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Synergistic Effect of Amino Acids and NPK on Growth Dynamics, Yield Components, and Grain Productivity of Inpari 32 Rice Variety (*Oryza sativa* L)

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Abstract: Rice productivity improvement is essential to support food security and sustainable agricultural development. This study aimed to evaluate the synergistic effects of amino acids and NPK fertilizer on growth dynamics, yield components, and grain productivity of the Inpari 32 rice variety (Oryza sativa L.). The experiment was conducted in Sukatani Village, Subang Regency, Indonesia, from July to October 2025 using a Randomized Block Design with nine treatment combinations consisting of three amino acid concentrations (5, 10, and 15 mL L^{-1}) and three NPK fertilizer doses (50, 100, and 150 kg ha^{-1}), replicated three times. Observed parameters included plant height, tiller number, leaf area index, productive tillers, panicle number, filled grains per panicle, 1000-grain weight, harvest dry grain yield, and milled dry grain yield. The results showed that the combination of 10 mL L^{-1} amino acids and 100 kg ha^{-1} NPK fertilizer produced the highest plant height (74.42 cm), tiller number (26.20 tillers), productive tillers (19.37), filled grains per panicle (126.57 grains), 1000-grain weight (26.50 g), and milled dry grain yield (7.93 kg $plot^{-1}$). The synergistic interaction between amino acids and NPK improved nutrient uptake efficiency and physiological performance, resulting in higher grain productivity. Therefore, the combined application of amino acids and NPK fertilizer can be recommended as an effective strategy for sustainable rice production.

Keywords: Amino acids; Grain productivity; NPK fertilizer; Rice growth; Yield components

Introduction

The agricultural sector in Indonesia plays a vital role in the nation's economy (Mukhlis et al., 2023). Development of the food crops subsector within the agricultural sector continues to be enhanced in an effort to achieve self-sufficiency and increase household income (Mukhlis et al., 2015; Mukhlis et al., 2022).

Rice (*Oryza sativa* L.) is a strategic food commodity that serves as the primary source of carbohydrates for more than half the world's population, particularly in Asia (Mohidem et al., 2022). In Indonesia, rice plays a crucial role in maintaining national food security and supporting the rural economy (Baratella et al., 2023). However, rice productivity has stagnated in the past two decades due to land degradation, declining soil fertility, and climate change, which has led to uncertain planting seasons. This situation demands a strategy to increase sustainable yields through the efficient use of agricultural resources. One prominent solution is the application of balanced fertilization, specifically NPK fertilizers, which provide the essential macronutrients

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nitrogen, phosphorus, and potassium to support plant growth and yield. However, the nutrient uptake efficiency of NPK fertilizers remains low because some elements are lost through volatilization, leaching, and soil fixation (Sundara et al., 2025). In this context, the use of natural biostimulants such as amino acids is an innovative approach that can improve physiological efficiency and plant productivity (Sun et al., 2024). Amino acids play a role in stimulating metabolic activity, enhancing nutrient absorption, and increasing plant resistance to environmental stress (Trovato et al., 2021). The combination of amino acids and NPK has the potential to create a synergistic effect that supports optimal vegetative and generative growth (Kamil et al., 2024). This strategy not only increases crop yields and fertilizer efficiency but also aligns with the principles of environmentally friendly, sustainable agriculture. Therefore, the integration of amino acid and NPK-based fertilization is an important alternative to increase the productivity of superior rice varieties such as Inpari 32 in facing the global challenges of food production.

Although NPK fertilizers play a crucial role in supporting vegetative and generative growth of rice plants, their nutrient uptake efficiency is often low (Du et al., 2022). This is due to various nutrient loss factors, such as nitrogen volatilization into the atmosphere, nutrient leaching into deeper soil layers, and phosphate and potassium fixation by soil particles, which reduces their availability to plants. Consequently, most of the applied nutrients are not optimally utilized by plants, resulting in reduced land productivity and increased production costs. This situation indicates that the sole use of inorganic fertilizers is not sufficient to address the challenge of sustainably increasing crop yields (J. Wang et al., 2025). Conventional approaches that rely solely on inorganic fertilizers often lead to nutrient imbalances in the soil and reduce the activity of soil microorganisms, which play a crucial role in nutrient cycling (Pahalvi et al., 2021). Excessive reliance on chemical fertilizers also leads to long-term soil degradation, characterized by decreased organic matter content, decreased cation exchange capacity, and disruption of soil structure (Dar et al., 2021). In this context, innovative fertilizer technologies are needed to increase the efficiency of inorganic fertilizer use while maintaining soil health. One potential approach is the integration of natural biostimulants such as amino acids into a balanced fertilization system.

Amino acids play a crucial role as natural biostimulants, supporting various physiological processes in plants (Alfosea-Simón et al., 2021). As basic components of proteins, amino acids play a role in activating metabolic enzymes related to photosynthesis, respiration, and new tissue formation. The presence of amino acids around plant roots can accelerate the formation of lateral roots and root hairs, thereby expanding the area for nutrient and water absorption (Manna et al., 2025). Furthermore, amino acids also function as natural chelators, helping increase the availability of micronutrients to plants. By increasing the efficiency of nutrient absorption and photosynthetic activity, plants become more vigorous, able to produce sufficient energy to support vegetative and generative growth, and are more resistant to environmental stress. The combination of amino acids and NPK fertilizer creates a significant synergistic effect in improving fertilizer efficiency and rice productivity. The nitrogen, phosphorus, and potassium elements in NPK fertilizers serve as the primary nutrient source supporting cell growth, root formation, and flowering, while amino acids accelerate physiological processes, ensuring optimal utilization of these nutrients (Khare et al., 2025). The synergy between the two can increase leaf area, which is directly related to plant photosynthetic capacity, increase the number of productive tillers, and enhance biomass accumulation during the growth phase. At the generative stage, this combination contributes to the formation of more panicles, an increase in the number of filled grains, and a higher 1,000-grain weight. Therefore, the use of amino acids in combination with NPK fertilizers not only increases dry grain yield but also strengthens nutrient efficiency and yield stability in sustainable rice production systems.

Numerous studies in various Asian countries, such as Thailand, India, and Indonesia, have shown that the separate use of amino acids and compound fertilizers (NPK) can positively impact rice growth and yield (Mirtaleb et al., 2021). Amino acid application has been shown to increase photosynthetic activity, improve root formation, and accelerate vegetative growth, leading to increased leaf area and plant vigor. Meanwhile, balanced NPK fertilization has been shown to be effective in increasing nutrient uptake efficiency, panicle number, and grain productivity, especially when the dosage and application time are adjusted to the plant's physiological needs (Basavarajappa et al., 2021). These research results indicate that both amino acids and compound fertilizers significantly contribute to increasing nutrient efficiency and rice yields under various agroecological conditions (Akter et al., 2024). Research comprehensively examining the synergistic effects of amino acids and NPK fertilizers on various physiological and agronomic parameters is still limited. Most previous studies have only examined the effect of one treatment alone or focused on specific growth parameters, such as plant height or grain weight, without linking the two in an integrated manner (Indriana et al., 2025). Few studies have explored how the combination of the two can affect overall yield components, such as leaf area index, number of productive tillers, number of panicles, 1,000-grain weight, and dry grain yield at harvest and milling. Therefore, more in-depth research is needed to uncover the synergistic interactions between amino acids and NPK, particularly in superior varieties such as Inpari 32, to gain a more complete scientific understanding of the mechanisms for increasing fertilizer efficiency and sustainable rice productivity (Syamsiah et al., 2025). This research also aims to provide a scientific basis for formulating sustainable fertilization strategies that can increase nutrient use efficiency without degrading environmental quality. The research results are expected to serve as a reference in the development of modern rice cultivation systems that are productive, environmentally friendly, and adaptive to changing agro-ecosystem conditions (Dinar et al., 2026).

Although numerous studies have reported the positive effects of amino acid-based biostimulants and NPK fertilizers when applied separately, limited information is available regarding their synergistic interaction on growth dynamics, yield components, and grain productivity of the Inpari 32 rice variety under irrigated lowland conditions. Most previous studies focused on individual physiological responses, such as plant height, chlorophyll content, or grain weight, without comprehensively evaluating the interaction between amino acids and NPK fertilizer across vegetative and generative growth stages. Therefore, this study was conducted to evaluate the synergistic effects of amino acid and NPK fertilizer combinations on plant growth, yield components, and grain productivity of Inpari 32 rice. The findings are expected to contribute to the development of efficient and sustainable fertilization strategies that improve nutrient use efficiency and rice productivity.

Method

Time and Place of Research

The research was conducted from July to October 2025 in Sukatani Village, Compreng District, Subang Regency, West Java, Indonesia. The study area is located at approximately 6°26' South Latitude and 107°48' East Longitude with an elevation of 26 m above sea level. The site was purposively selected because it represents one of the major irrigated rice production centers in Subang Regency.

Research Design

The experiment employed a Randomized Block Design (RBD) consisting of nine treatment combinations derived from three amino acid concentrations (5, 10, and 15 mL L^{-1}) and three NPK fertilizer doses (50, 100, and 150 kg ha^{-1}). Each treatment was replicated three times, resulting in 27 experimental plots measuring 3 m × 3 m. The independent variables were amino acid concentration and NPK fertilizer dose, while the dependent variables included plant height, tiller number, leaf area index, productive tillers, panicle number, filled grains per panicle, 1000-grain weight, harvest dry grain yield, and milled dry grain yield. Research materials consisted of Inpari 32 rice seeds, amino acid fertilizer, NPK fertilizer, organic fertilizer, and pesticides. Data were collected through direct field observations and laboratory measurements.

Research Procedure

Land preparation was performed through two stages of soil tillage using a hand tractor. Organic fertilizer was applied before transplanting. Rice seedlings were raised for 21 days and transplanted at a spacing of 25 cm × 25 cm. Amino acid and NPK fertilizers were applied at 7 and 14 days after planting (DAP) according to treatment combinations. Crop maintenance included irrigation, replanting, weeding, and pest management. Growth observations were conducted at 30, 45, and 60 DAP, while yield observations were carried out at harvest.

Data Analysis

The collected data were analyzed using Analysis of Variance (ANOVA) at a 5% significance level. Significant differences among treatments were further analyzed using Duncan's Multiple Range Test (DMRT) at α = 0.05.

Figure 1. Research flowchart illustrating the experimental procedure used to evaluate the synergistic effects of amino acids and NPK fertilizer on Inpari 32 rice

Result and Discussion

The present study demonstrated that the combined application of amino acids and NPK fertilizer significantly improved vegetative growth, yield components, and grain productivity of Inpari 32 rice. The treatment consisting of 10 mL L^{-1} amino acids combined with 100 kg ha^{-1} NPK fertilizer consistently produced the highest plant height, tiller number, leaf area index, productive tillers, panicle number, filled grains per panicle, 1000-grain weight, harvest dry grain yield, and milled dry grain yield. The improved performance was associated with enhanced nutrient uptake efficiency, increased photosynthetic activity, and better physiological development resulting from the synergistic interaction between amino acids and essential macronutrients. These findings indicate that integrating amino acid biostimulants with balanced NPK fertilization represents an effective and sustainable strategy for increasing rice productivity under irrigated lowland conditions.

Table 1. Effect of Amino Acid and NPK Combination on Plant Height at 30, 45, and 60 Days After Planting

Treatment		Plant Height (cm)		
		30 hst	45 hst	60 hst
A	(5 ml asam amino lr-1 and 50 kg NPK ha-1)	33.20 a	42.75 a	66.72 ab
B	(5 ml asam amino lr-1 and 100 kg NPK ha-1)	33.93 a	41.52 a	65.12 a
C	(5 ml asam amino lr-1 and 150 kg NPK ha-1)	33.82 a	41.30 a	64.18 a
D	(10 ml asam amino lr-1 and 50 kg NPK ha-1)	33.02 a	42.55 a	68.65 b
E	(10 ml asam amino lr-1 and 100 kg NPK ha-1)	34.77 a	46.43 b	74.42 c
F	(10 ml asam amino lr-1 and 150 kg NPK ha-1)	33.40 a	42.37 a	68.78 b
G	(15 ml asam amino lr-1 and 50 kg NPK ha-1)	35.38 a	42.63 a	65.12 a
H	(15 ml asam amino lr-1 and 50 kg NPK ha-1)	32.98 a	45.63 b	67.32 ab
I	(15 ml asam amino lr-1 and 100 kg NPK ha-1)	34.38 a	41.67 a	66.85 ab

At 30 days after planting (dap), plant height between treatments showed no significant differences, indicating that the initial response of plants to amino acids and NPK was relatively uniform. At 45 dap, treatments with 10–15 ml amino acids l¯f and 100 kg NPK ha¯f (treatments E and H) began to show higher growth than the other treatments. At 60 dap, treatment E achieved the highest plant height (74.42 cm), while treatments with other doses were lower. These findings confirm that the optimal combination of amino acids and NPK is effective in increasing plant growth in the middle to late stages.

Observation 30 HST Observation 45 HST Observation 60 HST

Figure 2. Field observation of Inpari 32 rice growth at 30, 45, and 60 days after planting (DAP) under different combinations of amino acids and NPK fertilizer

Table 2. Effect of Amino Acid and NPK Combinations on the Number of Tillers per Clump at 30, 45, and 60 Days After Planting

Treatment		Number of Children (fruits)		
		30 hst	45 hst	60 hst
A	(5 ml asam amino lr-1 and 50 kg NPK ha-1)	14,47 a	18,20 a	21,00 a
B	(5 ml asam amino lr-1 and 100 kg NPK ha-1)	14,73 a	18,53 a	20,93 a
C	(5 ml asam amino lr-1 and 150 kg NPK ha-1)	15,53 a	19,07 a	21,53 a
D	(10 ml asam amino lr-1 and 50 kg NPK ha-1)	17,53 b	21,07 b	22,87 b
E	(10 ml asam amino lr-1 and 100 kg NPK ha-1)	19,53 c	23,13 c	26,20 d
F	(10 ml asam amino lr-1 and 150 kg NPK ha-1)	19,00 c	22,53 c	24,93 c
G	(15 ml asam amino lr-1 and 50 kg NPK ha-1)	17,47 b	21,00 b	23,27 b
H	(15 ml asam amino lr-1 and 100 kg NPK ha-1)	17,33 b	20,73 b	23,27 b
I	(15 ml asam amino Ir-1 and 150 kg NPK ha-1	17.53 b	20,73 b	23.20 b

Based on tiller number data at 30, 45, and 60 days after planting (dap), it was seen that increasing the dosage of amino acids and NPK significantly affected tiller production. At 30 dap, the treatment with 10–15 ml of amino acids l¯f showed a higher tiller number than the 5 ml dose, with treatment E (10 ml of amino acids l¯f +

100 kg of NPK ha¯f) achieving the highest number (19.53 tillers). This difference became more pronounced at 45–60 dap, where treatment E still produced the most tillers (26.20 tillers at 60 dap), while treatments with lower or higher doses produced a lower number of tillers. This indicates that the optimal combination of amino acids and NPK significantly increases tiller number, especially in the middle to late growth phase.

Number of offspring 30 HST Number of offspring 45 HST Number of offspring 60 HST

Figure 3. Number of tillers of Inpari 32 rice at (a) 30 days after planting (DAP), (b) 45 DAP, and (c) 60 DAP under different combinations of amino acids and NPK fertilizer

Table 3. Effect of Amino Acid and NPK Combination on Leaf Area Index (ILD) at 30, 45, and 60 Days After Planting

Treatment		Number of Children (fruits)		
		30 hst	45 hst	60 hst
A	(5 ml asam amino lr-1 and 50 kg NPK ha-1)	3.54 b	6.60 a	7.69 a
B	(5 ml asam amino lr-1 and 100 kg NPK ha-1)	3.56 b	6.56 a	8.03 a
C	(5 ml asam amino lr-1 and 150 kg NPK ha-1)	3.44 ab	6.44 a	7.86 a
D	(10 ml asam amino lr-1 and 50 kg NPK ha-1)	4.26 b	7.54 b	8.75 bc
E	(10 ml asam amino lr-1 and 100 kg NPK ha-1)	4.87 c	8.83 d	9.98 d
F	(10 ml asam amino lr-1 and 150 kg NPK ha-1)	4.62 bc	8.42 cd	9.42 cd
G	(15 ml asam amino lr-1 and 50 kg NPK ha-1)	4.18 b	7.86 bc	8.92 bc
H	(15 ml asam amino lr-1 and 100 kg NPK ha-1)	4.71 c	8.65 d	9.82 d
I	(15 ml asam amino Ir-1 and 150 kg NPK ha-1	4.25 b	7.94 bc	9.01 bc

Based on the Leaf Area Index (LAI) data at 30, 45, and 60 Days After Planting (DAP), the combination of amino acids and NPK fertilizer significantly influenced leaf area development in Inpari 32 rice plants. At 30 DAP, treatments E (10 mL L^{-1} amino acid + 100 kg ha^{-1} NPK) and H (15 mL L^{-1} amino acid + 100 kg ha^{-1} NPK) produced the highest LAI values, reaching 4.87 and 4.71, respectively, and were significantly different from treatments receiving lower amino acid concentrations. Similar trends were observed at 45 DAP, where treatment E recorded the highest LAI value (8.83), followed by treatment H (8.65), indicating enhanced canopy development during the active vegetative growth stage. At 60 DAP, treatment E consistently produced the highest LAI value (9.98), followed by treatment H (9.82), while treatments D, G, and I showed intermediate responses, and treatments A, B, and C exhibited the lowest LAI values. The greater leaf area observed under treatments E and H indicates improved leaf expansion and canopy formation, which likely enhanced light interception and photosynthetic efficiency. These findings suggest that the synergistic interaction between amino acids and NPK fertilizer effectively promotes leaf area development, thereby supporting vegetative growth and contributing to higher rice productivity.

Table 4. Effect of Amino Acid and NPK Combination on the Number of Productive Tillers and the Number of Panicles per Clump

Treatment		Productive Tillers (number)	Number of Panicles (number)
A	(5 ml asam amino lr-1 and 50 kg NPK ha-1)	16.87 a	11.80 a
B	(5 ml asam amino lr-1 and 100 kg NPK ha-1)	17.20 ab	12.07 a
C	(5 ml asam amino lr-1 and 150 kg NPK ha-1)	16.87 a	12.33 ab
D	(10 ml asam amino lr-1 and n 50 kg NPK ha-1)	17.17 ab	14.87 c
E	(10 ml asam amino lr-1 and 100 kg NPK ha-1)	19.37 c	16.33 d
F	(10 ml asam amino lr-1 and 150 kg NPK ha-1)	18.10 b	14.47 c
G	(15 ml asam amino lr-1 and 50 kg NPK ha-1)	17.70 ab	13.67 bc
H	(15 ml asam amino lr-1 and 100 kg NPK ha-1)	19.20 c	16.47 d
I	(15 ml asam amino lr-1 and 150 kg NPK ha-1)	17.23 ab	12.80 ab

Based on data on productive tillers and panicle number, the combination of amino acid and NPK doses significantly affected the yield components of the plant. Treatments with 10–15 ml amino acid l^{-}f and 100 kg NPK ha^{-}f (treatments E and H) produced the highest productive tillers (19.37–19.20 fruits) and the highest number of panicles (16.33–16.47 fruits), while treatments with lower or higher doses of this combination showed lower values. These results indicate that the optimal combination of amino acids and NPK increases the formation of productive tillers and panicles, which has the potential to increase overall plant productivity.

Number of Productive Tillers Number of Panicles Filled Panicles

Figure 4. Yield components of Inpari 32 rice: (a) number of productive tillers, (b) number of panicles, and (c) number of filled grains per panicle under different combinations of amino acids and NPK fertilizer

Table 5. Effect of Amino Acid and NPK Combination on the Number of Filled Grains per Panicle and the Weight of 1000 Grains

Treatment		Number of Filled Grains (g)	1000-Grain Weight (g)
A	(5 ml asam amino lr-1 and 50 kg NPK ha-1)	105.67 a	22.93 a
B	(5 ml asam amino lr-1 and 100 kg NPK ha-1)	106.50 a	23.93 abc
C	(5 ml asam amino lr-1 and 150 kg NPK ha-1)	106.03 a	23.40 ab
D	(10 ml asam amino lr-1 and 50 kg NPK ha-1)	113.17 ab	24.60 bc
E	(10 ml asam amino lr-1 and 100 kg NPK ha-1)	126.57 c	26.50 d
F	(10 ml asam amino lr-1 and 150 kg NPK ha-1)	107.67 ab	24.17 abc
G	(15 ml asam amino lr-1 and 50 kg NPK ha-1)	116.33 b	24.70 bc
H	(15 ml asam amino lr-1 and 100 kg NPK ha-1)	126.33 c	26.93 d
I	(15 ml asam amino lr-1 and 150 kg NPK ha-1)	113.27 ab	24.93 c

Based on the data on the number of filled grains and 1000-grain weight, the treatment combining amino acids and NPK had a significant effect on grain quality. Treatments E (10 ml amino acid L^{-1} + 100 kg NPK ha^{-1}) and H (15 ml amino acid L^{-1} + 100 kg NPK ha^{-1}) produced the highest number of filled grains (126.33–126.57 g) and the highest 1000-grain weight (26.50–26.93 g), whereas treatments with lower or higher doses than this combination showed lower values. These results confirm that the optimal combination of amino acids and NPK can improve the physical quality of grains, which has the potential to support increased crop productivity and economic value (Mahmud et al., 2023).

Table 6. Effect of Amino Acid and NPK Combination on Harvest Dry Grain Yield per Hill and per Plot

Treatment		GKP per Hill (g)	GKP per Plot (kg)
A	(5 ml asam amino lr-1 and 50 kg NPK ha-1)	63.50 a	7.50 a
B	(5 ml asam amino lr-1 and 100 kg NPK ha-1)	65.50 ab	7.98 bc
C	(5 ml asam amino lr-1 and 150 kg NPK ha-1)	66.07 abc	7.88 b
D	(10 ml asam amino lr-1 and 50 kg NPK ha-1)	70.57 bc	8.05 bc
E	(10 ml asam amino lr-1 and 100 kg NPK ha-1)	80.53 d	9.03 d
F	(10 ml asam amino lr-1 and 150 kg NPK ha-1)	72.07 c	8.22 bc
G	(15 ml asam amino lr-1 and 50 kg NPK ha-1)	71.53 bc	8.10 bc
H	(15 ml asam amino lr-1 and 100 kg NPK ha-1)	78.87 d	8.97 d
I	(15 ml asam amino lr-1 and 150 kg NPK ha-1)	72.15 c	8.38 c

Based on the data of GKP per hill and per plot, the combination of amino acid and NPK dosages had a significant effect on harvest dry grain yield. Treatments E (10 ml amino acid L^{-1} + 100 kg NPK ha^{-1}) and H (15 ml amino acid L^{-1} + 100 kg NPK ha^{-1}) produced the highest GKP both per hill (80.53–78.87 g) and per plot (9.03–8.97

kg), whereas treatments with lower or higher doses than this combination resulted in lower GKP. These findings indicate that the optimal combination of amino acids and NPK is effective in increasing grain yield, supporting overall crop productivity and production efficiency (Wahyudin et al., 2024).

Table 7. Effect of Amino Acid and NPK Combination on Milled Dry Grain Yield per Hill and per Plot

Treatment		GKG per Hill (g)	GKG per Plot (kg)
A	(5 ml asam amino lr-1 and 50 kg NPK ha-1)	52.32 a	6.46 a
B	(5 ml asam amino lr-1 and 100 kg NPK ha-1)	53.27 a	6.43 a
C	(5 ml asam amino lr-1 and 150 kg NPK ha-1)	52.69 a	6.51 a
D	(10 ml asam amino lr-1 and 50 kg NPK ha-1)	53.12 a	6.32 a
E	(10 ml asam amino lr-1 and 100 kg NPK ha-1)	64.03 c	7.93 c
F	(10 ml asam amino lr-1 and 150 kg NPK ha-1)	53.28 a	6.90 ab
G	(15 ml asam amino lr-1 and 50 kg NPK ha-1)	53.52 a	6.71 ab
H	(15 ml asam amino lr-1 and 100 kg NPK ha-1)	59.01 b	7.28 b
I	(15 ml asam amino lr-1 and 150 kg NPK ha-1)	53.38 a	6.70 ab

Based on the data of GKG per hill and per plot, the combination treatment of amino acids and NPK showed a significant effect on milled dry grain yield. Treatment E (10 ml amino acid L^{-1} + 100 kg NPK ha^{-1}) produced the highest GKG both per hill (64.03 g) and per plot (7.93 kg), followed by treatment H (15 ml amino acid L^{-1} + 100 kg NPK ha^{-1}) with values of 59.01 g and 7.28 kg, respectively. Meanwhile, other treatments with lower or higher doses than this combination resulted in lower GKG. These findings indicate that the optimal dosage of amino acids and NPK plays an important role in improving the quality and quantity of milled dry grain, supporting overall crop productivity.

Field observations at 30 days after planting (DAP) showed that the combination treatments of amino acids and NPK had not yet shown a significant effect on the plant height of the Inpari 32 rice variety. Plant height at this stage was relatively uniform across treatments, ranging from 28–30 cm, indicating that the plant's physiological response to fertilizer application was still in the adaptation phase. This can be explained by the limited ability of the young root system to absorb additional nutrients from the soil, as well as field environmental conditions dominated by high rainfall, which leads to potential nitrogen loss through leaching and volatilization (Barłóg et al., 2022). Thus, in the early growth phase, most of the plant's nutrient requirements are still met by the soil's native nutrient reserves, while the effects of biostimulants and fertilizers have not yet been clearly manifested in the plant height parameter (Hamid et al., 2021). This condition reflects the physiological dynamics of rice plants in the early vegetative stage, where metabolic energy is more focused on the formation of primary roots and young leaf tissues rather than on stem elongation (Jingqing et al., 2025).

In the subsequent growth phase, i.e., at 45 to 60 DAP, the plant's response to the treatments began to show significant differences. The combination of 10 ml L^{-1} amino acids with 100 kg ha^{-1} NPK fertilizer produced the highest plant height, reaching 46.43 cm and 74.42 cm, respectively. This increase indicates a positive synergy between macronutrients (N, P, K) and the bioactive organic compounds contained in amino acids. Physiologically, this combination plays a role in enhancing nitrogenase enzyme activity and photosynthesis, strengthening meristematic tissue formation, and optimizing stem cell division and elongation. Field observations also showed that plants under the combination treatment had healthier morphology, erect stems, dark green leaves, and denser canopies, indicating higher photosynthetic efficiency (Ding et al., 2025). This phenomenon demonstrates that the presence of amino acids not only acts as an additional organic nitrogen source but also as a growth regulator that stimulates the synthesis of hormones such as auxins and cytokinins, which synergistically accelerate vegetative development (Jangra et al., 2022).

Empirical results and field observations confirm that the combination of amino acids and NPK fertilizer provides a more stable and efficient physiological effect compared to the application of inorganic fertilizer alone. The combination treatment showed better uniformity in plant height among hills, a lower coefficient of variation, and an increased rate of photosynthesis, indicated by darker green leaf color and thicker leaf structure. In contrast, the use of NPK without amino acid support at high doses tended to cause chlorosis symptoms in the lower leaves due to imbalanced nutrient uptake, which ultimately limited stem growth rate. This indicates that conventional NPK-based fertilization systems alone cannot efficiently overcome nutrient loss without the support of biostimulants that strengthen plant physiological functions and improve soil structure (Fuertes-mendiz et al., 2023). Thus, the combination of 10 ml L^{-1} amino acids and 100 kg ha^{-1} NPK proved most effective in enhancing the vegetative growth of the Inpari 32 rice variety. These findings provide an important scientific contribution to the development of sustainable fertilization strategies based on the synergy of organic and inorganic materials to support nutrient efficiency, high productivity, and the sustainability of modern agricultural systems.

The increase in the number of productive tillers in rice plants treated with the combination of amino acids and NPK fertilizer indicates that both treatments have a synergistic effect on vegetative growth (Tao et al., 2024). Based on field observations, plants treated with the combination of 10 ml L^{-1} amino acids and 100 kg ha^{-1} NPK exhibited greener leaf color, better plant vigor, and more uniform tiller numbers compared to other treatments. This suggests that amino acids act as biostimulants that enhance metabolic activity, particularly photosynthesis and root respiration, ultimately stimulating the formation of new tillers (Deveikyt & Blinstrubien, 2025). Physiologically, the glycine and glutamate content in amino acids functions as metal ion chelating agents, thereby increasing the efficiency of micronutrient uptake in the root zone. This enhanced micronutrient uptake also supports enzymatic activity and root cell division, reflected in greater root volume and higher root dry weight (Kumar et al., 2021).

Furthermore, compound NPK fertilizer supplies essential macronutrients (N, P, and K) that complement the plant's biochemical functions. Nitrogen (N) supports chlorophyll and protein formation, which plays a role in canopy growth and tiller formation, while phosphorus (P) is involved in nucleus formation and cell division in meristematic tissues, triggering the formation of new shoots (Abbas et al., 2022). Potassium (K) plays a role in photosynthate transport and cellular osmotic pressure regulation, thereby supporting water balance and physiological stability of the plant. Field notes indicate that plants receiving this combination dosage had a more branched root system that penetrated deeper soil layers, enabling more efficient nutrient and water uptake. This has direct implications for increasing the number of panicles per hill, 1000-grain weight, and harvest dry grain yield per plot (Apriyani et al, 2024).

This observed increase reinforces the assumption that amino acid application can improve NPK fertilization efficiency through enhanced nutrient availability, photosynthetic activity, and nutrient translocation toward plant reproductive organs (Saleem et al., 2023). Empirically, the research results showed that the optimum combination dose of 10 ml L^{-1} amino acids with 100 kg ha^{-1} NPK produced the highest number of tillers per hill (26.20 stems) and was significantly different from other treatments. These field findings also showed that plants receiving this combination treatment had a larger leaf area index and denser canopy, indicating an increased total photosynthetic capacity. Thus, the increase in grain productivity is not only due to macronutrient supply but also to the biocatalytic role of amino acids that support overall plant physiological efficiency (Chen et al, 2022).

Amino acid application has been shown to increase leaf chlorophyll content and accelerate the photosynthetic process, which has direct implications for improving the vegetative growth of rice plants. Amino acids act as basic protein components as well as biostimulants that accelerate enzyme and protein synthesis for new tissue formation. Their glycine and glutamate content also functions as chelating agents that aid micronutrient absorption, thereby increasing nutrient efficiency. Field notes indicate that plants treated with the combination of 10–15 ml L^{-1} amino acids and 100 kg ha^{-1} NPK fertilizer had dark green leaves, denser canopies, and faster growth rates compared to other treatments. This demonstrates that increased chlorophyll content accompanied by leaf expansion enhances photosynthetic capacity and photosynthate production. The resulting photosynthates are then used to support new tiller growth, root tissue formation, and stem enlargement, which physiologically reflects the optimization of plant metabolic processes (Yang & Zhou, 2025).

Chemically and agronomically, the combined application of amino acids and NPK fertilizer is able to create a nutrient balance that supports optimal plant growth. Nitrogen from NPK fertilizer enhances endogenous amino acid formation, while phosphorus supports cell division and lateral root development, and potassium plays a role in translocating photosynthetic products to productive plant organs (Wang et al. 2024). Field observations showed that plants receiving this combination treatment had a higher leaf area index, stronger root systems, and better nutrient uptake capacity. Further test results indicated that the treatment of 10 ml L^{-1} amino acids with 100 kg ha^{-1} NPK produced the highest leaf area index and was significantly different from other treatments, confirming a synergistic effect between organic biostimulants and inorganic fertilizers. Additionally, the increase in total nitrogen content contributed to increased chlorophyll levels, which strengthened photosynthetic efficiency and plant productivity (Nasar et al., 2021). Thus, the combination of these two treatments not only improves the physiological aspects of the plant but also provides a scientific basis for the implementation of sustainable fertilization strategies in modern rice cultivation systems.

The combination treatments of 10 ml L^{-1} and 15 ml L^{-1} amino acids with 100 kg ha^{-1} NPK produced the highest number of tillers per hill, reaching 19.37 and 19.20 stems, respectively, significantly different from other treatments. This increase in tiller number is closely related to the role of amino acids as biological catalysts in the synthesis of enzymes and growth hormones such as auxins, cytokinins, and gibberellins, which are involved in root formation, cell division, and new tiller formation. Physiologically, amino acids accelerate nitrogen metabolism and enhance photosynthetic activity, while NPK fertilizer supplies the macronutrients N, P, and K, which improve soil fertility and support vegetative tissue development (Wang et al., 2024). Field notes show that plants under these combination treatments had denser roots, dark green leaves, and better growth vigor, indicating an optimal nutrient balance between organic and inorganic supply. This condition confirms that the synergistic interaction between amino acids and NPK can accelerate productive shoot growth through mutually supporting physiological and biochemical mechanisms.

The increase in the number of panicles per hill also showed a positive response to the combination treatments. The amino acid treatments of 10–15 ml L^{-1} combined with 100 kg ha^{-1} NPK produced the highest number of panicles and were significantly different from other dosages, indicating the effectiveness of the optimum dosage in supporting the generative phase of the plant. Phosphorus in NPK fertilizer plays an important role in panicle formation and grain filling, while potassium supports photosynthate transport to reproductive organs and strengthens stem structure. Meanwhile, growth hormones synthesized from amino acids also stimulate panicle formation and reduce flower abortion (Parida et al., 2022). Field observations showed that plants under these combination treatments had longer panicles, more grains, and leaf greenness that persisted longer until the ripening phase. This proves that the application of amino acids together with NPK not only improves plant physiological efficiency but also has the potential to optimize grain yield through increased photosynthetic activity and nutrient balance that effectively supports the vegetative-to-generative transition.

The amino acid treatments of 10 ml L^{-1} and 15 ml L^{-1} combined with 100 kg ha^{-1} NPK fertilizer (E and H) produced the highest number of filled grains per panicle, reaching 126.57 and 126.33 grains, respectively, significantly different from other treatments. This phenomenon indicates a positive synergy between amino acids and NPK macronutrients in improving nutrient uptake efficiency and optimal seed formation. Physiologically, amino acids act as biostimulants that improve soil structure and increase nutrient availability through their chelating ability with respect to nitrogen, phosphorus, and potassium. This mechanism strengthens root absorption capacity for essential nutrients and reduces nutrient loss through leaching and soil fixation. Field notes show that plants under these combination treatments had longer panicles, more uniform grain filling, and leaf greenness that persisted longer until the ripening stage. This indicates that stable nutrient availability and high photosynthetic activity drive a more efficient increase in carbohydrate accumulation toward the grains (Rahman et al., 2025).

The increase in 1000-grain weight in combination treatments E and H, reaching 26.50 g and 26.93 g respectively, reinforces previous results that balanced nutrient availability plays an important role in grain formation and filling. Phosphorus (P) functions as a main component of metabolic energy (ATP and ADP) that regulates the translocation of photosynthates from leaves to grains, while potassium (K) supports the formation of dense grain tissue and strengthens panicle structure. Amino acids help accelerate protein synthesis and enzyme formation that support grain metabolic activity during the generative phase. Field observations showed that plants with the optimal combination treatment had fully filled, bright-colored, and uniform grains, indicating high physiological efficiency in utilizing energy from photosynthesis. Thus, the results of this study confirm that the combination of amino acids and NPK fertilizer not only increases grain productivity through improvements in key agronomic parameters but also has the potential to serve as a scientific basis for formulating sustainable fertilization strategies for efficient and environmentally friendly modern rice cultivation systems (Marina et al., 2022).

Amino acid application has been shown to increase total leaf chlorophyll content through enhanced nitrogen uptake, an essential element in the formation of chlorophyll molecules that play a direct role in photosynthesis (Felisberto et al., 2021). Nitrogen functions as a major structural component of amino acids and proteins that support vegetative growth, particularly the formation of leaf and stem tissues. The plant's ability to absorb nitrogen is a key indicator of fertilization effectiveness, because N availability in the rhizosphere determines photosynthetic efficiency and the translocation of photosynthates to storage organs (Daryono et al., 2021; Sari et al., 2019). Field observations showed that plants treated with the combination of 10 ml L^{-1} and 15 ml L^{-1} amino acids with 100 kg ha^{-1} NPK fertilizer had dark green leaves and remained photosynthetically active until the grain-filling stage, indicating optimal physiological performance. NPK fertilizer application synergistically enriches the availability of nitrogen, phosphorus, and potassium—essential macronutrients that support protein formation, metabolic energy (ATP and ADP), and carbohydrates that make up plant tissues (Hadisuwito, 2017). Previous research also supports these findings, where the combination of NPK with organic materials such as posbidik compost was able to increase the number of productive tillers, panicle length, and harvest dry grain weight (Kesuma, 2021).

The combination treatments of 10 ml L^{-1} and 15 ml L^{-1} amino acids with 100 kg ha^{-1} NPK fertilizer (E and H) produced the highest harvest dry grain yield, reaching 9.03 kg and 8.97 kg per plot, equivalent to 10.03 tons ha^{-1} and 9.97 tons ha^{-1}, significantly different from other treatments. This increase is closely related to the role of amino acids as biostimulants that strengthen soil microbial activity, improve root nutrient absorption capacity, and support the formation of productive tillers that contribute to final yield. During the generative phase, the abundance of nitrogen and phosphorus drives photosynthetic efficiency and increases carbohydrate reserves translocated to the grains (Sirappa & Waas, 2019; Sunadi et al., 2020). Field observations showed that plants under these combination treatments had dense panicles and fully filled grains, indicating an optimal grain-filling process. Meanwhile, the low NPK fertilizer dose (50 kg ha^{-1}) showed a significant decrease in grain weight due to low carbohydrate accumulation and limited metabolic energy for grain formation. Overall, the combination of amino acids and NPK plays a dual role: improving soil chemical and biological fertility while optimizing plant physiological functions, thereby supporting sustainable and efficient increases in rice productivity.

Acids and NPK fertilizer proved to have a significant effect on increasing milled dry grain yield per hill and per plot. The combination treatment of 10 ml L^{-1} amino acids with 100 kg ha^{-1} NPK (E) produced the highest milled dry grain weight per hill of 64.03 g and per plot of 7.93 kg, equivalent to 8.81 tons ha^{-1}, which was significantly different from other treatments. This yield increase indicates that this combination represents the optimal dosage for supplying essential nutrients for rice growth and productivity. The synergy between amino acids and NPK improves the absorption efficiency of nitrogen, phosphorus, and potassium, which play important roles in protein formation, chlorophyll synthesis, metabolic energy, and plant carbohydrates. N supports vegetative tissue formation and protein synthesis, P functions as an energy source and accelerates grain formation and ripening, while K plays a role in metabolism, photosynthesis, and regulating water balance and enzymes. The availability of these elements not only enhances photosynthesis and translocation of photosynthates to grains but also reduces flower and grain abortion rates, resulting in dense panicles and more complete grain filling. Thus, the combination of amino acids and NPK is able to create an optimal physiological and biochemical balance in plants, strengthen root growth, increase the number of productive tillers, and maximize milled dry grain yield per unit land area.

Conclusion

The present study demonstrated that the combined application of amino acids and NPK fertilizer significantly improved vegetative growth, yield components, and grain productivity of Inpari 32 rice. The treatment consisting of 10 mL L^{-1} amino acids combined with 100 kg ha^{-1} NPK fertilizer consistently produced the highest plant height, tiller number, leaf area index, productive tillers, panicle number, filled grains per panicle, 1000-grain weight, harvest dry grain yield, and milled dry grain yield. The improved performance was associated with enhanced nutrient uptake efficiency, increased photosynthetic activity, and better physiological development resulting from the synergistic interaction between amino acids and essential macronutrients. These findings indicate that integrating amino acid biostimulants with balanced NPK fertilization represents an effective and sustainable strategy for increasing rice productivity under irrigated lowland conditions. These findings are consistent with the results reported by Mirtaleb et al. (2021), who observed that amino acid application enhanced nutrient uptake efficiency and grain quality in rice. Similar results were reported by Basavarajappa et al. (2021), indicating that balanced NPK fertilization significantly improved tiller formation and yield components. Furthermore, Tao et al. (2024) demonstrated that integrated nutrient management combining organic and inorganic nutrient sources enhanced rice productivity and nutrient use efficiency.

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T.K.D., W.J.: Developing ideas, data collection, analyzing, writing, reviewing, and responding to reviewers' comments; C.S.P., I.M.: supervising data collection, analyzing data, reviewing data and writing; M.K.: reviewing scripts and writing.

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The authors declare no conflict of interest.

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