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Optimization of N, P, and K Fertilizer Rates for 'IPB 13S' Rice

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Abstract

Fertilizer recommendations for newly released rice varieties need to be optimized because nutrient requirements may vary among varieties and growing environments. 'IPB 13S' is a newly released rice variety developed by IPB University, and information regarding its optimal nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) requirements is still limited. Therefore, this study aimed to determine the optimal rates of N, P_2O_5, and K_2O fertilizers for 'IPB 13S' rice. The study was conducted from May to September 2024 at the Sawah Baru Experimental Farm, Dramaga, Bogor, Indonesia. Three fertilizer experiments (N, P_2O_5, and K_2O) were arranged in a randomized complete block design (RCBD) with five fertilizer levels (0%, 50%, 100%, 150%, and 200% of the regional recommended rate) and three replications. Growth parameters, yield components, grain yield, and nutrient use efficiency were evaluated. Data were analyzed using analysis of variance, orthogonal polynomial analysis, and quadratic regression. The results showed that N, P_2O_5, and K_2O applications significantly affected plant growth, yield components, grain yield, and nutrient use efficiency. Quadratic regression analysis identified optimal fertilizer rates of 170 kg N/ha, 53 kg P_2O_5/ha, and 71 kg K_2O/ha, resulting in the highest predicted grain yield. These findings indicate that variety-specific fertilizer recommendations are needed to optimize grain yield and nutrient use efficiency in the 'IPB 13S' rice variety.

Keywords: fertilizer optimization, macronutrients, precision agriculture, relative yield

Introduction

Rice (*Oryza sativa* L.) is a principal food crop consumed by about half of the global population, with around 90% of its cultivation occurring in Asia, a trend that continues to rise alongside population growth (Devkota et al., 2019). The population of Indonesia was projected to reach 281.6 million in 2023. In 2024, the rice harvested area was 10.05 million hectares, reflecting a reduction of 167,250 hectares or 1.64% from the 2023 harvest area of 10.21 million hectares, alongside the growing population. Rice production in 2024 is projected to be 52.66 million tons of dry milled grain (GKG), reflecting a reduction of 1.32 million tons or 2.45% from the 2023 production of 53.98 million tons of GKG (Statistics Indonesia, 2024). Rice production is anticipated to rise by 40% by 2040 (Gu et al., 2021).

Efforts to increase rice productivity involve not only improvements in irrigation and land management but also the adoption of superior rice varieties (Paiman et al., 2020). 'IPB 13S' is one of the newly released rice varieties developed by IPB University. To achieve its yield potential, the variety must be supported by appropriate fertilization practices. Nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) are essential macronutrients that regulate plant growth, development, and grain production. Therefore, balanced nutrient management is required to optimize productivity and fertilizer use efficiency (Liu et al., 2021; Noulas et al., 2023).

Fertilizer use in rice cultivation continues to increase. However, excessive and unbalanced

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fertilizer application does not always result in higher yields. In addition to increasing production costs, inappropriate fertilizer use may reduce nutrient use efficiency, accelerate soil degradation, and negatively affect the environment (Khmelevtsova et al., 2023; Zainudin & Kusumawati, 2021). Therefore, fertilizer recommendations should be developed based on crop requirements and soil fertility conditions to ensure sustainable rice production (Wanjari et al., 2022).

Balanced fertilizer application should ideally be based on soil analysis results (Rani et al., 2022). However, soil testing is often costly and labor intensive, limiting its application under field conditions. The multi-nutrient response approach provides an alternative method for generating preliminary fertilizer recommendations (Waugh et al., 1973). This approach to fertilizer management is particularly important for newly released rice varieties because nutrient requirements and fertilizer use efficiency may differ among varieties (Suwarto et al., 2021). Current fertilizer recommendations are generally developed at the regional level and may not adequately account for variations in soil fertility and varietal responses. As a newly released rice variety, information regarding the response of 'IPB 13S' to nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) fertilization is still limited. Therefore, this study aimed to determine the optimal rates of N, P_2O_5, and K_2O fertilizers for the 'IPB 13S' rice variety.

Material and Methods

The study was conducted from May to September 2024 at Sawah Baru Experimental Farm located in Babakan, Dramaga, Bogor, Indonesia. Soil analysis and plant nutrient assessment were conducted at the Testing Laboratory of the Department of Agronomy and Horticulture, IPB University. The materials used were seeds of the 'IPB 13S' variety, urea fertilizer (46% N), SP36 (36% P_2O_5), and KCl (60% K_2O).

The soil in the experimental area was categorized as slightly acidic (pH 5.72), with moderate organic carbon content (2.42%), moderate total nitrogen content (0.28%), very high phosphorus content according to the Olsen method (965.48 ppm), low exchangeable potassium content (16.31 mg/100 g), and high cation exchange capacity (26.85 cmol/kg).

These soil characteristics are generally comparable to those reported in many irrigated rice-growing areas in Indonesia, where soils commonly range from slightly acidic to neutral and often exhibit variable nutrient availability depending on fertilization history and management practices (Zainudin & Kesumaningwati, 2021). The very high available phosphorus content observed in the experimental field may be associated with the long-term application of phosphorus fertilizers, whereas the relatively low potassium content indicates the importance of balanced nutrient management (Wanjari et al., 2022). Therefore, the soil conditions at the site were considered suitable for evaluating fertilizer responses, although fertilizer recommendations may need to be adjusted according to local soil fertility status.

This study consisted of three simultaneous experiments: nitrogen, phosphorus, and potassium fertilization experiments. The study employed a randomized complete block design with a single factor, specifically the rate of inorganic fertilizer at five levels: 0%, 50%, 100%, 150%, and 200% of the reference rate, with three replications for each level. The fertilizer rates for each treatment were as follows: (1) N: 0, 80.5, 161.0, 241.5, and 322.0 kg N/ha; (2) P_2O_5: 0, 18.0, 36.0, 54.0, and 72.0 kg P_2O_5/ha; and (3) K_2O: 0, 30.0, 60.0, 90.0, and 120.0 kg K_2O/ha. The reference rates were based on the recommended rates of individual fertilizers for rice cultivation in the rice fields of Dramaga District, Bogor Regency, namely 350 kg urea/ha (161 kg N/ha), 100 kg SP36/ha (36 kg P_2O_5/ha), and 100 kg KCl/ha (60 kg K_2O/ha) (Ministry of Agriculture, 2022). Each experimental series consisted of 15 experimental units. Measurements were conducted for each experimental unit.

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Research Procedures

Land preparation was completed two weeks before transplanting. Rice seedlings were transplanted at 21 days after seeding using a 5:1 row arrangement with a spacing of 15 cm × 30 cm, following the standard planting practice for irrigated rice in the study area. Fertilizers were uniformly applied under puddled soil conditions. Urea was applied in three equal splits at 7, 25, and 45 days after transplanting (DAT). SP36 was applied once at 7 DAT, while KCl was applied in two equal splits at 7 and 42 DAT (Faisal et al., 2019). Harvesting was conducted when approximately 90% of the grains on the panicle had turned yellow.

The measured variables included plant height (cm), number of tillers, percentage of productive tillers, SPAD value, crop growth rate (CGR) (g/m^2 per day), N, P_2O_5, and K_2O use efficiency (kg of grain per kg of N, P, and K supply), number of grains per panicle, percentage of filled grains per panicle (%), grain yield per 7.92 m^2 (kg), grain yield (tons/ha).

The crop growth rate was determined using the methodology provided by Santana et al., (2021):

$$\mathrm{CGR} = \frac{(W_2 - W_1)}{A\ x\ (t_2 - t_1)}$$

Where: W_1 and W_2 are the plant dry weights (g) measured at times t_1 and t_2, respectively; A is the ground area (m^2); and ($t_2 - t_1$) is the time interval between observations (days).

Nitrogen, phosphorus, and potassium use efficiency was calculated using the following formulas (Congreves et al., 2021):

NUE = grain dry weight (kg/ha)/total N supply (kg/ha)

PUE = grain dry weight (kg/ha)/total P_2O_5 supply (kg/ha)

KUE = grain dry weight (kg/ha)/total K_2O supply (kg/ha)

Where: NUE: N use efficiency, PUE: P_2O_5 use efficiency, KUE: K_2O use efficiency.

Data Analysis

The observational data for each variable were subjected to analysis of variance (ANOVA) at α = 0.05. Prior to ANOVA, the data were examined to ensure that the assumptions required for parametric analysis were reasonably met. When significant treatment effects were detected, treatment means were compared using Duncan's multiple range test (DMRT) at 5% significance level. DMRT was selected because it is widely used in agronomic and fertilizer-response studies and provides adequate sensitivity for detecting differences among fertilizer rate treatments. When the experimental results showed the same response pattern, the three graphs were interpreted together to determine the N, P_2O_5, and K_2O requirements (Waugh et al., 1973). To determine the optimal fertilizer rate, a quadratic regression analysis was conducted with the equation: $y = ax^2 + bx + c$ with y = grain yield, x = fertilizer rate, and a, b, c = constants. The optimal fertilizer rate was determined from the quadratic regression equation ($y = ax^2 + bx + c$). The first derivative of the equation was $dy/dx = 2ax + b$. The optimal value of x was obtained by setting the first derivative equal to zero ($dy/dx = 0$), resulting in: $x = -b/(2a)$. Statistical analysis was conducted using Microsoft Excel 2016 and RStudio.

Results and Discussion

Morphological Components

The application of nitrogen (N) at different rate levels significantly influenced plant height, tiller number per clump, productive tiller percentage, and crop growth rate (CGR) (Table 1). Plant height showed a significant quadratic response ($y = -0.0009x^2 + 0.2546x + 83.061$), increasing from 87.9 cm in the control treatment to 108.2 cm at 241.5 kg N/ha, although no significant increase was observed at higher N rates. Similarly, tiller number per clump exhibited a highly significant quadratic response ($y = -0.0019x^2 + 0.5756x + 60.166$), increasing from 11.9 tillers in the control

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to 20.5 tillers at 322.0 kg N/ha, but without significant differences from the 80.5–241.5 kg N/ha treatments. These results indicate that nitrogen promoted vegetative growth and tiller development, thereby increasing the potential number of panicles per unit area. The proportion of productive tillers also showed a highly significant quadratic response ($y = -0.0029x^2 + 0.7419x + 56.953$), reaching a maximum of 72% at 80.5 kg N/ha before declining to 62% at 322.0 kg N/ha. This decline suggests that excessive N application stimulated vegetative growth without proportionally increasing productive tillers. Crop growth rate (CGR) increased significantly with N application and followed a quadratic response ($y = -0.005x^2 + 0.1544x + 6.006$), rising from 5.3 g/m^2 per day in the control to 18.5 g/m^2 per day at 322.0 kg N/ha. However, the increase above 161.0 kg N/ha was not statistically significant, indicating that additional N provided limited growth benefits once crop nutrient demand had been largely satisfied.

The application of P_2O_5 fertilizer significantly affected all measured growth parameters (Table 1). Plant height exhibited a significant quadratic response ($y = -0.0012x^2 + 0.2769x + 84.8$), increasing by 19.7% over the control and reaching its maximum at 36.0 kg P_2O_5/ha. Similarly, tiller number per clump followed a quadratic response ($y = -0.0019x^2 + 0.4993x + 69.39$), increasing from 13.5 tillers in the control treatment to 19.3–20.3 tillers at 36.0–72.0 kg P_2O_5/ha, with no significant differences among these rates. These results indicate that phosphorus promoted vegetative growth and tiller development, thereby increasing the potential number of panicles per unit area. The proportion of productive tillers also showed a significant quadratic response ($y = -0.0036x^2 + 0.8814x + 49.728$), increasing from 50% in the control treatment to 72%–73% at 18.0–36.0 kg P_2O_5/ha before declining to 65% at 72.0 kg P_2O_5/ha. This suggests that excessive phosphorus application increased tiller production without proportionally improving tiller productivity. Crop growth rate (CGR) likewise followed a quadratic response ($y = -0.0005x^2 + 0.1504x + 8.4016$), with the highest value observed at 72.0 kg P_2O_5/ha. However, the absence of consistent statistical differences at higher P rates indicates that phosphorus use efficiency declined beyond the optimal level, resulting in limited additional benefits for crop growth.

The application of K_2O fertilizer significantly affected plant height, tiller number per clump, productive tiller percentage, and crop growth rate (CGR) (Table 1). Plant height increased linearly with K_2O application, from 94.5 cm in the control treatment to 109.6 cm at 120 kg K_2O/ha, representing a 16.0% increase. Similarly, the number of tillers per clump increased from 11.6 in the control to 20.5 at 120 kg K_2O/ha, equivalent to a 76.7% increase. These results indicate that potassium promoted vegetative growth and tiller development, thereby increasing the potential number of panicles per unit area. The proportion of productive tillers exhibited a highly significant quadratic response ($y = -0.0034x^2 + 0.8464x + 45.904$), reaching a maximum of 76% at 60 kg K_2O/ha before declining to 61% at 120 kg K_2O/ha. This finding suggests that moderate potassium application was sufficient to optimize tiller productivity, whereas higher rates provided limited additional benefits. Crop growth rate (CGR) increased linearly with increasing K_2O application, from 9.2 g/m^2 per day in the control to 21.8 g/m^2 per day at 120 kg K_2O/ha. The increase in CGR indicates greater biomass accumulation and confirms the important role of potassium in supporting overall plant growth and productivity.

The application of nitrogen (N) fertilizer significantly influenced flag leaf development and chlorophyll concentration, as indicated by SPAD values (Table 2). Flag leaf length exhibited a highly significant linear response to increasing nitrogen rates. The shortest flag leaf length (30.1 cm) was observed in the nitrogen-free treatment, whereas the longest (37.0 cm) was recorded at the highest rate of 322.0 kg N/ha. This result indicates that nitrogen promoted leaf elongation through its role in protein synthesis, cell division, and overall vegetative growth. Since the flag leaf is the primary photosynthetic organ during grain filling, longer leaves may contribute to greater assimilate production for grain development.

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Flag leaf area also increased substantially during both the heading and harvest stages. At heading, the response was linear, reaching a maximum area of 55.9 cm^2 at 241.5 kg N/ha. At harvest, the increase followed a highly significant quadratic trend described by the equation $y = -3.857x^2 + 14.986x + 11.18$. The expansion of flag leaf area indicates that nitrogen enhanced the photosynthetic surface available for light interception and carbon assimilation, thereby supporting plant growth and yield formation. SPAD values, which reflect leaf chlorophyll concentration, showed different responses depending on the observation stage. At the heading stage, no significant differences were observed among treatments, although a slight increasing trend occurred with increasing N application. At harvest, SPAD values increased significantly in a quadratic manner, as described by the equation $y = 0.0011x^2 + 0.3321x + 76.336$, with the highest value (41.2) recorded at 241.5 kg N/ha. The increase in SPAD values indicates greater chlorophyll accumulation and improved nitrogen status of the plants, which may enhance photosynthetic activity and prolong leaf functionality during grain filling. However, the diminishing response at higher N rates suggests that chlorophyll accumulation reached a near-optimal level and additional nitrogen provided limited physiological benefits.

Table 1

Plant Height, Number of Tillers, Productive Tillers Percentage, and Crop Growth Rate of 'IPB 13S' Rice Variety under Various N, P, and K Fertilizer Rates

Fertilizer rate (kg/ha)	Plant height (cm)	Number of tillers per clump	Productive tillers percentage (%)	CGR (g/m^2 per day)
		N		
0	87.9 b	11.9 b	61	5.3 c
80.5	106.1 a	18.2 a	72	13.2 b
161.0	105.2 a	20.0 a	68	17.3 ab
241.5	108.2 a	20.4 a	65	16.2 ab
322.0	107.6 a	20.5 a	62	18.5 ab
Response pattern#	Q*	Q**	Q**	Q*
		P (P_2O_5)		
0	91.2 b	13.5 b	50	7.8 c
18.0	107.8 a	19.3 a	72	15.9 b
36.0	109.3 a	20.3 a	73	18.5 ab
54.0	107.9 a	19.8 a	72	18.7 ab
72.0	103.8 a	19.7 a	65	19.4 a
Response pattern#	Q**	Q**	Q**	Q**
		K (K_2O)		
0	94.5 b	11.6 b	57	9.2 b
30.0	108.6 a	18.9 a	69	17.0 a
60.0	109.5 a	20.3 a	76	17.3 a
90.0	107.4 a	18.5 a	70	18.8 a
120.0	109.6 a	20.5 a	61	21.8 a
Response pattern#	L*	L**	Q**	L**

Notes. Values followed by the same letter in the same column and for each type of fertilizer are not significantly different based on DMRT at α = 0.05; # = orthogonal polynomial test for fertilizer rate; L = linear; Q = quadratic; *= significant at 0.05 level; ** = significant at 0.01 level; CGR = crop growth rate per clump.

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The application of phosphorus fertilizer (P_2O_5) significantly influenced several leaf growth parameters, particularly during the heading stage, as well as chlorophyll content measured using SPAD values. Flag leaf length increased significantly with increasing P_2O_5 rates, showing a clear linear response. Flag leaf length increased from 31.2 cm in the absence of phosphorus to 37.5 cm at 54.0 kg P_2O_5/ha, representing a 20.9% increase. This result indicates that phosphorus promoted leaf development by supporting root growth, energy transfer, and metabolic processes required for cell division and tissue expansion. Since the flag leaf is the main source of photosynthates during grain filling, improved flag leaf development may contribute to enhanced assimilate production and grain formation. Flag leaf area at harvest also increased significantly in a linear manner, from 39.3 cm^2 in the control treatment to 56.7 cm^2 at 54.0 kg P_2O_5/ha. The larger leaf area suggests that phosphorus improved canopy development and increased the photosynthetic surface available for light interception. Consequently, plants with adequate phosphorus nutrition may achieve greater biomass production and support higher predicted grain yield. SPAD values at harvest exhibited a highly significant quadratic response to increasing P_2O_5 rates, as described by the equation $y = -0.0016x^2 + 0.48x + 67.186$. The lowest SPAD value (27.7) was recorded in plants that did not receive phosphorus, whereas the highest value (43.1) was observed at 72.0 kg P_2O_5/ha. The increase in SPAD values indicates an improvement in leaf greenness and chlorophyll concentration, reflecting better nutritional status and photosynthetic capacity. However, the quadratic response suggests that the benefits of additional phosphorus diminished at higher application rates, indicating that phosphorus requirements were largely satisfied within the tested rate range.

The application of potassium fertilizer (K_2O) significantly affected several physiological parameters, particularly flag leaf area and SPAD values, which reflect chlorophyll concentration. Flag leaf length showed no significant differences at either the heading or harvest stages, suggesting that potassium application had little effect on leaf elongation. Although a tendency toward longer leaves was observed at 90.0 and 120.0 kg K_2O/ha, the differences were not sufficient to indicate a consistent response. This finding suggests that flag leaf length in 'IPB 13S' is less sensitive to potassium availability than other leaf growth characteristics. In contrast, flag leaf area increased substantially following K_2O application. At both the heading and harvest stages, the response to increasing K_2O rates followed a quadratic trend, as described by the regression equations $y = -0.0011x^2 + 0.3092x + 34.229$ and $y = -3.9571x^2 + 34.957x - 11.24$, respectively. The maximum leaf area was observed at 60.0 kg K_2O/ha, reaching 62.6 cm^2 at heading and 65.9 cm^2 at harvest. The increase in flag leaf area indicates that potassium enhanced leaf development and canopy formation, thereby increasing the photosynthetic surface available for light interception and assimilate production. Because the flag leaf is a major source of photosynthates during grain filling, a larger leaf area may contribute to improved grain development and yield formation. SPAD values displayed different response patterns across growth stages. At the heading stage, a significant quadratic response was observed, described by the regression equation $y = -0.0011x^2 + 0.3321x + 76.336$, whereas at harvest a linear response was recorded. SPAD values increased from 27.1 in the control treatment to 44.7 at the highest rate of 120.0 kg K_2O/ha. The increase in SPAD values suggests that potassium improved leaf physiological performance by supporting chlorophyll maintenance and photosynthetic activity. Higher chlorophyll concentrations may enhance carbon assimilation and prolong leaf functionality during the grain-filling period, thereby contributing to better crop performance under field conditions.

The application of nitrogen (N) fertilizer significantly affected several yield components of rice, particularly panicle length, the number of grains per panicle, and grain yield per plot (Table 3). Panicle length showed a substantial increase with higher nitrogen rate, following a clear linear response pattern. The longest

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panicle, measuring 28.7 cm, was observed at the highest nitrogen rate of 322.0 kg N/ha, whereas the shortest panicle, at 24.3 cm, was recorded in the control treatment without nitrogen application. This result indicates that nitrogen promoted reproductive growth and panicle development. The number of grains per panicle exhibited a highly significant quadratic response to increasing nitrogen rate, as described by the equation $y = -0.0023x^2 + 0.6206x + 59.811$. The minimum grain count was observed in the control treatment (125.6 grains), whereas the maximum (223.5 grains) was achieved at 161.0 kg N/ha. The increase in grain number suggests that adequate nitrogen availability enhanced spikelet formation and grain production. The proportion of fully matured grains showed no significant variation among treatments, ranging from 67% to 72%. This suggests that while the overall grain count increased, grain filling efficiency was relatively unaffected by nitrogen application. Grain yield per plot showed a highly significant quadratic response to nitrogen application, as represented by the regression equation $y = -0.002x^2 + 0.4405x + 76.209$. The maximum yield of 4.1 kg per 7.92 m^2 was observed at 80.5 kg N/ha, followed by 3.8 kg at 241.5 kg N/ha. Conversely, yield decreased at the highest rate

Table 2

Flag Leaf Length, Flag Leaf Area, and SPAD Values of 'IPB 13S' Rice Variety Under Various N, P, and K Fertilizer Rates

Fertilizer rate (kg/ha)	Flag leaf length (cm)	Flag leaf area (cm^2)		SPAD values	
		Heading	Harvest	Heading	Harvest
			N		
0	30.1 c	31.2 b	33.5 b	34.7	24.7 b
80.5	33.4 b	41.5 ab	49.6 a	46.3	39.6 a
161.0	32.1 bc	50.6 a	51.1 a	52.0	40.7 a
241.5	33.9 b	55.9 a	58.7 a	50.0	41.2 a
322.0	37.0 a	52.7 a	53.2 a	50.0	40.8 a
Response pattern#	L**	L**	Q*	ns	Q**
			P (P_2O_5)		
0	31.2	37.6	39.3 b	30.8 b	27.7 b
18.0	36.0	42.0	49.6 ab	50.6 a	40.1 a
36.0	36.1	47.1	48.8 ab	43.1 a	41.9 a
54.0	37.5	47.3	56.7 a	45.4 a	42.4 a
72.0	36.8	52.1	55.4 ab	48.1 a	43.1 a
Response pattern#	L*	ns	L*	ns	Q**
			K (K_2O)		
0	33.5	34.4 b	36.0 c	32.1 b	27.1 b
30.0	33.8	56.4 a	59.7 ab	43.4 a	42.1 a
60.0	36.8	62.6 a	65.9 a	42.0 a	39.6 a
90.0	38.4	48.4 ab	52.0 b	42.6 a	40.6 a
120.0	37.1	56.7 a	57.1 ab	44.2 a	44.7 a
Response pattern#	ns	ns	Q*	Q*	L*

Notes. Values followed by the same letter in the same column and for each type of fertilizer are not significantly different based on DMRT at α = 0.05; # = orthogonal polynomial test for fertilizer rate; ns = not significant; L = linear; Q = quadratic; * = significant at 0.05 level; ** = significant at 0.01 level.

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of 322.0 kg N/ha to 3.0 kg, while the lowest yield of 2.6 kg was recorded in the control treatment. These results indicate that moderate nitrogen application was sufficient to maximize grain yield, whereas excessive N input did not provide additional yield benefits.

The application of phosphorus fertilizer (P_2O_5) significantly influenced several yield components of rice, notably panicle length, number of grains per panicle, and grain yield per plot. Panicle length exhibited a marked linear increase, with the maximum value of 29.0 cm observed at a rate of 72.0 kg P_2O_5/ha, while the minimum value of 26.7 cm was recorded in the control treatment without phosphorus application. This result suggests that phosphorus supported reproductive development and panicle formation. The number of grains per panicle exhibited a significant quadratic response to increasing P_2O_5 rates, described by the equation $y = -0.0013x^2 + 0.3348x + 80.077$. The control treatment produced the fewest grains (178.3), whereas the highest number (231.5 grains per panicle) was recorded at 18.0 kg P_2O_5/ha. At rates above this level, higher phosphorus applications did not significantly increase the number of grains per panicle, indicating that phosphorus requirements for grain formation were largely satisfied at moderate application rates. The proportion of filled grains showed no significant

Table 3

Panicle Length, Number of Grains per Panicle, Percentage of Filled Grains, and Grain Yield per Plot of 'IPB 13S' Rice Variety under Various N, P, and K Fertilizer Rates

Fertilizer rate (kg/ha)	Panicle length (cm)	Number of grains per panicle	Percentage of filled grains (%)	Grain yield per plot (kg)
		N		
0	24.3 b	125.6 b	67	2.6 c
80.5	28.6 a	206.0 a	72	4.1 a
161.0	27.6 a	223.5 a	67	3.4 abc
241.5	27.9 a	210.7 a	68	3.8 ab
322.0	28.7 a	218.0 a	70	3.0 bc
Response pattern#	L**	Q**	ns	Q**
		P (P_2O_5)		
0	26.7 c	178.3 b	67	3.2 b
18.0	28.9 a	231.5 a	71	4.3 a
36.0	27.7 b	229.5 a	66	4.6 a
54.0	28.4 ab	220.7 a	70	4.2 a
72.0	29.0 a	223.4 a	66	4.6 a
Response pattern#	L*	Q*	ns	Q*
		K (K_2O)		
0	25.3 b	184.4 b	66	3.5 b
30.0	30.2 a	235.4 a	73	4.6 a
60.0	28.6 a	234.1 a	71	4.6 a
90.0	28.4 a	232.9 a	74	4.2 a
120.0	28.7 a	243.4 a	72	4.1 a
Response pattern#	ns	L**	L*	Q**

Notes. Values followed by the same letter in the same column and for each type of fertilizer are not significantly different based on DMRT at α = 0.05; # = orthogonal polynomial test for fertilizer rate; ns = not significant; L = linear; Q = quadratic; * = significant at 0.05 level; ** = significant at 0.01 level; plot = 7.92 m^2.

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variation across treatments, ranging from 66% to 71%. This suggests that phosphorus application had little effect on grain filling efficiency under the conditions of this study. Grain yield per plot exhibited a highly significant quadratic response, described by the equation $y = -0.0014x^2 + 0.3991x + 72.529$, with peak production (4.6 kg per 7.92 m^2) observed at both 36.0 and 72.0 kg P_2O_5/ha. These results indicate that phosphorus application improved yield formation; however, the greatest benefit was achieved within a moderate rate range, beyond which additional phosphorus provided limited yield improvement.

The application of potassium fertilizer (K_2O) did not result in significant differences in panicle length among treatments; however, a general trend of increasing panicle length with higher potassium rates was observed. The maximum panicle length (30.2 cm) was recorded at a rate of 30.0 kg K_2O/ha, whereas the minimum length (25.3 cm) was observed in the control treatment without potassium application. This trend suggests that potassium contributed to reproductive growth, although its effect on panicle elongation was limited. The number of grains per panicle exhibited a strong linear increase, with the lowest value recorded in the control treatment (184.4 grains) and the highest at 120.0 kg K_2O/ha (243.4 grains). This result indicates that potassium played an important role in spikelet development and grain formation, likely through its involvement in assimilate transport and enzyme activation. The proportion of filled grains increased linearly with increasing K_2O application, ranging from 66% to 74%, with the highest percentage was recorded at 90.0 kg K_2O/ha. The increase in filled grains suggests that adequate potassium nutrition supported grain filling and improved the conversion of spikelets into harvestable grains. Grain yield per plot exhibited a highly significant quadratic response, with peak production (4.6 kg per 7.92 m^2) achieved at 30.0 and 60.0 kg K_2O/ha. Yield declined at the highest rate of 120.0 kg K_2O/ha (4.1 kg), although the reduction was not statistically significant. These results indicate that moderate potassium application was sufficient to maximize yield, whereas higher K_2O rates provided limited additional benefits under the conditions of this study.

The nutrient use efficiency curves exhibited a quadratic response pattern, increasing up to an optimal rate and declining with further fertilizer application (Figure 1). Nitrogen use efficiency (NUE) peaked at 80.5 kg N/ha, producing 62.2 kg grain per kg N applied, before declining sharply to 11.2 kg grain per kg N at 322.0 kg N/ha. Similarly, the highest phosphorus use efficiency (PUE) was observed at 36.0 kg P_2O_5/ha, reaching 154.3 kg grain per kg P_2O_5 applied, whereas the maximum potassium use efficiency (KUE) was attained at 30.0 kg K_2O/ha, producing 186.6 kg grain per kg K_2O applied. These results indicate that nutrient utilization was most efficient at moderate fertilizer rates, where nutrient supply was sufficient to support crop growth without exceeding plant demand. Beyond the optimal rate, efficiency declined markedly, suggesting that additional fertilizer inputs contributed less to grain production. Excess nutrients may not have been effectively absorbed by plants and could have been lost through leaching, fixation, or other soil processes. Therefore, the application of fertilizers above the optimal rate is unlikely to improve productivity and may reduce nutrient use efficiency under field conditions.

The graph illustrates the relationship between nitrogen (N) fertilizer rate and predicted grain yield of 'IPB 13S' rice, showing a quadratic response described by the regression equation $y = -0.00005x^2 + 0.017x + 3.5205$, with a coefficient of determination (R^2) of 0.4615. Increasing nitrogen rate initially enhanced predicted grain yield; however, beyond a certain threshold, additional nitrogen resulted in lower yields. This response indicates that nitrogen availability supported crop growth and yield formation up to an optimal level, after which the efficiency of N utilization declined. The regression model suggests that the optimal rate for maximum production is approximately 170 kg N/ha, with a predicted grain yield of approximately 5 t/ha (Figure 2). These findings demonstrate that applying nitrogen at the optimal rate is essential to maximize productivity while avoiding excessive fertilizer inputs that provide limited yield benefits.

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Figure 1

Efficiency of N, P (P_2O_5), and K (K_2O) use of 'IPB 13S' Rice Variety, A. N Fertilizer Rate, B. P_2O_5 Fertilizer Rate, C. K_2O Fertilizer Rate

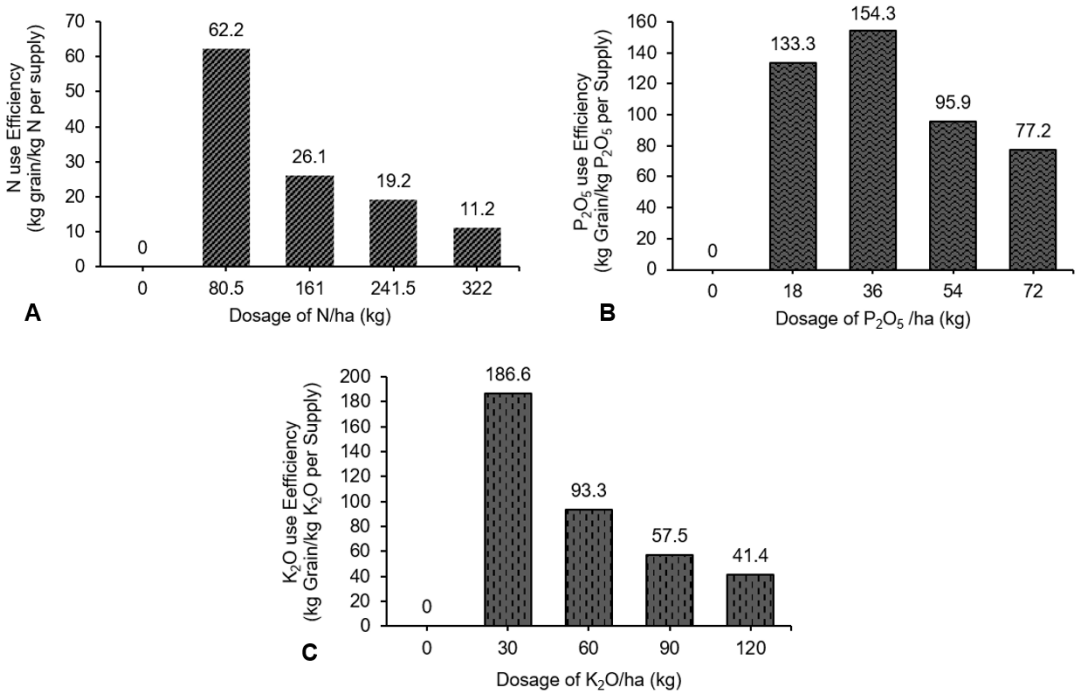
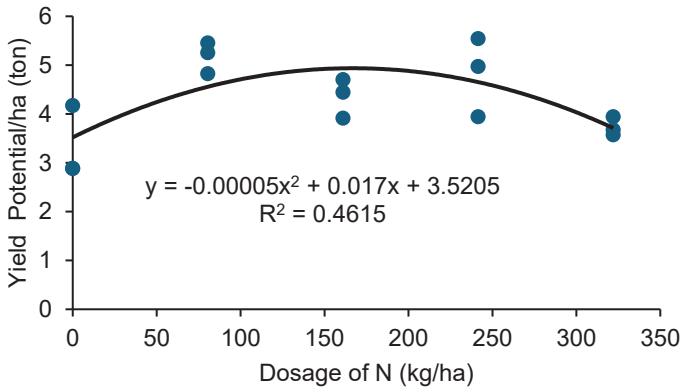


Figure 2

Predicted Grain Yield at Various N Fertilizer Rates



The graph illustrates the relationship between phosphate fertilizer rate (P_2O_5) and predicted grain yield (t/ha). The observed response followed a quadratic pattern, described by the regression equation $y = -0.0006x^2 + 0.0636x + 4.1887$, with a coefficient of determination (R^2) of 0.5906. The optimal rate for achieving maximum yield, as predicted by the regression equation, was approximately 53 kg P_2O_5/ha, with a predicted grain yield of nearly 5.9 t/ha (Figure 3). This result indicates that phosphorus application improved yield formation up to an optimal level by supporting root development, nutrient uptake, and reproductive growth. Beyond this rate, additional phosphorus was unlikely to provide substantial yield benefits, suggesting that the phosphorus requirement of 'IPB 13S' had been largely fulfilled.

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The graph depicts the relationship between potassium fertilizer rate (K_2O) and predicted grain yield. The relationship followed a downward-opening parabolic curve, described by the regression equation $y = -0.0003x^2 + 0.0426x + 4.4141$, with a coefficient of determination (R^2) of 0.624. The negative quadratic coefficient indicates that predicted grain yield increased with potassium application up to a certain level, after which it declined at higher rates. The regression equation suggests that the optimal K_2O application rate is approximately 71 kg K_2O/ha, resulting in a maximum predicted grain yield of approximately 5.9 t/ha (Figure 4). This result indicates that adequate potassium nutrition supported grain production through its role in photosynthate translocation, enzyme activation, and grain filling. However, potassium application beyond the optimal rate provided limited additional benefits, suggesting that the K requirement of 'IPB 13S' had been sufficiently met at moderate application levels.

Figure 3

Predicted Grain Yield at Various P (P_2O_5) Fertilizer Rates

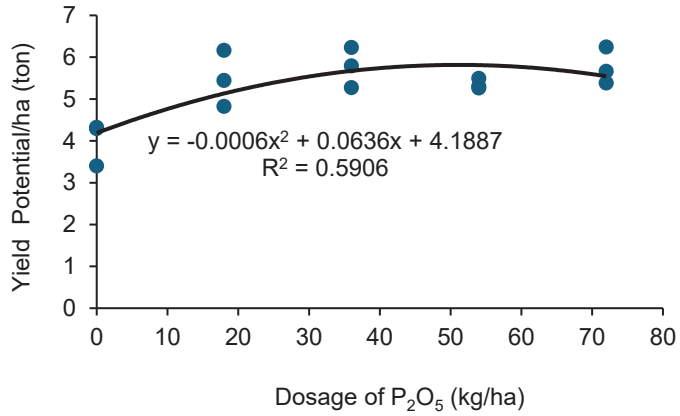
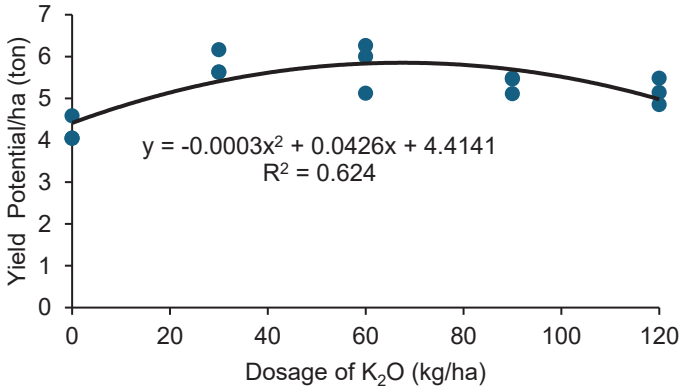


Figure 4

Predicted Grain Yield at Various K (K_2O) Fertilizer Rates



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Discussion

Applied nitrogen substantially influences rice physiological activity and photosynthesis (Zhang et al., 2020). Increased nitrogen availability can enhance plant height by promoting growth and internode elongation. Nitrogen application also promotes cellular development and stem growth (Wu et al., 2020). Nitrogen is essential for photosynthate production, and increased nitrogen availability generally promotes tiller growth in rice (He et al., 2024). Higher nitrogen availability can increase dry matter production and stimulate plant growth, thereby increasing crop growth rate (Schmierer et al., 2021). However, when nitrogen application exceeds crop requirements, grain yield may decline (Ma et al., 2023). Nitrogen use efficiency generally decreases as nitrogen application rate increases. This may be attributed to flooded conditions in rice cultivation, which create anaerobic conditions that can increase nitrogen losses through volatilization and leaching (Mondal et al., 2023).

Leaf nitrogen and chlorophyll contents are generally positively associated with nitrogen availability (Fathi, 2022). Soil nutrient availability influences nutrient composition and uptake; therefore, increasing nitrogen application can increase plant nitrogen status. The flag leaf is an important photosynthetic organ in rice. Tanaka et al. (2022) reported that increased nitrogen content in the flag leaf enhances photosynthetic activity during the grain-filling period. Nitrogen is an essential component of chlorophyll; hence, an increased nitrogen supply can enhance chlorophyll content in leaves (Han et al., 2021).

The panicle length exhibits a notable reaction to nitrogen administration in rice plants. Nitrogen constitutes a component of the auxin hormone, which is involved in the processes of cell division and elongation in plants (Widodo & Damanhuri, 2021). Excessive nitrogen fertilizer application can diminish rice plant tolerance to lodging and stress, resulting in reduced yields (Wei et al., 2025). Excessive nitrogen application can extend the grain-filling duration, diminish the grain-filling rate, and elevate chalkiness in rice grains (Sun et al., 2022).

Proper phosphorus fertilization has been demonstrated to enhance the morphology and physiology of rice plants. Phosphorus is essential for plants because it is a component of adenosine triphosphate (ATP), which plays a central role in cellular energy transfer (Maulidan & Putra, 2024). Phosphorus application can increase plant height and tiller number (Shankar et al., 2023). Nonetheless, excessive phosphorus fertilizer may reduce yield. Adequate phosphorus availability in the soil can increase the photosynthetic rate and promote plant growth (Afriani et al., 2021). The reduced responsiveness of plants to increased phosphorus application is likely attributable to the high availability of phosphorus in the soil. The phosphorus concentration in leaves may show limited response to additional phosphorus fertilizer when soil phosphorus availability is already high.

Phosphorus fertilization in rice plants leads to an elongation of the flag leaf as phosphorus rate increases. Phosphorus is essential in multiple phases of photosynthesis, including ATP synthesis, the primary source of cellular energy, and the production of ribulose-1,5-bisphosphate (RuBP), a crucial component of the Calvin cycle. Insufficient phosphorus availability can impede ATP synthesis, diminishing photosynthetic activity and obstructing plant growth (Khan et al., 2023). This energy facilitates the expansion of leaf tissues, including both the length and breadth of the flag leaf in rice plants.

The quantity of phosphorus affects panicle length in rice plants. Phosphorus can enhance enzyme activity, root growth, and nutrient uptake, thereby supporting panicle development (Zhou et al., 2023). Excessive phosphorus application can diminish the quantity of grains per plant, lower grain weight, and ultimately decrease production (Jorfi et al., 2022). Proper and effective phosphorus application enhances agricultural productivity (Zhou et al., 2023).

Potassium application can affect plant height, tiller number, and crop growth rate in rice. Applying K_2O markedly influences potassium availability in the soil, with increasing rates

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improving plant nutrient status (Hartati et al., 2018). This enables plants to assimilate available nutrients more effectively. Potassium is vital for numerous physiological processes, including photosynthesis and enzyme activity. Potassium application has been shown to improve growth performance in rice, including dry matter accumulation, leaf area index, and tiller number (Mishra et al., 2024). Nonetheless, leaf nutrient content during the heading stage after high-rate K_2O fertilization was below the essential threshold or showed no discernible response to the application. This response may result from nutrient translocation from the leaves to other plant organs, such as the panicles, during the reproductive stage.

Potassium fertilization can enhance leaf growth and development by promoting leaf expansion and increasing leaf area, thereby supporting photosynthesis and transpiration as well as photosynthate production (Zhao et al., 2025). Leaf area is an important determinant of photosynthetic productivity (Khan et al., 2021). Chlorophyll is an important component of plant photosynthesis, and photosynthetic pigment levels generally increase with potassium availability (Zhang et al., 2024). Siddiqui et al. (2021) reported that potassium application can sustain carbon assimilation rates, promote chlorophyll metabolism, increase chlorophyll content, and maintain photosynthetic activity in plants.

Adequate potassium fertilization can promote panicle development in rice. Potassium is essential for numerous metabolic processes and aids in maintaining osmotic and turgor pressure equilibrium in plants, promoting water absorption and nutrient transport (Ul-Allah et al., 2020). Sufficient water availability inside plant tissues facilitates the growth of elongated panicles. Potassium increases the peak grain filling rate, optimizing grain filling (Xu et al., 2023). While augmenting potassium rates might enhance grain weight, excessive application may result in a reduction in grain output. This decrease may result from the antagonistic influence of elevated potassium concentrations on the absorption of other vital minerals, including calcium and magnesium, due to competitive ion uptake at the root level (Xie et al., 2021). Overall, the results indicate that balanced fertilization is essential for maximizing crop performance while maintaining efficient nutrient utilization. The optimal fertilizer rates identified in this study improved several agronomic traits of 'IPB 13S' rice, including productive tiller percentage, grain number per panicle, grain yield, and nutrient use efficiency. The results demonstrated that balanced nutrient application is important for achieving optimal crop performance, whereas excessive fertilizer application did not consistently improve yield. However, a direct comparison between the optimal rates identified in this study and the current regional fertilizer recommendations could not be made because regional recommendation treatments were not included in the experimental design. Therefore, further studies are needed to evaluate the performance of the proposed fertilizer rates relative to existing recommendations under similar growing conditions.

The identification of specific optimal rates for N, P_2O_5, and K_2O in 'IPB 13S' suggests that fertilizer requirements may vary among rice varieties. The distinct response patterns observed for each nutrient indicate that generalized fertilizer recommendations may not always maximize predicted grain yield and nutrient use efficiency. Therefore, the development of variety-specific fertilizer recommendations may provide a more effective approach for optimizing the productivity of newly released rice varieties such as 'IPB 13S'.

Conclusions

The optimal fertilization recommendation for the 'IPB 13S' rice variety cultivated in Sawah Baru, Dramaga District, Bogor Regency, is based on the predicted grain yield per hectare, and the initial soil conditions, which include a slightly acidic pH (5.72), moderate organic carbon content (2.42%), moderate total nitrogen content (0.28%), very high Olsen phosphorus (P_2O_5) levels (965.48 ppm), low potential potassium (K_2O) content (16.31 mg/100 g), and high cation

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exchange capacity (CEC) (26.85 cmol/kg). The recommended fertilizer application rates are 170 kg N/ha, 53 kg P_2O_5/ha, and 71 kg K_2O/ha.

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