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Full Length Article

Study of the Nutrient Uptake Patterns for the Better Use of Controlled Release Compound Fertilizer in Rice Plant

Stefina Liana Sari[1*], Muhamad Rahman Djuwansah[2], Benny Joy[3], Emma Trinurani Sofyan[3], Mahfud Arifin[3], Tati Nurmala[4] and Astri Nur Istyami[5]
[1]*Doctoral Program, Faculty of Agriculture, Universitas Padjadjaran, Bandung, West Java, Indonesia*
[2]*National Research and Inovation Agency (BRIN), Indonesia*
[3]*Department of Soil Science, Faculty of Agriculture, Universitas Padjadjaran, Bandung, West Java, Indonesia*
[4]*Department of Agronomy, Faculty of Agriculture, Universitas Padjadjaran, Bandung, West Java, Indonesia*
[5]*Department of Bioenergy Engineering and Chemugry, Institut Teknologi Bandung, Indonesia*
[*]For correspondence: stefina.liana@unpad.ac.id; stefinalianasari25@gmail.com
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Abstract

This research aimed to enhance the efficiency of controlled release fertilizers (CRF) by analyzing nutrient uptake patterns of nitrogen (N), phosphorus (P) and potassium (K) in rice plants and modifying the shape and contact surface area of the fertilizer. The study employed a descriptive-exploratory approach, commencing with a literature review and qualitative research. Two rice field locations, Rice Field A in Katapang-Soreang District and Rice Field B in South Margahayu, Bandung Regency, West Java, were selected based on physiographic approach. Sampling point were determined and weekly plant samples were collected from each rice field for quantitative analysis. Key variables included the uptake of N, P and K, supported by ancillary variables such as initial soil analysis and dry weight of rice plants. Nutrient uptake data serves as a reference for modification, involving weekly accumulation calculations of nutrient requirements until week 10. Curve fitting was then performed to find a suitable polynomial equation, followed by applying a differential mathematical model to visualize the fertilizer's form. Validation of the similarity between Rice Fields A and B was conducted through soil analysis, statistical tests on the dry weight of rice plants and nutrient uptake. The research results indicated that the soil chemical properties in both rice fields were within normal ranges. Plant age variation influenced the dry weight of rice plants and nutrient uptake rates. The equation of a third-order polynomial curve has been identified as a reference equation in the application of differential models to modify and visualize the form of fertilizers. This study provides insights into the development of more efficient CRF which has the potential to contribute to global rice farming productivity and environmental sustainability. © 2024 Friends Science Publishers

Keywords: Controlled release fertilizer; Fertilizer shape modification; Nutrient uptake pattern; Mathematical model

Introduction

Rice is a vital staple food worldwide (Mahajan *et al*. 2017) and billion people obtain their calories from rice grains on a daily basis (Jabran *et al*. 2018) particularly in Asia. Effective and efficient fertilization strategies are crucial for sustaining rice production (Li *et al.* 2020). Proper fertilization can enhance harvest yields, crop quality and overall agricultural resource utilization efficiency. However, many agricultural nations face significant challenges due to inefficient fertilization practices, including South Asia like India, Nepal, and Bangladesh (Aryal *et al.* 2021), China (Hu *et al.* 2019; Martínez-Dalmau *et al.* 2021), Africa (Warra and Prasad 2020), Latin America and North America (Craswell 2021), Europe (Garske and Ekardt 2021) and Southeast Asia (Rashmi *et al.* 2020). Inappropriate fertilization doses or timing can lead to resource wastage and negative environmental impacts (Chen *et al.* 2018), such as environmental pollution from excessive nutrient release into the soil and water bodies.

To address these challenges, research on controlled release fertilizer (CRF) has garnered significant attention. CRF represents an intriguing alternative to enhance fertilization efficiency (Lawrencia *et al.* 2021). These fertilizers are designed to release nutrients gradually according to plant requirements (Vejan *et al.* 2021; Firmanda *et al.* 2022), reducing waste, promoting plant growth balance, and mitigating negative environmental impacts (Fertahi *et al.* 2021; Trenkel 2021) associated with conventional fertilization.

Research of Li *et al.* (2018) showed that controlled release urea significantly reduced NH_3 volatilization by 23–

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62% and surface runoff N loss by 8–58% compared to Urea prill. According to Lee *et al.* (2015), CRF reduced evaporation by 67%. Based on Hartati *et al.* (2020), chitosan-coated CRF could slow down N dissolution by 25.43% at 12 weeks of incubation compared to 43.43%. These findings indicate the potential for improving CRF efficiency, suggesting that efforts to enhance efficiency in this regard may yield meaningful results, especially considering that the issue of inefficiency is prevalent in many countries.

In this study, efforts to enhance CRF efficiency involve modifying CRF's shape and contact surface area using mathematical models. Mathematical modeling has proven successful in various agricultural aspects, including the development of advanced fertilizer prototypes (Babii *et al.* 2022). Mathematical modeling is crucial for understanding controlled release mechanisms and providing insights into factors influencing CRF properties. According to Irfan *et al.* (2018), nutrient release is influenced by granule radius, layer thickness and fertilizer granule diffusion coefficients. Model results can be compared with experiments to validate model reliability.

The model development in this context entails using differential mathematical models using cumulative nutrient uptake data from rice plants over 10 weeks. This data serves as a reference for designing an ideal fertilizer geometry profile with a release pattern tailored to plant needs. The fertilizer geometry model is derived from polynomial equations of nutrient uptake in plants for CRF development to improve efficiency and agricultural sustainability. Therefore, further investigation is needed on how rice plants' N, P and K uptake patterns over 10 weeks can be visualized into fertilizer forms using this differential mathematical model. This step is expected to provide valuable insights into utilizing optimal nutrient proportions at each stage of plant growth, aiming to develop more efficient and sustainable CRF.

Materials and Methods

Location determination, sampling, and parameters

The research was conducted using an exploratory method. Observations and sample collection were carried out in two rice fields located in the Katapang-Soreang District (107º34'22"E, 7º00'42"S) and South Margahayu (107º34'01"E, 6º58'16"S), Bandung Regency, West Java, Indonesia. These locations were selected based on a physiographic approach, similarity in agroclimatic conditions, and cultivation techniques. The research design falls into the category of descriptive research involving observation, sample collection, and quantitative analysis. Land use in Location A was previously dedicated to intensive rice cultivation with NPK fertilization at a recommended dose of 400 kg/ha and cultivation techniques following local farmer practices. Rice productivity per season typically ranged between 5 to 6 tons per hectare. Location B represented rice cultivation relying on ammonium sulphate fertilizer with a dose of 200 kg/ha and tofu factory wastewater flowing along the irrigation watercourse. Laboratory analysis indicated that the wastewater did not contain harmful compounds but had 2.58% organic carbon, 0.79% total-N, 0.31% total P_2O_5, and 0.56% K_2O. The As, Hg, Pb, Cd, Ni and Cr levels in wastewater met the irrigation water quality standards, indicating the absence of harmful contaminants that could affect plant growth or quality. The potential average yield ranged from 4.5 to 5 tons/ha. Critical parameters in this study included the uptake of N, P and K as the main variables, supported by soil analysis and dry weight analysis of plants as ancillary variables. N uptake was determined through digestion using the Kjeldahl method. Extraction for P and K uptake utilized the wet digestion method with HNO_3 and $HClO_4$, followed by P determination using colorimetry and K determination using a flame photometer (AOAC 2019). Soil initial analysis included several variables such as organic carbon, soil pH, total-N content, potential P_2O_5, and K_2O using 25% HCl extract, and soil texture. The determination is based on the technical guidelines by Jones (2018).

Sampling and analysis of soil chemical properties

Sampling and Analysis: Determination of the nutrient needs of rice plants in the field was conducted through plant tissue analysis. One of the values taken and calculated is derived from the analysis of nutrient uptake by rice plants. Data on the nutritional needs of plants were collected every week after planting (WAP) starting from 1 WAP, 2 WAP, 3 WAP, and so on until 10 WAP to create a representative curve. The sample collection was determined using the random sampling method. The number of samples was calculated based on the Slovin's equation as follows:

$$n = \frac{N}{1 + (N \text{ x } e^2)}$$

Where: n = sample size

N = population

e^2 = percentage of desired sampling error (95% confidence level and 5% error rate).

Plant tissue analysis began with the sample preparation stage, including weighing the fresh and dry weights of the plants, drying (air-dried at room temperature for 48 h oven-dried at 65°C for 24 h) and grinding the oven-dried samples using a porcelain mortar. Next, the analysis involved N, P and K. The data obtained over the 10 weeks were processed using Microsoft Office Excel to visualize the nutrient uptake pattern and curve equations.

Modeling

The data on nutrient absorption obtained each week formed the basis for creating the fertilizer model. The modeling began by calculating the accumulation of nutrient requirements each week up to week-10. After obtaining the cumulative nutrient absorption values for each week in percentage units (assuming that up to the week-10 was 100% of the total provided nutrients), the next step was curve fitting to find the polynomial equation with the most appropriate order of equations. This equation was derived (applied to the differential mathematical model) to visualize the geometry of the fertilizer with a specific scale.

Curve fitting

After obtaining data on the cumulative nutrient requirements for each week up to week-10, the next step was determining the most suitable polynomial model for this data. In the case of a polynomial curve, we sought a polynomial that fits our data through curve fitting. The polynomial degree depicts the level of polynomial complexity. For instance, a polynomial of degree two or quadratic was $ax^2 + bx + c$, while a polynomial of degree three or cubic was $ax^3 + bx^2 + cx + d$. The choice of the polynomial degree could be based on domain knowledge or experimentation. After choosing the polynomial degree, the next step was calculating the polynomial parameters, which involved adjusting the coefficients in the polynomial equation so that the determined polynomial curve was the best fit for our data. The adjustment was done using the least squares quadratic regression method. Finally, we could interpret the results of this polynomial model in the context of the problem at hand.

Visualizing fertilizer form

The last step was to visualize the geometry based on the model. This visualization took the form of a three-dimensional image depicting the cross-sectional profile of the fertilizer obtained from graphical data. After obtaining the polynomial equation or the function $y(x)$ against x, the next step was to find the first derivative of this equation, $z(x)$, using the differential transformation method. This derivative function could depict the rate at which nutrients should be released from the fertilizer at every specific time interval. Assuming that nutrient release was directly proportional to the surface area of the fertilizer in contact with the growing medium solution, the curve from the equation $z(x)$ served as the profile of the cross-sectional area of the fertilizer against position. Assuming that the fertilizer's cross-section was circular, the profile of the diameter of the fertilizer against position could be expressed in the form of an equation corresponding to the area equation of a circle. This equation was the mathematical relationship between the diameter d and the cross-sectional area of the fertilizer [Fertilizer cross-sectional area $A = kz(x)$]. If the area under the curve was calculated assuming a circular cross-section, then the area formed by the equation plus the area beneath it, as the curve $z(x)$ produced a shadow beneath it, representing the three-dimensional visualization of the fertilizer.

Determining constants

The constants referred to were the constants of the nutrient release rate of the fertilizer. These constants were sought through experimental trials, specifically through soaking fertilizer in a water medium. This testing was done separately to find only the constant. The main observation variable was the thickness of the fertilizer decreasing every week in the soak. The calculated data was the average thickness of the fertilizer lost or dissolved each week.

Statistical data analysis

Data processing, including mean and standard deviation calculations, and comparisons between various sample groups, were carried out using Microsoft Office Excel and SPSS software. Additionally, statistical analysis was performed to identify relationships or patterns within the dataset. As supporting data to ensure the difference in the amount of absorbed nutrients and the absence of the Location's influence on the N, P and K absorption curve patterns, statistical tests were conducted with Factor 1 being Location and Factor 2 being Plant age. DMRT test was performed after knowing the significant difference from the ANOVA test.

Results

Results of initial soil analysis

Soil chemical properties can significantly influence plant nutrient uptake. There was a slight difference in the initial soil analysis results between Location A and B (Table 1). The recorded pH values in the Soreang District were 7.02, and in the Margahayu District, these were 6.77, both indicating a neutral pH level. This pH condition is suitable for rice plant growth. The organic carbon content in the Soreang District was 2.84% (medium), while in the Margahayu District, it was 1.94% (low). The total N content recorded in the Soreang District was 0.20% (low), whereas in the Margahayu District, it was 0.39% (medium), indicating the need for additional organic carbon and N sources. The potential P_2O_5 content (extracted with 25% HCl) in the Soreang and Margahayu Districts was 86.21 mg/100 g (very high) and 56.21 mg/100 g (high), respectively, while the K_2O content was 68.94 mg/100 g (very high) and 48.94 mg/100 g (high). The soil in both locations had a clay texture. Overall, the soil analysis results in both locations indicated normal conditions.

Rice plant dry weight

The soil chemical properties could indirectly influence nutrient uptake, subsequently affecting the dry weight of rice plants. The dry weight parameters of rice plants did not significantly differ at the location until the ninth week after

Table 1: Soil Analysis of the two sampling locations

No.	Parameters	Location A[1]		Location B[2]	
		Value	Criteria**	Value	Criteria*
1.	pH: H_2O	7.02	Neutral	6.77	Neutral
2.	Organic - C (%)	2.84	Medium	1.94	Low
3.	N Total (%)	0.20	Low	0.39	Medium
4.	P_2O_5 HCl 25 % (mg/100 g)	86.21	Very High	56.21	High
5.	P_2O_5 - Olsen (mg. kg^{-1} P)	18.33	High	11.14	Medium
6.	K_2O HCl 25 % (mg/100 g)	68.94	Very High	48.94	High
7.	Texture:	-	Clay	-	Clay
	Sand (%)	9		8	
	Silt (%)	36		38	
	Clay (%)	55		54	

Descriptions: Location A: Rice Plant Sampling Location - Sukamukti, Katapang, (Altitude: 107º34'22"E, Longitude: 7º00'42"S); Location B: Rice Plant Sampling Location - South Margahayu, Bandung Regency (Altitude: 107º34'01"E, Longitude: 6º58'16"S)

Table 2: Response of rice plants in different locations and plant ages to dry weight

Plant Age (WAP)	Dry Weight (gram)	
	Location A	Location B
1	0.54 ± 0.06 a A	0.44 ± 0.05 a A
2	1.10 ± 0.75 a A	0.80 ± 0.11 a A
3	3.21 ± 1.51 a A	3.79 ± 1.22 ab A
4	8.37 ± 1.06 b A	8.09 ± 0.12 b A
5	14.15 ± 1.33 c A	13.57 ± 0.40 c A
6	39.37 ± 1.29 d A	39.62 ± 0.78 d A
7	49.12 ± 3.25 e A	50.16 ± 1.01 e A
8	55.27 ± 2.89 f A	55.89 ± 2.02 f A
9	97.30 ± 8.53 g A	95.39 ± 9.82 g A
10	132.37 ± 19.70 h B	126.91 ± 5.37 h A

Description: WAP = Weeks After Planting. The average numbers followed by the same letter are not significantly different based on the DMRT test at a 5% significance level. Capital letters are read vertically, comparing between 2 Locations for the same type of fertilizer

planting (Table 2). However, by the end of the observation period, a significant difference in the dry weight of rice plants was evident between the two locations.

N-uptake

The ANOVA revealed a highly significant interaction between plant age and location on N in plant tissues. Table 3 shows significant differences in N-uptake between locations A and B, evidenced by different notations observed horizontally. The significant differences indicate the influence of different types of N fertilizers used in the cultivation process. N-uptake in Location B tended to be higher than in Location A due to the use of ZA fertilizer containing higher N compared to the NPK 15-15-15 fertilizer used in Location A. Significant variations in N content in plant tissues occurred every week because, in the early growth stage, plants prioritize root and leaf development. At this stage, N uptake is relatively low because the plant does not require a large amount of N for photosynthesis and vegetative growth. Most of energy is allocated to structural development and expanding water and other nutrient absorption (Sun *et al.* 2019; Iatrou *et al.* 2021).

P-uptake

The differences in plant location and age also significantly influence the P content in plant tissues (Table 3). Every week, the P content in plants increased. Younger plants would exhibit different P requirements compared to older plants. On the other hand, location differences, especially soil conditions, also impact the P content of plants, as evidenced by significant disparities in the same growth stage cultivated in different soil conditions. Additionally, plants cultivated in different locations may experience variations in soil P availability, potentially affecting P uptake by plant roots. Soil acidity and nutrient composition can also influence a plant's P availability and uptake. Factors such as the need for P at various growth stages, soil P availability, and the interaction between plant age and environmental factors can affect P uptake and accumulation by plants.

Table 3: Nitrogen, phosphorus and potassium uptake by rice plant in different locations and ages

Plant age (WAP)	Nitrogen Content (%)		Phosphorus Content (%)		Potassium Content (%)	
	Location A	Location B	Location A	Location B	Location A[1]	Location B[2]
1	2.02 ± 0.02 a A	2.48 ± 0.57 a B	0.25 ± 0.04 a B	0.18 ± 0.02 a A	0.77 ± 0.08 a B	0.74 ± 0.04 a A
2	2.18 ± 0.02 a A	2.86 ± 0.09 b B	0.63 ± 0.08 c B	0.58 ± 0.11 c A	0.84 ± 0.05 b A	0.81 ± 0.04 b A
3	2.62 ± 0.02 b A	3.31 ± 0.76 c B	0.74 ± 0.07 d A	0.70 ± 0.02 d A	0.86 ± 0.02 b A	0.83 ± 0.05 b A
4	3.13 ± 0.36 c A	3.85 ± 0.54 d B	0.83 ± 0.06 e A	0.82 ± 0.04 e A	0.93 ± 0.08 c A	0.96 ± 0.07 c A
5	3.30 ± 0.39 cd A	4.19 ± 0.42 ef B	1.13 ± 0.05 g A	1.10 ± 0.12 g A	1.21 ± 0.10 d A	1.28 ± 0.06 d B
6	3.36 ± 0.21 cd A	4.31 ± 0.68 fg B	1.18 ± 0.06 g A	1.17 ± 0.07 h A	1.34 ± 0.04 e A	1.33 ± 0.04 e A
7	3.46 ± 0.13 d A	4.46 ± 0.71 fg B	1.07 ± 0.06 f B	0.96 ± 0.04 f A	1.46 ± 0.04 g B	1.39 ± 0.02 f A
8	2.51 ± 0.24 b A	4.54 ± 0.13 g B	0.72 ± 0.21 d A	0.85 ± 0.09 e B	1.37 ± 0.08 f A	1.41 ± 0.04 f B
9	2.46 ± 0.18 b A	4.01 ± 0.08 de B	0.52 ± 0.06 b A	0.52 ± 0.14 c A	0.97 ± 0.04 c A	0.94 ± 0.05 c A
10	2.02 ± 0.40 a A	3.05 ± 0.07 b B	0.50 ± 0.05 b B	0.42 ± 0.02 b A	0.85 ± 0.06 b B	0.74 ± 0.01 a A

Description: WAP = Weeks After Planting. The average numbers followed by the same letter are not significantly different based on the DMRT test at a 5% significance level. Capital letters are read vertically, comparing between 2 Locations for the same type of fertilizer

Fig. 1: Map of rice plant sampling locations: (**a**) Location A: Rice Plant Sampling Location - Sukamukti, Katapang, (Altitude: 107º34'22"E, Longitude: 7º00'42"S); (**b**) Location B: Rice Plant Sampling Location - South Margahayu, Bandung Regency (Altitude: 107º34'01"E, Longitude: 6º58'16"S)

K-uptake

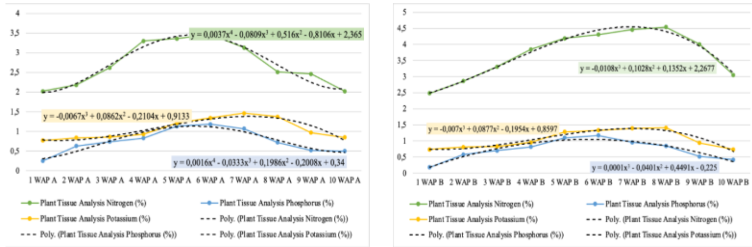
Like K in plant tissues (Table 3), there were significant differences based on the plant's location and age. The concentration of K in plant tissues increased with plant growth and the rising demand for K in metabolic processes and physiological functions such as protein synthesis, osmotic pressure regulation, and nutrient transport. However, after reaching its peak in the vegetative phase, the concentration of K in plant tissues reached a saturation point. At this point, K uptake by plants tended to stabilize, and the K concentration in plant tissues remained relatively constant even as the plant continued to grow. After this phase, the K concentration in plant tissues decreased.

Nutrient uptake patterns

The nutrient requirements of nitrogen (N), phosphorus (P), and potassium (K) in rice plants from locations A and B, analyzed over a period of 10 weeks, exhibit slight differences, particularly noticeable at the peak of the N curve (Fig. 1a, b and Fig. 2a, b). The solid lines on the curve represent the actual nutrient uptake patterns of rice plants based on quantitative laboratory analysis, while the dashed lines represent the trend lines based on the polynomial model, analyzing visually and representing the mathematical patterns or trends in the data. There was an increase in N levels in both Location A and B from the first week towards the second week, continuing to rise. Maximum N uptake in rice occurred in Location A during the sixth week, while in Location B, it peaked in the eighth week. Subsequently, in the following weeks, a decline was observed. The apex of the curve for P-uptake in both locations appeared between the seventh and eighth weeks, gradually diminishing thereafter. In contrast, for K, an increase occurred in both locations in the sixth week, followed by a subsequent decrease.

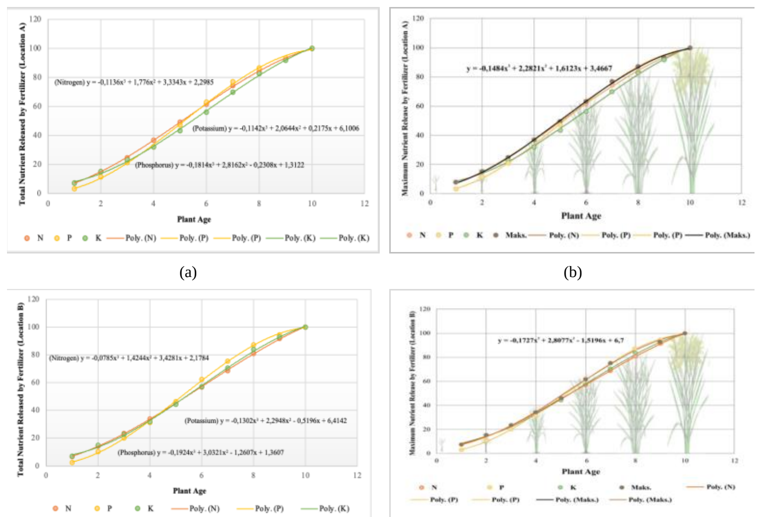
Fertilizer model

The nutrient uptake patterns of N, P and K in plants for each week up to the age of 10 weeks have been elucidated based on (Fig. 2a, b) while cumulatively, nutrient uptake can be



(a) (b)

Fig. 2: Pattern of N, P and K Nutrient Requirements in Rice Plants During 10 Weeks: (**a**) Nutrient Uptake Pattern in Location A; (**b**) Nutrient Uptake Pattern in Location B



(a) (b) (c) (d)

Fig. 3: (**a**) Derivatives of the N, P, and K Uptake Curves at Location A; (**b**) The third-order polynomial equation derived from the outermost line of the N, P and K uptake curves at Location A; (**c**) Derivatives of the N, P, and K Uptake Curves at Location B; (**d**) The third-order polynomial equation derived from the outermost line of the N, P and K uptake curves at Location B

modeled using (Fig. 3a, c). Processed patterns for curve fitting were derived from the equations of cumulative uptake curves over 10 weeks, representing the outermost lines of the curve to obtain maximum values at each coordinate, as depicted in (Fig. 3b, d). The outermost lines indicate the maximum nutrient values (of N, P and K) that can be supplied by the fertilizer based on plant requirements derived from uptake values. The equations used are equations (1) and (2).

Location A:

$$y = -0.1484x^3 + 2.2821x^2 + 1.6123x + 3.4667 \qquad (1)$$

Remark: y = Cumulative nutrient requirement of rice in percentage; x = Age of the plant in weeks (DAP); p1 = -0.1484; p2 = 2.2821; p3 = 1.6123; p4 = 3.4667.

Location B:

$$y = -0.1727x^3 + 2.8077x^2 - 1.5196x + 6.700 \qquad (2)$$

Remark: y = Cumulative nutrient requirement of rice in percentage; x = Age of the plant in weeks (DAP); p1 = -0.1727; p2 = 2.8077; p3 = 1.5196; p4 = 6.7.

Based on the conducted curve fitting, the suitable mathematical model determined is a third-order polynomial equation with the maximum line equation. Thus, the rate of nutrient release from the fertilizer can be expressed as the first derivative of $y(x)$ with respect to x. In this equation, y represents the cumulative nutrient required by rice in percentage units, while x represents time in days. Therefore, the rate of nutrient release by fertilizer can be expressed as the first derivative of (x) with respect to x. This rate is expressed in the equation;

Location A:

$$z(x) = dy(x)/dx = 3(-0.1484)\, x^2 + 2(2.2821)\, x + 1.6123 \qquad (3)$$

The equation of the derivative curve is:

$$y = -0.4452\, x^2 + 4.5642\, x + 1.6123 \qquad (4)$$

Location B:

$$z(x) = dy(x)/dx = 3(-0{,}1727)\, x^2 + 2(2{,}8077)\, x + 1{,}5196 \qquad (5)$$

The equation of the derivative curve is:

$$y = -0{,}5181x^2 + 5{,}6154x + 1{,}5196 \qquad (6).$$

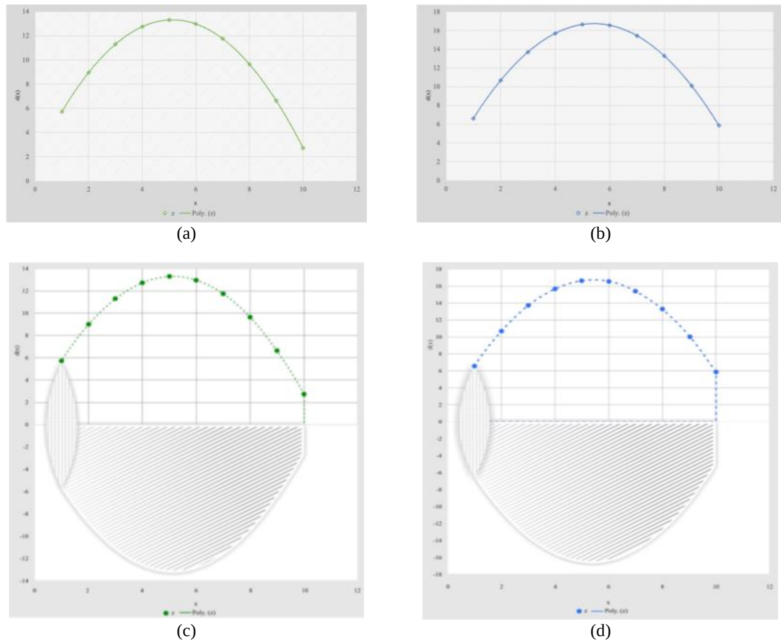


Fig. 4: (a) Nutrient release rate of NPK in rice plants (Location A), which is the derivative equation of the previous model. (**b)** Nutrient release rate of NPK in rice plants (Location B), which is the derivative equation of the previous model. **(c)** Depicts the geometric profile of the fertilizer assuming a three-dimensional cross-section in a circular shape from Location A. **(d)** Depicts the geometric profile of the fertilizer assuming a three-dimensional cross-section in a circular shape from Location B

Equations (3) and (5) represent the fertilizer release rate, where $z(x)$ denotes the nutrient release rate in percentage per day, with its derivatives given by equations (4) and (6). These equations are visualized using the curve model in (Fig. 4a, b). Assuming cumulative release of N, P and K is directly proportional to the surface area of fertilizer contact with the growing medium (Fig. 4c, d) can be interpreted as the cross-sectional profile of the fertilizer seen from its position, with the three-dimensional cross-section of the circular-shaped fertilizer. The fertilizer diameter profile at its position can be expressed as an equation corresponding to the circle area equation.

Discussion

Utilizing a differential mathematical model serves as a new foundation for modifying nutrient release in Compound Controlled-Release Fertilizer (CRF). This modification focuses on altering the release zone's shape and surface area to control the nutrient release rate. This method is more accurate as it is based on the nutrient uptake patterns of plants. Soil chemical properties are considered in determining sampling locations as they indirectly affect nutrient availability and uptake rates in the soil. According to Moe *et al.* (2019) and Shankar *et al.* (2021), N is a crucial nutrient for plant growth and protein synthesis. Adequate N supply supports optimal plant growth (Singh 2018; Xiong *et al.* 2021). Balanced availability of P and K is also essential (Du *et al.* 2021), as both elements play a crucial role in nutrient metabolism and transportation within plants.

The used compound NPK fertilizer by local farmers impacted soil contents of total-N, potential-P_2O_5, K_2O at Location A. According to Dai *et al.* (2021), the use of NPK is a major contributor to the increase in soil nutrient content. Compound NPK provides a more balanced nutrient supply (Budiono *et al.* 2019). Another contributing factor may be the slower nutrient release mechanism from NPK fertilizer (Roy *et al.* 2021), which positively influences soil nutrient availability. The ZA fertilizer used at Location B contains N from NH_4, sulfur from sulfuric acid, and a small amount of carbon, N, P and K from wastewater, resulting in fewer nutrients, especially primary macronutrients like P and K. The soil organic carbon content below 2% at Location B indicates a relatively low level of organic matter, including residues from decomposed or dead organisms (Gross and Harrison 2019; Polyakov and Abakumov 2021), including plant residues (Laik *et al.* 2021), humus, and other organic materials (Murindangabo *et al.* 2023). The presence of organic carbon content of 1.94% in wastewater carried by irrigation water represents a significant source of organic carbon for soil fertility at Location B.

Furthermore, the total N, P_2O_5 and K_2O contents in wastewater contribute additional N needed by rice plants. Although the average yield potential is slightly lower (ranging from 4.5 to 5 tons/ha) in this location, the utilization of ZA fertilizer and decomposed wastewater still provides essential nutrients for plant growth while complying with irrigation water standards. Thus, crop productivity still meets standards and is not significantly different from Location A. However, it is essential to note that these results are observational and further analysis is needed to understand in more detail the factors influencing the differences in the total-N, P_2O_5 and K_2O soil content between the two locations.

The age of plants influences plant growth and production. Generally, as the plants' age increases, the plants' dry weight also increases due to prolonged photosynthetic processes (Qaderi *et al.* 2019). The growth can be indirectly influenced by nutrient availability and factors such as soil type, water availability, and other environmental factors (Wu *et al.* 2018; Xu *et al.* 2020), which may not significantly differ between the two research locations. In the early weeks until the ninth week of planting, there was no significant difference in the dry weight of rice plants between the two locations. The indifference indicates that factors influencing plant growth and production during this period are relatively similar in both locations. However, by the 10^{th} week, there is a significant difference in the dry weight parameter of rice plants between the two locations.

The age of the plants also significantly affects the requirements for N (Wu *et al.* 2019; Dubey *et al.* 2021), P (Irfan *et al.* 2019) and K content (Peng *et al.* 2018) in plant tissues. In the early growth stage, plants prioritize root and leaf development, leading to relatively low N uptake as it is not required in large quantities for photosynthesis and vegetative growth. Additionally, P in plant tissues is utilized for leaf formation (Bakri *et al.* 2020; Mahmoodi *et al.* 2020). As the plant size increases during the vegetative phase, where leaf and stem growth dominate, K uptake increases significantly. Besides plant age, the growing location also plays a crucial role in the nutrient content in plant tissues. Environmental conditions (Kumarathilaka *et al.* 2018), such as soil characteristics (Oladele *et al.* 2019), climate and fertilizer management at each location, can influence nutrient availability and uptake by plants (Chen *et al.* 2021a). Therefore, it is essential to consider location-specific factors when designing effective fertilization strategies.

The significant interaction between plant age and location indicates that rice plant tissues' N, P and K content may vary. The observed sigmoid curve in the N, P and K content in plant tissues has significant implications for fertilizer management. Proper nutrient application during the intensive vegetative phase can enhance plants nutrient availability (Shankar *et al.* 2021) and promote optimal growth. However, based on findings from; Moreno-moreno *et al*. (2018), Calderón *et al*. (2020) and Chen *et al.* (2021b), excessive fertilization in later growth stages may not provide significant benefits and may lead to excess nutrients in the soil.

The analysis results of N, P and K in rice plants in both locations are suspected to be influenced by environmental conditions, one of which is nutrient availability in the soil (Guo *et al.* 2019; Geisseler *et al.* 2020). Differences in fertilization practices affect the timing of maximum nutrient uptake by plants. According to the research by Kuppusamy *et al.* (2017) and Bhatt *et al.* (2019), primary macronutrients, such as N, P and K, are supplied in large amounts through organic and inorganic fertilizer applications. Different timing of maximum nutrient uptake in different locations may result from different nutrient supplies (Shrestha *et al.* 2020). Fertilization in Location A has adhered to the standard NPK application and dosage for rice plants, while in Location B, it is still based on the cultivation techniques of local farmers. However, the nutrient uptake patterns based on time are almost similar, as evidenced by the shape of the nutrient uptake curve, forming a parabolic curve with a third-order polynomial equation. In the early vegetative stage, rapid nutrient uptake occurs when nutrients are sufficiently available (Ghosh *et al.* 2020). As plant growth progresses, some nutrients become increasingly scarce and nutrient uptake reaches saturation when one of these nutrients becomes limited. Towards the reproductive phase, nutrient levels in plant tissues decrease as the absorbed nutrients are used for various metabolic processes and transformations within plant tissues (Ravshanov *et al.* 2023).

The findings support the use of mathematical models in understanding nutrient release patterns from fertilizers, as evidenced by Zhao *et al.* (2017); Irfan *et al.* (2018); Babii *et al.* (2022), who employed mathematical models in fertilizer prototype development. The study reveals the enduring consistency of a third-order polynomial model in describing nutrient release patterns from fertilizers, despite divergent soil properties and nutrient uptake by rice plants in two locations. This aligns with the theory proposing a consistent sigmoidal nutrient uptake curve, reflecting initial slow growth or decline, followed by rapid growth, and subsequent deceleration (Timilsena *et al.* 2015; Prasad and Mailapalli 2018; Tariq *et al.* 2022). Despite potential parameter variations, the overall sigmoidal pattern remains steadfast. Validated mathematical models from two distinct locations form a sturdy base for fertilizer development. This model offers a potential framework for adapting other fertilizers to match nutrient release rates for crops beyond rice. Additional research is needed to assess the model's validity and applicability across diverse crops and agricultural settings.

Conclusion

Different locations, particularly due to variations in fertilization practices, influence the timing of the maximum absorption of specific nutrients by rice plants. However, the nutrient uptake pattern remains consistent despite variations in the concentrations of N, P and K in plant tissues. Additionally, variations in plant age can impact the dry weight of plants and the rates of N, P and K uptake. The research findings support using a third-order polynomial curve model as the basis for fertilizer modification. This model has been validated in two observation locations and produces a similar curve shape for nutrient uptake. The first derivative of the cumulative plant uptake rate equation can depict the geometric profile of the fertilizer with a three-dimensional circular cross-section. This model can release nutrients accurately based on the plant's requirements in each growth phase, thus enhancing fertilization efficiency and reducing residue.

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Author Contributions

Conceptualization, SLS, MRD and ANI; methodology, SLS and ETS; software, SLS, and ANI; validation, BJ, MRD and MA; formal analysis, ETS, BJ, and SLS; investigation, RJ, ETS, MA and TN; resources, SLS, BJ, and ETS; data curation, SLS, MRD and TN; writing original draft preparation, SLS, RD and ETS; writing review and editing, SLS, MRD and BJ; visualization, SLS and MRD; supervision, BJ, MA, ETS and TN; project administration, SLS, ANI; funding acquisition, SLS. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

All authors declare no conflict of interest

Data Availability

Data presented in this study will be available on a fair request to the corresponding author.

Ethics Approval

Not applicable to this paper

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