitted with a fourth-order polynomial, whose first derivative describes the uptake-rate as a function of time. Assuming that nutrient release is proportional to the exposed (uncoated) surface area of the tablet, this uptake-rate function was treated as the radius of successive circular cross-sections and revolved about the time axis (a solid-of-revolution approach) to generate the three-dimensional tablet form. The remaining surface was then coated, leaving only the modelled zone exposed.

Two limitations of this reference design should be noted. First, the uptake curve derives from a single rice study; it is therefore used here strictly as a comparative design target rather than a universally applicable demand curve. Second, the model was validated only for tablet fabrication and for reproducing the intended release geometry; it was not validated agronomically, because

plant uptake was not measured in the present incubation study. Full derivation of the model is provided in the companion study [11].

2.3 Experimental Design

The experiment used a factorial completely randomized design (CRD) with two factors. The first factor was the incubation medium (M1 = soil, M2 = water), and the second was tablet-fertilizer modification (A = uncoated tablet, B = coated tablet, C = shape-adjusted tablet). Tablet C was the selectively coated, shape-adjusted tablet obtained from the modelling described previously (Shape-Adjustment Modelling). Each of the six treatment combinations was replicated five times, giving 30 experimental units. All soil and fertilizer analyses were carried out at the Soil Chemistry and Plant Nutrition Laboratory, Faculty of Agriculture, Universitas Padjadjaran, Sumedang, Indonesia.

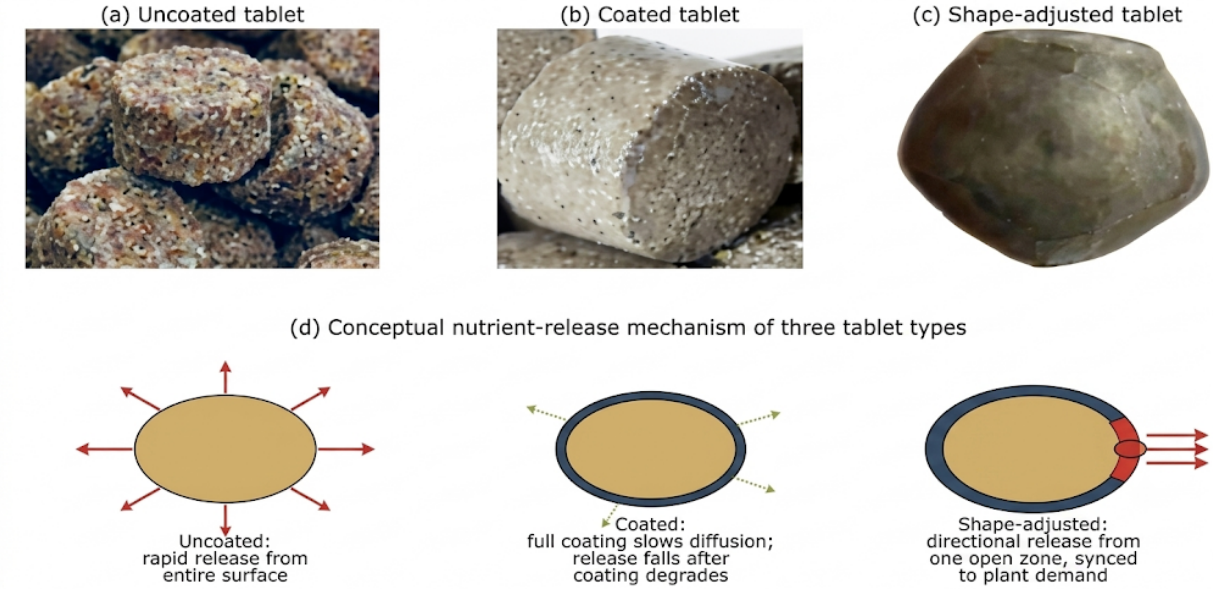


Fig 1. The three tablet-fertilizer types evaluated in this study: (a) uncoated tablet, (b) coated tablet, and (c) shapeadjusted tablet. The red-circled area marks the single uncoated release zone. Panel (d) is a conceptual diagram of their release mechanisms, contrasting rapid omnidirectional release (uncoated), coating-limited release (coated), and directional release from one active zone (shape-adjusted).

2.4 Incubation Procedure

Inceptisol soil collected from Jatinangor (West Java, Indonesia) and deionized water were used as the two incubation media. Before fertilizer application, the pH and initial nutrient content of both media were determined to confirm uniform starting conditions (methods listed in Table 1). For each experimental unit, 250 g of air-dried, 2-mm-sieved soil or 250 mL of deionized water was placed in a 450-mL plastic incubation cup. One fertilizer tablet, of equal nutrient mass across treatments, was enclosed in a non-reactive polymer mesh bag (60 mesh) and suspended from a wire support fixed to the rim of the cup. This arrangement kept the tablet centred within the medium and allowed it to be retrieved without disturbance. Throughout the incubation, soil

moisture was maintained near field capacity. Samples of soil and water were taken from each unit every two weeks over an eight-week period (T0, T2, T4, T6, T8) to determine cumulative nutrient release and the residual fraction (see Section 2.6, Data Analysis).

Table 1. Methods and interpretive criteria for initial soil and water analysis.

No.	Parameter (unit)	Method	Interpretive criteria
		Soil analysis	
1.	pH (H_2O)	Potentiometric, pH meter	<4.5 very acid; 4.5–5.5 acid; 5.6–6.5 slightly acid; 6.6–7.5 neutral; >7.5 alkaline
2.	pH (1 mol L^{-1} KCl)	Potentiometric, pH meter	–
3.	Organic-C (%)	Walkley & Black	<1 poor; 1–2 low; 2–3 medium; 3–5 high; >5 very high
4.	Total-N (%)	Kjeldahl	<0.1 poor; 0.1–0.2 low; 0.21–0.5 medium; 0.51–0.75 high; >0.75 very high
5.	C/N	C-organic ÷ total-N	<5 poor; 5–10 low; 11–15 medium; 16–25 high; >25 very high
6.	P_2O_5, HCl 25 % (mg/100 g)	HCl 25 % extraction, spectrophotometry	<15 poor; 15–20 low; 21–40 medium; 41–60 high; >60 very high
7.	P_2O_5, Olsen (mg kg^{-1} P)	Olsen extraction, spectrophotometry	<5 poor; 5–10 low; 11–15 medium; 16–20 high; >20 very high
8.	K_2O, HCl 25 % (mg/100 g)	HCl 25 % extraction, flame photometry	<10 poor; 10–20 low; 21–40 medium; 41–60 high; >60 very high
9.	CEC (cmol kg^{-1})	NH_4OAc extraction	<5 poor; 5–16 low; 17–24 medium; 25–40 high; >40 very high
10.	Exchangeable K, Na, Ca, Mg (cmol kg^{-1})	NH_4OAc extraction, flame photometry	Per Fahmuddin et al. [16] class limits
11.	Base saturation (%)	Σ base cations ÷ CEC × 100	<20 poor; 20–40 low; 41–60 medium; 61–80 high; >80 very high
12.	Exchangeable Al^{3+}, H^{+} (cmol kg^{-1})	KCl extraction, titrimetric	–
13.	Al saturation (%)	Al cations ÷ total cations × 100	<5 poor; 5–10 low; 10–20 medium; 20–40 high; >40 very high
14.	Texture (sand, silt, clay %)	Hydrometer	USDA soil-texture triangle
		Water analysis	
15.	pH	Potentiometric, pH meter	<5.5 acidic; 5.5–6.5 slightly acidic; 6.5–8.5 neutral; >8.5 alkaline
16.	Electrical conductivity (dS m^{-1})	Conductivity meter	<0.25 very low; 0.25–0.75 low; 0.75–2.25 moderate; 2.25–4.00 saline; >4.00 saline hazard

Note: Criteria after Fahmuddin et al. [16].

Nutrient concentrations were determined using standard wet-chemical methods, following AOAC [17] and the technical guidelines of Fahmuddin et al. [16]. Total N was measured by the Kjeldahl method involving digestion with concentrated sulfuric acid and a selenium catalyst, distillation with 40 % (w/v) sodium hydroxide, and titration with 0.1 mol L^{-1} HCl). For P and K, samples were digested in a nitric acid–perchloric acid (4:1, v/v) mixture until clear. Phosphorus was then quantified colorimetrically by the molybdenum-blue method using a UV–Vis spectrophotometer at 882 nm, and K was determined by atomic absorption spectrophotometry

(AAS) in flame-emission mode. All reagents were of analytical grade (Merck, Darmstadt, Germany), and each analysis was performed in triplicate.

2.5 Soil and Water Analysis Methods

Initial soil and water characterisation followed the procedures of Fahmuddin et al. [16]. Specifically, the pH of both media was measured potentiometrically using a calibrated pH meter. Soil organic carbon was determined by the Walkley and Black method, and total nitrogen by the Kjeldahl method. Available phosphorus was extracted using both HCl 25% and Olsen extraction methods, followed by spectrophotometric quantification. Exchangeable bases (K, Na, Ca, and Mg) were extracted with NH_4OAc and measured by flame photometry, while cation-exchange capacity (CEC) was determined by NH_4OAc extraction. Soil texture was assessed using the hydrometer method, and the electrical conductivity of the water was measured using a conductivity meter. All parameters, analytical methods, and interpretive criteria are summarised in Table 1. Each analysis was performed in triplicate.

2.6 Data Analysis

For each experimental unit, cumulative release (%) was calculated as the mass of N, P, or K recovered in the medium at the final sampling divided by the total mass of that nutrient initially loaded in the tablet, multiplied by 100. The residual fraction was then determined as 100 % minus cumulative release. The response variables were therefore the cumulative release and residual fractions of total N, total P_2O_5, and total K_2O.

Data were analysed by two-way analysis of variance (ANOVA) appropriate to the factorial CRD, partitioning the variation into the main effects of medium and fertilizer modification and their interaction, at the 5 % significance level. Treatment means (n = 5) are reported with their standard deviations. Where the F-test was significant, means were separated using Duncan's Multiple Range Test (DMRT) at the 5 % level.

To compare each release profile with the reference rice uptake curve without relying on visual inspection, a deviation index was computed as the mean absolute difference (in percentage points) between the time-normalised weekly release and the time-normalised reference uptake across the five sampling times; a lower index indicates closer correspondence. The complementary overlap (%) quantifies the shared area under the two normalised curves. All analyses were performed in SPSS.

3. Results and Discussion

3.1 Initial Soil and Water Properties

Initial characterisation confirmed the starting condition of both media (Table 2). The soil pH was 6.83 in H_2O (neutral) and 5.93 in 1 mol L^{-1} KCl, within the range generally regarded as optimal

for nutrient availability [18]. Organic-C (1.94 %) and total-N (0.18 %) were both low. A low background N pool limits the soil's own contribution to the nutrient concentrations measured during incubation [19,20]. However, low organic carbon can also reduce microbial activity and nitrogen mineralization; because these microbiological and N-transformation processes were not measured, this characterisation is used only to describe the incubation matrix rather than to claim biologically favourable conditions.

Among macronutrients, P_2O_5 (HCl 25 %) was high (56.21 mg/100 g) and P_2O_5 (Olsen) medium (11.14 ppm), while K_2O (HCl 25 %) was high (48.94 mg/100 g). This high background K is noted so that K subsequently measured in the medium can be attributed predominantly to the tablet rather than to the soil. The cation-exchange capacity (24.39 cmol kg^{-1}, medium) indicated moderate retention capacity, and base-cation analysis showed exchangeable K of 0.61 cmol kg^{-1} (high), Na 0.53 (medium), Ca 7.11 (medium), and Mg 2.39 (high), with a base saturation of 43.62 % (medium fertility [21]). The soil was clayey (9 % sand, 36 % silt, 55 % clay [22]), and Al saturation was negligible (0.95 %). The water was neutral (pH 7.02) with very low electrical conductivity (0.09 dS m^{-1}). These background properties are reported only to define the two media.

Table 2. Initial chemical properties of the soil and water incubation media.

No.	Parameter	Unit	Value	Criteria
	Soil Analysis			
1.	pH (H_2O)	–	6.83	Neutral
2.	pH (1 mol L^{-1} KCl)	–	5.93	–
3.	Organic-C	%	1.94	Low
4.	Total-N	%	0.18	Low
5.	C/N	–	5.22	Low
6.	P_2O_5 (HCl 25 %)	mg/100 g	56.21	High
7.	P_2O_5 (Olsen)	mg kg^{-1} P	11.14	Medium
8.	K_2O (HCl 25 %)	mg/100 g	48.94	High
9.	CEC	cmol kg^{-1}	24.39	Medium
10.	Exchangeable K	cmol kg^{-1}	0.61	High
11.	Exchangeable Na	cmol kg^{-1}	0.53	Medium
12.	Exchangeable Ca	cmol kg^{-1}	7.11	Medium
13.	Exchangeable Mg	cmol kg^{-1}	2.39	High
14.	Base saturation	%	43.62	Medium
15.	Exchangeable Al^{3+}	cmol kg^{-1}	0.52	–
16.	Exchangeable H^+	cmol kg^{-1}	0.21	–
17.	Al saturation	%	0.95	Poor
18.	Texture (sand/silt/clay)	%	9 / 36 / 55	Clay
	Water Analysis			
19.	pH	–	7.02	Neutral
20.	Electrical conductivity	dS m^{-1}	0.09	Very low

Note: Criteria after the technical guidelines for soil, plant, water, and fertilizer analysis [16].

3.2 Nutrient-Release Pattern Relative to a Reference Rice Uptake Curve

The three tablet types produced distinctly different weekly release profiles when compared with the literature-derived reference rice uptake curve. To make the comparison explicit and quantitative, the time-normalised weekly release of each tablet was plotted against the time-

normalised reference curve (Fig 2), and the correspondence was summarised by the deviation index and overlap defined in Section 2.6.

For the uncoated tablet (Fig 2a), release was very rapid at the start of incubation and then declined steeply, so that most of the release profile fell outside the reference curve. This produced the largest deviation index (11.3 percentage points) and the lowest overlap with the reference (71.8 %). A front-loaded profile of this kind means that, under field conditions, a large fraction of the nutrient would be released early—before a crop could take it up—which has been associated with an increased potential for early-stage leaching and volatilization [23,24]. These loss pathways were not measured in the present study.

The coated tablet (Fig 2b) showed a more regulated profile, with release rising to a peak near week 4 (T4) and then falling as the coating degraded; its deviation from the reference was intermediate (deviation index 4.8 percentage points; overlap 88.0 %). This is consistent with reports that coated and controlled-release fertilizers moderate release [25] but lose effectiveness once the coating is fully degraded [11]. The coated tablet thus released more evenly than the uncoated tablet but did not sustain release through the full incubation period.

The shape-adjusted tablet (Fig 2c) showed the closest correspondence to the reference curve, with the smallest deviation index (2.9 percentage points) and the highest overlap (92.7 %): release rose to a peak near week 4 and then declined gradually while maintaining measurable release to the end of incubation. Because most of its surface was coated and dissolution proceeds directionally from a single defined zone, its release was more gradual and evenly distributed over time than that of the other tablets. These results indicate that, under incubation, the shape-adjusted design produced the release profile most similar in shape to the reference rice uptake curve. However, whether this closer correspondence improves plant uptake or reduces field loss remains to be validated.

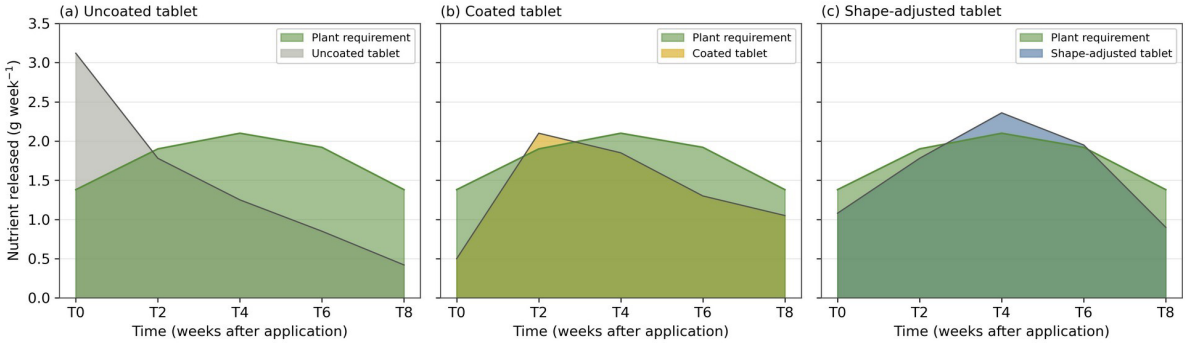


Fig 2. Time-normalised weekly nutrient release of (a) the uncoated, (b) the coated, and (c) the shape-adjusted tablet, each overlaid on the time-normalised reference rice uptake curve (green). T0–T8 denote weeks of incubation (sampled every two weeks). A smaller non-overlapping area corresponds to a lower deviation index (see Data Analysis).

3.3 Cumulative Nutrient Release in Soil and Water

Cumulative N, P, and K release at the end of incubation differed significantly among treatments (Table 3). For every nutrient, the two-way ANOVA showed significant main effects of medium and fertilizer modification and a significant medium × modification interaction (all $p < 0.001$), indicating that the effect of modification on release depended on the medium. Release was consistently higher in water than in soil for every nutrient and tablet type, reflecting the greater solubilising contact in the aqueous medium. For nitrogen, the uncoated tablet released the most in water (99.97 %), whereas in soil the shape-adjusted tablet released the most (91.91 %) and the coated tablet the least (78.61 %). The rapid, near-complete release of the uncoated tablet is the pattern that, in field soils, has been associated with N loss through volatilization, denitrification, and leaching [26]; the coated tablet released N more slowly [27]. These loss pathways were not measured here and are cited only as context for the observed release behaviour.

For phosphorus, release was highest in water for the uncoated tablet (99.43 %), while in soil the shape-adjusted tablet released the most (88.65 %). High concentrations of dissolved P are a recognised contributor to eutrophication risk in receiving waters [28], although no aquatic transport or water-quality endpoint was assessed here. The coated tablet released P more slowly in soil (65.53 %) [26,8]. Potassium followed a similar trend: the shape-adjusted tablet released the most K in both water (97.65 %) and soil (98.10 %), whereas the coated tablet released the least K in soil (59.51 %); K is highly soluble and readily lost under wet conditions [29]. Overall, the coated tablet retained the largest undissolved fraction, while the shape-adjusted tablet showed the most complete release in soil combined with the smallest deviation from the reference curve (Fig 2c). Standard deviations for all treatments are given in Table 3.

Table 3. Cumulative N, P, and K released (%, mean ± standard deviation, n = 5) from the tablet fertilizers under the various treatments at the end of incubation.

Medium	Uncoated (A)	Coated (B)	Shape-adjusted (C)
	N released from total fertilizer (%)		
Soil	85.95 ± 0.79 b B	78.61 ± 1.07 c B	91.91 ± 1.17 a B
Water	99.97 ± 0.02 a A	96.28 ± 0.55 ab A	98.71 ± 0.62 a A
	P released from total fertilizer (%)		
Soil	68.87 ± 1.18 b B	65.53 ± 0.48 bc B	88.65 ± 1.18 a B
Water	99.43 ± 0.14 a A	99.96 ± 0.03 a A	98.65 ± 0.54 a A
	K released from total fertilizer (%)		
Soil	86.22 ± 2.22 b B	59.51 ± 1.48 d B	98.10 ± 1.82 a B
Water	93.90 ± 0.45 bc A	95.94 ± 0.36 b A	97.65 ± 0.76 ab A

Note: Values are mean ± standard deviation (n = 5). Means followed by the same letter are not significantly different by DMRT at the 5 % level; lowercase letters compare fertilizer types within the same medium, uppercase letters compare media within the same fertilizer type. A = uncoated tablet, B = coated tablet, C = shape-adjusted tablet.

3.4 Residual Nutrients in the Tablet

The residual nutrient fraction—the proportion of applied N, P, or K remaining undissolved in the tablet at the end of incubation—is the complement of release (residual = 100 % − release).

Fig 3 presents these residues for the soil (Fig 3a) and water (Fig 3b) media. In soil, the coated tablet (B) left the largest residues, retaining 21.39 % of N, 34.47 % of P, and 40.49 % of K undissolved. The high K residue indicates that a large fraction of the loaded K remained inside the tablet under these conditions. The shape-adjusted tablet (C) left the smallest residues (N 8.09 %, P 11.35 %, K 1.90 %). This lower residue follows directly from its directional design: with most of the surface coated and a single defined release zone, dissolution advances progressively from that zone through the tablet body. Consequently, by the end of incubation, a greater proportion of the loaded nutrient had dissolved than in the fully coated tablet, whose intact coating restricted contact between the nutrient core and the medium. A lower residue therefore reflects greater dissolution from the tablet, not necessarily greater plant-available or retained nutrient, which was not measured. The uncoated tablet (A) gave intermediate soil residues (N 14.05 %, P 31.13 %, K 13.78 %), consistent with a fast but uncontrolled release.

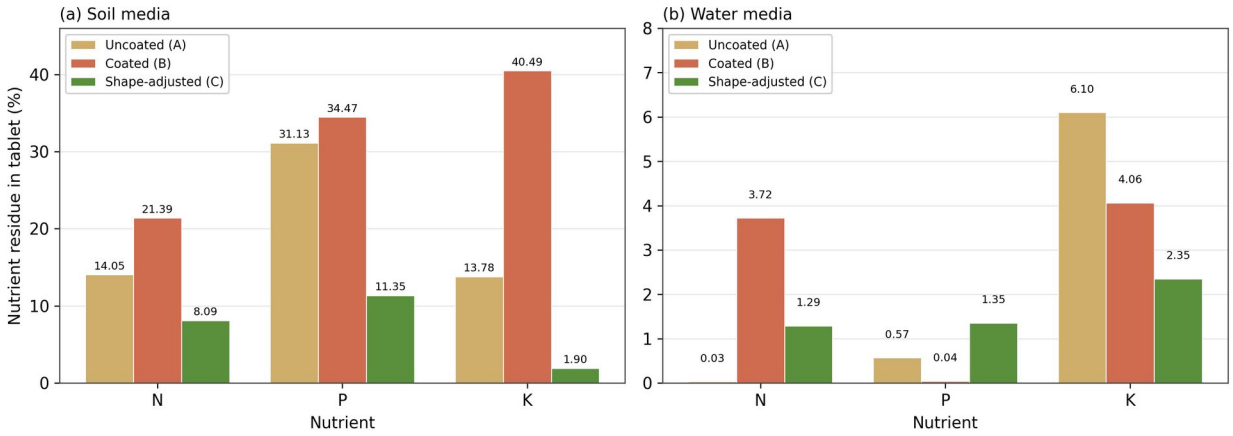


Fig 3. Residual N, P, and K remaining in the tablet (% of applied nutrient) after incubation in (a) soil and (b) water media for the uncoated (A), coated (B), and shape-adjusted (C) tablets. Note the different y-axis scales between panels. Residual values equal 100 % minus the corresponding release values in Table 3.

In water (Fig 3b), residues were small for all tablets because dissolution was almost complete by the end of the eight-week incubation; nevertheless, the differences remain informative. The uncoated tablet retained almost none of its load (N 0.03 %, P 0.57 %, K 6.10 %), indicating that its nutrients had dissolved almost entirely. Because sampling was performed every two weeks, the exact timing of dissolution within each interval could not be resolved. The coated tablet retained N 3.72 %, P 0.04 %, and K 4.06 %, while the shape-adjusted tablet retained slightly more N (1.29 %) and P (1.35 %) and the least K (2.35 %). The somewhat higher P residue of the shape-adjusted tablet is consistent with a more gradual release of P, whereas its low residues overall indicate that the directional release zone governed dissolution in a reproducible way. Taken together, the residue data mirror the release results: under incubation, the shape-adjusted tablet gave the most gradual and reference-consistent release, while the uncoated and fully coated tablets represented the two extremes of too-fast and too-incomplete release.

4. Conclusion

This study compared three tablet-fertilizer modification strategies—no modification (uncoated), surface coating (coated), and shape adjustment (shape-adjusted)—under controlled soil and water incubation. Nutrient release differed significantly with medium, modification, and their interaction (all $p < 0.001$). The uncoated tablet released nutrients almost completely and abruptly (up to 99.97 % of N and 99.43 % of P in water) and showed the largest deviation from the reference rice uptake curve. Conversely, the coated tablet released nutrients more slowly but left the largest undissolved residues in soil, including 40.49 % of its potassium. The shape-adjusted tablet produced the most gradual release, the smallest residues in soil, and the closest correspondence to the reference uptake curve (deviation index 2.9 percentage points; overlap 92.7 %).

These conclusions apply strictly to nutrient release and residue behaviour measured under laboratory incubation. Because nutrient uptake, loss pathways (leaching, volatilization, denitrification), and crop performance were not measured, the results should not be interpreted as demonstrating field efficiency, reduced environmental impact, or synchronisation with actual crop demand. Validation under plant-growth and field conditions, together with direct measurement of nutrient uptake and loss, is required before such agronomic or environmental benefits can be claimed. Future work should also focus on developing biodegradable coatings and testing these formulations across different crops and soil types.

Abbreviations

AAS	Atomic Absorption Spectrophotometry.
ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
BRIN	National Research and Innovation Agency (Badan Riset dan Inovasi Nasional).
CRD	Completely Randomized Design.
CRFs	Controlled Release.
DMRT	Duncan's Multiple Range Test.
HCl	Hydrocloric Acid.
K_2O	Potassium Oxide.
KCl	Potassium Chloride.
N	Nitrogen.
NPK	Nitrogen, Phosphorus, Potassium.
NUE	Nitrogen Use Efficiency.
P_2O_5	Phosphorus Pentoxide.
PAA	Polyacrylic Acid.
SPSS	Stastistical Package for the Social Sciences.
UV-Vis	Ultraviolet-Visible.

Data Availability Statement

The raw data and statistical analysis supporting the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.20826388.

CRediT Authorship Contribution Statement

Stefina Liana Sari: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Muhamad Rahman Djuwansah**: Conceptualization, Methodology, Resources, Supervision, Writing – review and editing. **Emma Trinurani Sofyan**: Investigation, Data curation, Validation, Writing – review and editing. **Rahmat Budiarto**: Investigation, Software, Visualization, Writing – review and editing. **Astri Nur Istyami**: Formal analysis, Validation, Resources, Writing – review and editing. **Rizky Maulana Ramadhan**: Data curation, Investigation, Project administration, Writing – review and editing. **Zainal Abidin Muhammad:** Formal analysis, Investigation, Validation.

Declaration of Competing Interest

The authors of this manuscript declare no conflict of interest or competing interest.

Declaration of Use of AI in the Writing Process

The author(s) used Claude (Anthropic) during the preparation of this manuscript to improve grammar, refine sentence clarity, and check consistency of formatting and terminology. After using the tool/service, the author(s) carefully reviewed and edited the content and take full responsibility for the content of the publication.

Acknowledgements

The authors gratefully acknowledge the Soil Chemistry and Plant Nutrition Laboratory and the Faculty of Agriculture, Universitas Padjadjaran, for the valuable support and facilities provided throughout this research.

References

[1] Bortoletto-Santos R, Ribeiro C, Polito WL. Controlled release of nitrogen-source fertilizers by natural-oil-based poly(urethane) coatings: The kinetic aspects of urea release. Journal of Applied Polymer Science 2016;133. https://doi.org/10.1002/app.43790.

[2] Adlim M, Zarlaida F, Zuraida Z, Darusman D. Simple and Environmental Friendly Preparation and Characterization of Slow Release Urea Tablet Made of Rice Husk Ash Composite with. Pakistan Journal of Life and Social Sciences 2018;16:20–6. https://www.researchgate.net/publication/328293944_Simple_and_environmental_friendly_preparation_and_characterization_of_slow_release_urea_tablet_made_of_rice_husk_ash_composite_with_chitosan_coating

[3] Koestoer RH, Ligayanti T, Kartohardjono S, Susanto H. Down-streaming Small-Scale Green Ammonia to Nitrogen-Phosphorus Fertilizer Tablets for Rural Communities. Emerging Science Journal 2024;8. https://doi.org/10.28991/ESJ-2024-08-02-016

[4] Zhang Z, He F, Zhang Y, Yu R, Li Y, Zheng Z, et al. Experiments and modelling of potassium release behavior from tablet biomass ash for better recycling of ash as eco-friendly fertilizer. Journal of Cleaner Production 2018;170:379–87. https://doi.org/10.1016/J.JCLEPRO.2017.09.150.

[5] Trenkel. Slow and Controlled-Release and stabilized Fertilizers 2013;3. https://repo.upertis.ac.id/1628/1/2010_Trenkel_slow%20release%20book.pdf

[6] Lee YL, Ahmed OH, Wahid SA, Aziz ZFA. Biochar tablets with and without embedded fertilizer on the soil chemical characteristics and nutrient use efficiency of zea mays. Sustainability (Switzerland) 2021;13:4878. https://doi.org/10.3390/su13094878

[7] Soti P, Fleurissaint A, Reed S, Jayachandran K. Effects of Control Release Fertilizers on Nutrient Leaching, Palm Growth and Production Cost. Agriculture (Switzerland) 2015;5: 1135-45. https://doi.org/10.3390/agriculture5041135

[8] Lawrencia D, Wong SK, Low DYS, Goh BH, Goh JK, Ruktanonchai UR, et al. Controlled release fertilizers: A review on coating materials and mechanism of release. Plants 2021;10:238. https://doi.org/10.3390/plants10020238.

[9] Legese W, M. Taddesse A, Kibret K, Wogi L. Effects of natural and modified zeolite based composite fertilizers on slow release and nutrient use efficiency. Heliyon 2024;10:e25524. https://doi.org/10.1016/j.heliyon.2024.e25524

[10] Sharma N, Singh A. A Review on Changes in Fertilizers, From Coated Controlled Release Fertilizers (CRFs) to Nanocomposites of CRFs. International Journal of Agricultural Science and Research 2019;9. https://doi.org/10.24247/ijasrapr20197. https://www.researchgate.net/publication/334192480_A_REVIEW_ON_CHANGES_IN_FERTILIZERS_FROM_COATED_CONTROLLED_RELEASE_FERTILIZERS_CRFS_TO_NANOCOMPOSITES_OF_CRFS

[11] Sari SL, Djuwansah MR, Joy B, Sofyan ET, Arifin M, Nurmala T, et al. Study of the Nutrient Uptake Patterns for the Better Use of Controlled Release Compound Fertilizer in Rice Plant. International Journal of Agriculture and Biology 2024;31. https://doi.org/10.17957/IJAB/15.2145.

[12] Cui Y, Xiang Y, Xu Y, Wei J, Zhang Z, Li L, et al. Poly-acrylic acid grafted natural rubber for multi-coated slow release compound fertilizer: Preparation, properties and slow-release characteristics. International Journal of Biological Macromolecules 2020;146. https://doi.org/10.1016/j.ijbiomac.2020.01.051

[13] Xu Z, Guo Y. Preparation and performance of degradable slow-release fertilizer coating material by a new ionic crosslinked hydrogel material. Journal of Environmental Chemical Engineering 2023;11:110785. https://doi.org/10.1016/j.jece.2023.110785

[14] Balashanmugavel B, Subramani M, Vunnam V, Kasiviswanathan SCB. Synthesis, characterization and analysis of biodegradable polymer-coated urea fertilizers for controlled nutrient release. Polymer Bulletin 2024;81:15533–49. https://doi.org/10.1007/s00289-024-05431-6.

[15] Soltys LM, Mironyuk IF, Tatarchuk TR, Tsinurchyn VI. Zeolite-based Composites as Slow Release Fertilizers (Review). Physics and Chemistry of Solid State 2020;21:89-104. https://doi.org/10.15330/pcss.21.1.89-104.

[16] Fahmuddin A, Sulaeman, Suparto, Eviati. Petunjuk Teknis Analisis Kimia Tanah, Tanaman, Air dan Pupuk. Petunjuk Teknis Analisis Kimia Tanah, Tanaman, Air Dan Pupuk 2005:129–44. https://doi.org/10.30965/9783657766277_011

[17] AOAC. Official Methods of Analysis -Meneral determination. AOAC International 2019;1. https://www.aoac.org/wp-content/uploads/2019/08/Front-Matter-List-of-Changes-2.pdf

[18] Neina D. The role of soil pH in plant nutrition and soil remediation. Applied and Environmental Soil Science 2019;2019:5794869. https://doi.org/10.1155/2019/5794869.

[19] Araújo BR, Romão LPC, Doumer ME, Mangrich AS. Evaluation of the interactions between chitosan and humics in media for the controlled release of nitrogen fertilizer. Journal of Environmental Management 2017;190:122-31. https://doi.org/10.1016/j.jenvman.2016.12.059.

[20] Li Y, Sun Y, Liao S, Zou G, Zhao T, Chen Y, et al. Effects of two slow-release nitrogen fertilizers and irrigation on yield, quality, and water-fertilizer productivity of greenhouse tomato. Agricultural Water Management 2017;186:139-46. https://doi.org/10.1016/j.agwat.2017.02.006.

[21] Olorunfemi IE, Fasinmirin JT, Akinola FF. Soil physico-chemical properties and fertility status of long-term land use and cover changes: A case study in forest vegetative zone of Nigeria. Eurasian J Soil Sci 2018;7. https://doi.org/10.18393/ejss.366168. https://www.researchgate.net/publication/325337799_Soil_physico-

chemical_properties_and_fertility_status_of_long-term_land_use_and_cover_changes_A_case_study_in_Forest_vegetative_zone_of_Nigeria

[22] Hamoud YA, Shaghaleh H, Sheteiwy M, Guo X, Elshaikh NA, Khan NU, et al. Impact of alternative wetting and soil drying and soil clay content on the morphological and physiological traits of rice roots and their relationships to yield and nutrient use-efficiency. Agric Water Manag 2019;223. https://doi.org/10.1016/j.agwat.2019.105706 https://www.sciencedirect.com/science/article/abs/pii/S0378377419308741

[23] Li M, Liu Y, Luo L, Ying S, Jiang P. Effects of different biogas slurry application patterns on nitrogen and phosphorus losses in a paddy field. Paddy and Water Environment 2024;22: 521–533. https://doi.org/10.1007/s10333-024-00982-w.

[24] Zhou J. The effects of organic fertilizer on loss risk of nitrogen and phosphorus in paddy ponded water. Environmental Science and Pollution Research 2023;30:55529–40. https://doi.org/10.1007/s11356-023-26296-8.

[25] Asadu CO, Ezema CA, Ekwueme BN, Onu CE, Onoh IM, Adejoh T, et al. Enhanced efficiency fertilizers: Overview of production methods, materials used, nutrients release mechanisms, benefits and considerations. Environmental Pollution and Management 2024;1:32–48. https://doi.org/10.1016/j.epm.2024.07.002.

[26] Benlamlih FZ, Lamhamedi MS, Pepin S, Benomar L, Messaddeq Y. Evaluation of a new generation of coated fertilizers to reduce the leaching of mineral nutrients and greenhouse gas (N2o) emissions. Agronomy 2021;11:1129. https://doi.org/10.3390/agronomy11061129.

[27] Beig B, Niazi MBK, Jahan Z, Hussain A, Zia MH, Mehran MT. Coating materials for slow release of nitrogen from urea fertilizer: a review. Journal of Plant Nutrition 2020;43: 1510-33. https://doi.org/10.1080/01904167.2020.1744647.

[28] Ngatia L, Taylor R. Phosphorus Eutrophication and Mitigation Strategies. Phosphorus - Recovery and Recycling, 2019. https://doi.org/10.5772/intechopen.79173.

[29] Lu D, Dong Y, Chen X, Wang H, Zhou J. Comparison of potential potassium leaching associated with organic and inorganic potassium sources in different arable soils in China. Pedosphere 2022;32:330–8. https://doi.org/10.1016/S1002-0160(21)60077-2.