AGROSAINS
Jurnal Penelitian Agronomi
pISSN: 1411-5786; eISSN: 2655-7339

Agrosains : Jurnal Penelitian Agronomi 28(1): 28-35, 2026
https://jurnal.uns.ac.id/agrosains/article/view/115717
DOI: http://dx.doi.org/10.20961/agsjpa.v28i1.115717

Morphophysiological Characterization and Size of Source and Sink in Upland Rice under Different N Conditions

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Received: February 9, 2026; **Revised**: April 17, 2026; **Accepted**: April 24, 2026

ABSTRACT

Nitrogen is an essential nutrient that plays a key role in regulating growth, physiological processes, and yield formation in lowland rice, primarily through its influence on the source-sink balance. Yield variation among upland rice varieties is closely related to differences in photosynthetic capacity, assimilation efficiency, and grain filling during the generative phase. Therefore, understanding the response of source and sink morphophysiological traits and upland rice yield components to nitrogen application under dryland conditions is crucial. This study aimed to evaluate the morphophysiological characteristics of sources and sinks and to assess the effect of various nitrogen doses on source (g) and sink (g) size in several lowland rice varieties. The study was conducted in a dryland area using a split-plot design in a randomized block design. Nitrogen dose treatments consisted of 30 kg N ha^{-1} (62.5 kg ha^{-1} urea equivalent) and 115 kg N ha^{-1} (250 kg ha^{-1} urea equivalent) as the main plot, while upland rice varieties IPB 9G, IPB 10G, Inpago 8, and Situpatenggang were used as subplots. The results showed significant varietal differences in physiological traits, yield components, and source-sink balance in response to nitrogen application. Among the tested varieties, IPB 9G showed the most stable performance, characterized by high source and sink sizes, optimal yield components, and a relatively stable harvest index. Increasing nitrogen application to 115 kg N ha^{-1} improved physiological indicators and sink capacity, contributing to increased yield potential. These findings highlight that nitrogen response is strongly influenced by varietal characteristics and assimilation utilization efficiency, emphasizing the importance of determining variety-specific optimal nitrogen levels for dryland rice under dryland conditions.

Keywords: assimilate allocation; dryland cultivation; photosynthetic capacity

Cite this as: Lazuardi, D. A., Lubis, I., & Purnamawati, H. (2026). Morphophysiological Characterization and Size of Source and Sink in Upland Rice under Different N Conditions. *Agrosains: Jurnal Penelitian Agronomi*, *28*(1), 28-35. DOI: http://dx.doi.org/10.20961/agsjpa.v28i1.115717

INTRODUCTION

Rice (*Oryza sativa* L.) is a major global food commodity and plays a central role in food security, making it crucial to increase productivity in various ecosystems, including drylands. In marginal ecosystems, rice productivity is often constrained by water and nutrient availability, especially nitrogen (N), so yield enhancement strategies need to combine plant physiology and efficient nutrient management (Santosa et al., 2024). In the context of yield physiology, the source–sink relationship is a key factor, because grain yield is determined by source capacity (green canopy area and duration, N and chlorophyll content, photosynthesis rate) and sink capacity (panicle size and number, number of filled spikelets, and grain filling efficiency). Varieties or cultivation technologies capable of forming large sources and large sinks simultaneously tend to have higher yields and nitrogen use efficiency (NUE) than combinations of small sources and sinks (He et al., 2021).

Nitrogen itself is an essential nutrient that plays a role in the formation of chlorophyll, proteins, and photosynthetic enzymes, thus greatly determining the source capacity of rice plants. Increasing the N dose generally increases the leaf area index, chlorophyll content, photosynthesis rate, and yield components such as the number of productive tillers and spikelets, both in paddy rice and rice under water stress conditions (Abdou et al., 2021). Various studies show that the right combination of N and water management, such as integrative crop management or alternate wetting and moderate drying irrigation systems, can increase yields, NUE, and water productivity through improvements in source–sink characteristics, root growth, and canopy physiological activity (Zhang et al., 2017).

However, excessive N fertilization does not always result in increased yields. It can reduce N efficiency and pose a risk of environmental damage, necessitating an approach based on "N-efficient varieties" and more precise N management (Huang et al., 2019). Recent research shows that there are significant differences between rice varieties in their response to N availability, both at the morphological level (e.g., canopy architecture and root system), physiological level (leaf N and chlorophyll content, photosynthesis rate, antioxidant enzyme activity), and sink characteristics (number of spikelets, grain-to-leaf ratio, non-structural carbohydrate content and remobilization) that contribute to variations in yield and NUE. Varieties classified as nitrogen-efficient varieties (NEVs) generally exhibit larger sink size, "stronger" flag leaves (thick, high N and chlorophyll content), better canopy structure, and higher root activity and post-flowering N transport, enabling them to maintain photosynthesis and grain filling for longer (Zhu et al., 2022). However, most of these studies still focus on paddy rice and have not explicitly examined the relationship between source–sink morphophysiological characteristics and N efficiency in upland rice in rain-fed ecosystems that often experience water deficits (Wu et al., 2025).

This knowledge gap highlights the need for integrated research comparing several upland rice genotypes at various N levels, linking morphological indicators (leaf area, productive tillers, panicle components), physiological indicators (N and chlorophyll content, photosynthesis rate, non-structural carbohydrate dynamics, root activity), as well as yield components and NUE parameters. Such an approach is in line with findings that coordination between large sink size and high post-flowering source capacity is key to achieving high yields and N efficiency in rice (Huang et al., 2019). Therefore, research on the source–sink relationship specific to upland rice varieties under different N management is expected to provide a scientific basis for the development of more efficient, water-stress-adaptive, and sustainable N fertilization strategies in dryland areas.

MATERIALS AND METHODS

This study was conducted from December 2024 to May 2025 at the Sawah Baru Experimental Farm and supported by analyses at the Advanced Laboratory and the Agronomy and Horticulture Testing Laboratory, Faculty of Agriculture, IPB University. The study used a completely randomized block design with two factors and three replications. The first factor was dryland rice varieties, namely IPB 9G, IPB 10G, Inpago 8, and Situpatenggang. The second factor is the nitrogen dose in the form of urea fertilizer, namely 62.5 kg urea ha^{-1} and 250 kg urea ha^{-1}, equivalent to 30 kg N ha^{-1} and 115 kg N ha^{-1} respectively.

This dosage was formulated based on the basic recommendations for nitrogen fertilization in upland rice (Adi et al., 2019). Thus, 30 kg N ha^{-1} was used as a low dose, while 115 kg N ha^{-1} was used as a high dose above the reference recommendation to evaluate the response of varieties to N availability. This is in line with the N dose range of 60–120 kg N ha^{-1} that has been widely tested in upland rice (Oliveira et al., 2020). Each plot unit measures 3 m × 4 m, with a tile size of 1.5 m × 1.5 m. Each treatment combination was repeated three times, resulting in 24 experimental units. The land was plowed and divided into plots, then initial soil samples were taken compositely from five points diagonally at a depth of 0–20 cm, mixed homogeneously, and analyzed for total N, potential P, and total K to describe the initial nutrient status before planting, as is common practice in upland rice fertilization studies such as in the previous upland rice study (Oliveira et al., 2020).

Planting was carried out one week after the plot was plowed, with a planting distance of 50 cm × 10 cm using 7 seeds per hole, resulting in 45 planting holes per plot. Six sample plants were selected from each plot unit for observation. Chicken manure, SP-26, and KCl were applied according to the basic recommendations for the location, while urea was applied three times according to the treatment, namely at 0, 4, and 8 weeks after planting. The plants were harvested simultaneously at 110 days after planting, which was within the harvest age range. This was in accordance with the fertilization pattern for upland rice (Adi et al., 2019).

Observations included soil nutrient testing prior to cultivation. Growth and morphophysiological characteristics included the number of tillers, flag leaf length and width, relative chlorophyll content using SPAD, photosynthesis rate using Li-Cor 6800CT, and source-sink capacity. The yield components observed included panicle length, number of panicles per hill, total number of grains per panicle, percentage of filled grains, 1000-grain weight, grain weight per hill, grain weight per plot (g m^{-2}), Pn: Photosynthetic rate (μmol CO_2 m^{-2} s^{-1}), gs (Stomatal Conductance): mmol H_2O m^{-2} s^{-1}, WUE (Water Use Efficiency): μmol CO_2 $mmol^{-1}$ H_2O and harvest index.

The source capacity is calculated using the following formula :

$$(\mathbf{TPDW_H - TDM_h + NSC_h})$$

The source capacity is calculated using the following formula :

$$(\mathbf{TGY \times FGW\ per\ grain})$$

Description :

$TPDW_H$	:	Total plant dry weight at harvest (g)
TDM_h	:	Total dry matter at heading (g)
NSC_h	:	Non-structural carbohydrate at heading (g)
TGY	:	Total Grain Yield
FGW	:	Filled grain weight per grain (g)

The data were analyzed using analysis of variance (ANOVA) according to a completely randomized design using RStudio and Microsoft Excel 2010 software. If there was a significant effect, a Duncan Multiple Range Test (DMRT) was performed at a significance level of 5%.

RESULT AND DISCUSSION

This study aims to analyze the morphophysiological characteristics of the source and sink of several varieties of upland rice and to analyze the effect of nitrogen on the size of the source and sink of several varieties of upland rice. Several morpho-agronomic characteristics, such as the number of tillers, panicle length, number of grains per panicle, and 1,000-grain weight, play a role in determining the source and sink capacity and the source-sink balance of upland rice/rainfed dryland (Ichsan et al., 2021).

The research results generally have several observation parameters that have a significant effect on the treatment of the upland rice varieties used, such as the length and width of the flag leaf, panicle length,

Table 1. Number of tillers per treatment of several upland rice varieties and nitrogen conditions

Treatment	4 WAP	5WAP	6 WAP	7 WAP	8 WAP
Variety					
IPB 9G	9.52	10.94	11.44	12.00	13.58
IPB 10G	13.36	14.48	14.75	15.74	18.33
Inpago 8	12.30	15.14	16.34	16.56	18.14
Situpatenggang	11.44	13.33	13.55	13.93	18.80
Pr (>F)	ns	ns	ns	ns	ns
KK (%)	20.04	24.37	20.83	26.21	26.36
Nitrogen Conditions					
62.5 kg N	11.17	12.49	13.33	13.92	16.55
250 kg N	12.13	14.45	14.71	15.21	17.87
Pr (>F)	ns	ns	ns	ns	ns

Description: Numbers in one column followed by the same letter are not significantly different according to DMRT with α= 5%, *: significance level 5%; **: significance level 1%; ns: Not Significant. WAP : Week after planting.

Table 2. Soil analysis before planting

Parameter	Result	Unit	Description
N-Total	0.24	%	Currently
P-Potential	199.65	mg P_2O_5/100g	High
K-Total	16.99	mg K_2O_5/100g	Currently

number of panicles per clump, total number of grains, weight of 1000 grains, grain weight per clump, grain weight per plot, harvest index, and sink in plants. Differences in upland rice varieties cause noticeable differences in morphophysiological characteristics (Ahadiyat et al., 2020)

The research results generally show several observation parameters that have a significant effect on the nitrogen dosage treatment used, such as flag leaf length, number of panicles per clump, total grain yield, stomatal conductance, and sink in plants. In line with the research by Du (2022), it is stated that the application of N fertilizer, especially in combination with NPK, improves root morphology (length, number, biomass) and root physiology (oxidation activity, active absorption area), thereby increasing N absorption and rice yield.

Table 1 shows that the number of tillers in upland rice across different varieties and nitrogen levels observed at 4–8 WAP was not statistically significantly different. The Pr (>F) values marked with tn across all observation periods confirm that there was no significant effect of either variety or nitrogen application level. This indicates that all treatments produced relatively similar tiller formation responses, so that no statistical distinction could be made between treatments that produced higher or lower tiller numbers.

Although there were descriptive variations in the mean values between treatments, these differences were not large enough to reach the predetermined level of statistical significance. The response of plant biomass to nitrogen addition was also influenced by initial soil conditions, where already high total nitrogen content could reduce the effect of additional nitrogen on plant growth (Liu et al., 2024). Furthermore, in dryland upland rice cultivation systems, these results are consistent with previous findings that the response of rice tillering to nitrogen fertilization is greatly influenced by initial soil nutrient status and growing conditions and does not always show significant differences under conditions of relatively adequate nutrient availability (Esang and Ikeh, 2021). Soil analysis results show that the total nitrogen content of 0.24% is classified as moderate, indicating that the soil is still capable of supporting early vegetative growth of plants, but is insufficient to meet nitrogen requirements in the later stages of growth and yield formation.

The soil fertility rating categories for the parameters N-total, P-potential, and K-total in Table 2 refer to the soil chemical property interpretation criteria developed by the Soil Research Institute. Based on these criteria, the N-total content of 0.24% is classified as moderate, as it falls within the range of 0.10–0.30%. The P-potential value of 199.65 mg P_2O_5/100 g soil is classified as high, as it is above the high category limit of >40 mg P_2O_5/100 g soil. Meanwhile, the total K content of 16.99 mg K_2O/100 g soil is classified as moderate, as it falls within the range of 10–20 mg K_2O/100 g soil. This classification is used to interpret soil fertility status, which can then be used as a basis for crop nutrient management. This assessment refers to the criteria for interpreting soil chemical properties as proposed by the Soil Research Institute (2009) and further explained in soil science literature by Hardjowigeno (2015).

Table 3 shows that the IPB 9G variety has flag leaf characteristics with greater length and width compared to other varieties. The flag leaf is the main photosynthetic organ during the grain filling phase, so a larger leaf surface area has the potential to increase solar radiation absorption and assimilate accumulation, which supports yield formation. In line with the research by Liana et al. (2021), it is explained that the contribution of flag leaves to assimilation for grain filling reaches about 50% of the total assimilation used during the grain filling phase. In contrast, the IPB 10G variety has relatively smaller flag leaves. This condition is thought to be related to the genetic characteristics of the variety, which tends to optimize the allocation of photosynthates to reproductive organs rather than vegetative organ development. Smaller leaf size does not always reflect

Table 3. Leaf width and length of several upland rice varieties and nitrogen conditions

Treatment	Flag Leaf Width and Length	
	Width (cm)	Lenght (cm)
Varieties		
IPB 9G	1.98 a	37.29 a
IPB 10G	1.36 b	26.04 c
Inpago 8	1.48 b	34.92 a
Situpatenggang	1.57 b	30.54 b
Pr (>F)	0.00**	0.00**
KK (%)	12.49	7.84
Nitrogen Conditions		
62.5 kg N	1.56	31.11 a
250 kg N	1.63	33.29 b
Pr (>F)	ns	0.05*

Description: numbers in one column followed by the same letter are not significantly different according to DMRT with α= 5%, *: significance level 5%; **: significance level 1%; ns: Not Significant.

Table 4. Yield components of several upland rice varieties and nitrogen conditions

Treatment	Length Panicle (cm)	Number of Panicles per Cluster	Total Grain Yield	Presentation of Grain Yield (%)	Weight of 1000 Grains of Paddy (g)
Varieties					
IPB 9G	33.58 a	13.50 a	1,318.16 a	81.62	29.16 a
IPB 10G	24.78 c	10.66 b	927.50 b	80.54	28.00 ab
Inpago 8	29.83 b	11.91 b	927.16 b	77.18	28.66 a
Situpatenggang	23.83 c	9.00 c	617.33 c	69.04	26.66 b
Pr (>F)	0.00**	0.00**	0.00**	ns	0.01*
KK (%)	6.13	9.19	14.93	14.56	4.42
Nitrogen Condition					
62.5 kg N	27.43	10.41 b	875.33 b	74.81	27.75
250 kg N	28.58	12.12 a	1,019.75 a	79.38	28.50
Pr (>F)	ns	0.00**	0.02*	ns	ns

Description: numbers in one column followed by the same letter are not significantly different according to DMRT with α= 5%, *: significance level 5%; **: significance level 1%; ns: Not Significant

low photosynthetic capacity, as varieties with optimal leaf area index and high photosynthetic efficiency are still capable of producing good productivity (Hidayat et al., 2022).

From a fertilization perspective, applying 250 kg ha^{-1} of nitrogen resulted in longer and wider flag leaves compared to a dose of 62.5 kg ha^{-1}. This shows that increased nitrogen availability promotes vegetative leaf growth, which plays an important role in increasing photosynthetic capacity prior to panicle formation. Nitrogen functions as a major component of chlorophyll and enzymatic proteins that regulate cell division and enlargement in leaves, thus directly affecting the morphological development of flag leaves (Wijayanti et al., 2021).

The IPB 9G variety showed higher yield components compared to other varieties, indicating that the ability to form productive panicles and a greater number of grains are the main factors determining yield, as reported in research findings that increased rice yields are closely related to sink enlargement through the number of panicles and grains per plant. This is also because larger sink size is the main component that determines high grain production in rice plants (Mai et al., 2021).

Nitrogen treatment had a significant effect on the number of panicles per hill and total grain yield, but had no significant effect on panicle length, grain filling percentage, and 1,000-grain weight (Table 4). This is in line with research findings that explain that increasing the total number of spikelets in rice plants through nitrogen application is a dominant factor in increasing yield components in rice plants. Meanwhile, its effect on average grain filling and grain weight tends to be smaller and not very significant (Liu et al., 2024). The insignificant effect of nitrogen on 1,000-grain weight and grain filling percentage indicates that the grain filling process is more determined by the physiological capacity of the plant and genetic factors than by increased nitrogen availability during the grain filling phase (Qun et al., 2023). Overall, these results confirm that the response of upland rice yield components to nitrogen is component- and variety-specific, so nitrogen fertilization strategies need to be tailored to the physiological characteristics of the variety to achieve optimal yield efficiency.

The results of observations of grain weight per clump, grain weight per plot, and harvest index show differences in the response of rice varieties to nitrogen availability. The IPB 9G variety showed the highest performance with grain weight per plant reaching 25.55 g and plot yield of 1,150 g m^{-2}, reflecting greater sink capacity and more efficient grain filling under optimal nitrogen conditions (Table 5). These findings are in line with reports that nitrogen fertilization plays an important role in increasing panicle formation and grain filling, but the level of yield response is largely determined by the genetic potential

Table 5. Grain weight per cluster, grain weight per plot, and harvest index of several varieties of upland rice and nitrogen conditions

Treatment	Weight of Grain per Clump (g)	Weight of Grain per Square Meter* (g m^{-2})	Harvest Index
Varieties			
IPB 9G	25.55 a	1,150.00 a	0.46 a
IPB 10G	18.14 bc	816.66 bc	0.37 ab
Inpago 8	20.37 ab	916.66 ab	0.39 ab
Situpatenggang	12.22 c	550.00 c	0.28 b
Pr (>F)	0.00**	0.00**	0.01*
KK (%)	27.21	27.22	26.68
Nitrogen Conditions			
Nitrogen 62.5 kg/ha	17.77	800.00	0.40
Nitrogen 250 kg/ha	20.36	916.66	0.35
Pr (>F)	ns	ns	ns

Description: Numbers followed by the same letter in the same column indicate no significant difference based on the DMRT α 5% test. *: Plot size 1.5 x 1.5 m, *: significance level 5%; **: significance level 1%; ns: Not Significant

Table 6. Photosynthesis of single leaves of rice plants during the primordia-heading and heading-harvest phases

Treatment	Photosynthesis					
	Heading			Harvest		
	Pn	gs	WUE	Pn	gs	WUE
Varieties						
IPB 9G	16.83	0.62	26.63	13.54	0.50	26.86
IPB 10G	18.71	0.73	25.70	16.93	0.62	28.39
Inpago 8	18.41	0.78	23.82	14.96	0.61	25.22
Situpatenggang	18.45	0.81	24.00	13.92	0.55	25.71
Pr (>F)	ns	ns	ns	ns	ns	ns
KK (%)	20.82	19.07	22.23	23.28	17.41	26.87
Nitrogen Conditions						
62.5 Kg N	18.08	0.70	25.94	15.07	0.52 b	29.46
250 Kg N	18.12	0.77	24.14	14.61	0.62 a	23.63
Pr (>F)	ns	ns	ns	ns	0.02*	ns

Description: Numbers followed by the same letter in the same column indicate no significant difference based on the DMRT α 5% test. Pn: Photosynthetic rate (μmol CO_2 m^{-2} s^{-1}), g_s (Stomatal Conductance): mmol H_2O m^{-2} s^{-1}, WUE (Water Use Efficiency): μmol CO_2 $mmol^{-1}$ H_2O, *: 5% significance level; **: 1% significance level; ns: Not Significant.

of the variety, nitrogen uptake efficiency, and the sink's ability to store photosynthetic products (Syarifa et al., 2022).

Nitrogen treatment in the study had no significant effect on grain weight per plant, grain weight per plot, or harvest index. This shows that increasing the nitrogen dose in upland rice cultivation does not always increase economic value if the genetic capacity of the plant is already sufficient, as reported that the response of upland rice yields to nitrogen is closely related to superior varieties and environmental conditions at the time of the study (Qi et al., 2025).

Although the photosynthetic rate of individual leaves (Pn) during the primordia, heading, and harvest phases showed variations between varieties, these differences were not statistically significant and therefore could not represent the overall photosynthetic capacity of the plants (Table 6). This is because plant photosynthesis is influenced not only by the photosynthetic activity of individual leaves, but also by canopy characteristics such as leaf area index (LAI), which plays a role in light interception and biomass accumulation. Therefore, the integration of leaf physiological properties and canopy structure is the main determinant of rice productivity (Susilawati et al., 2022).

Water use efficiency (WUE) increased from the heading phase to harvest in all varieties, with IPB 10G showing the highest WUE value. This indicates that varieties with the highest WUE values are able to maintain photosynthesis with more efficient water loss, in line with the general characteristics of upland rice, which is adaptive to dry land and water-limited conditions (Jing et al., 2025). The application of 250 kg N ha^{-1} increased stomatal conductance (gs) and WUE compared to the 62.5 kg N ha^{-1} dose, but this increase was not always followed by a proportional increase in net photosynthesis rate, indicating limitations in the physiological efficiency of nitrogen utilization at high supply levels and indications of nitrogen saturation in plants (Sutaryo et al., 2023).

The graph Figure 1 shows that across all treatments regardless of variety or nitrogen fertilization rate sink values were consistently higher than source values, indicating that the capacity of sink organs to receive and accumulate photosynthates was more dominant than the ability of source organs to produce assimilates during the observation period.

The statistically non-significant differences in source values on the upland rice variety graph indicate that the photosynthetic capacity and assimilate production of

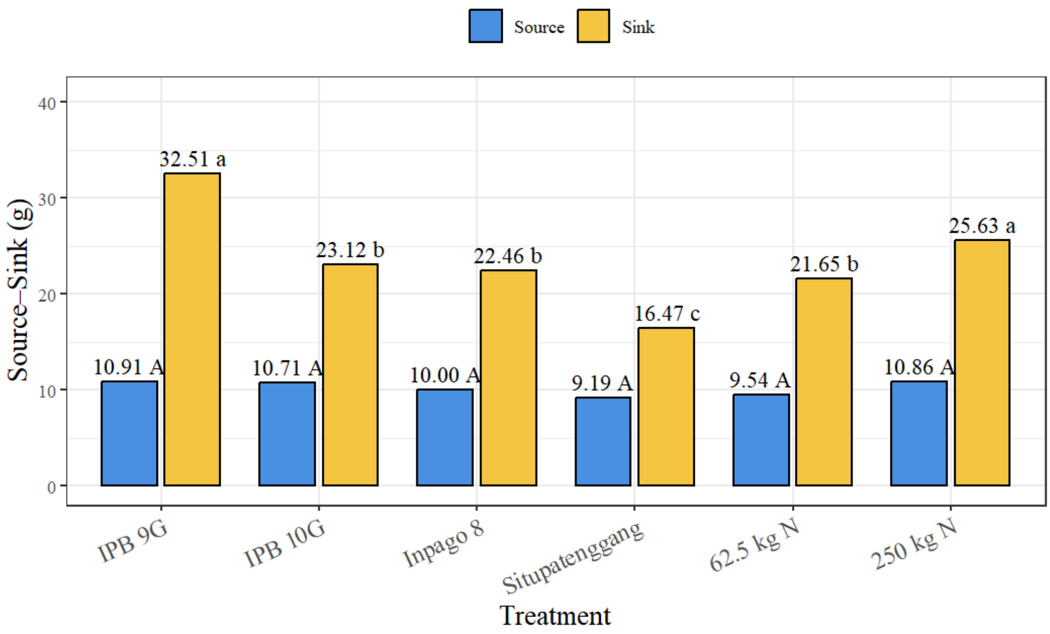

Figure 1. Source and sink capacity of several upland rice varieties and nitrogen conditions

IPB 9G, IPB 10G, Inpago 8, and Situpatenggang are essentially equivalent, although IPB 9G is numerically slightly higher. This suggests that potential yield differences among genotypes are more likely determined by sink capacity and efficiency (grain number and filling, source–sink balance and assimilate flow efficiency) than by differences in the leaves' ability to produce assimilates. Previous research has also shown that high-yielding varieties generally possess a combination of adequate leaf area, high photosynthetic rates, and strong sinks (sufficient grain number and good grain filling), whereas source–sink imbalance (excessively large sinks or inefficient assimilate flow) can increase empty grains even when source capacity is sufficient (Vishwakarma et al., 2023). This imbalance between source and sink is common during the seed filling phase, where a strong sink is not always accompanied by an adequate supply of assimilates, making remobilization and photosynthesis efficiency important factors in determining final crop yield (Yang et al., 2024).

Meanwhile, regarding the sink, the highest value among the varieties was observed in IPB 9G, with a value of 32.51 compared to the other varieties used. This indicates that IPB 9G possesses greater source photosynthetic capacity and seed-filling potential, as well as a relatively better source-sink balance, thereby supporting higher yield potential compared to other varieties such as Situ Patenggang, which exhibited the lowest source and sink values. These findings align with the concept that varieties with higher source-sink capacity tend to have better productivity due to more optimal assimilation utilization efficiency (Pan et al., 2022).

In addition, the response to nitrogen application is also clearly visible in the graph. The high nitrogen treatment of 250 kg N ha^{-1} produced higher source and sink values of 10.86 g and 25.63 g, respectively, compared to the low nitrogen treatment of 62.5 kg N ha^{-1} which produced source and sink values of 9.54 g and 21.65 g, respectively. This indicates that increasing the nitrogen dose can increase the photosynthetic capacity and vegetative growth of the source and expand the sink capacity by increasing the number and filling of grains, thereby contributing to an increase in overall crop yield potential. The role of nitrogen in improving the efficiency of assimilate utilization during the grain filling phase has also been reported in the literature, where increased N availability can increase sink capacity and improve the source–sink balance in rice plants (Zhang et al., 2023).

CONCLUSION

The research results show that the IPB 9G variety exhibits the best morphological characteristics in terms of the widest and longest flag leaves. The plant's physiological characteristics showed the highest values at the heading+15 stage for gs (stomatal conductance) with a nitrogen dose of 250 kg N ha^{-1}. The IPB 9G variety has source characteristics that are relatively similar to other upland rice varieties. However, it exhibits the highest sink characteristics among the IPB 9G variety and a nitrogen dose of 250 kg N ha^{-1}. Overall, the IPB 9G variety exhibited the highest yield components and crop yields for panicle length, number of panicles per plant, total grain yield, 100-grain weight, grain weight per plant, grain weight per plot, and harvest index. A nitrogen dose of 250 kg N ha^{-1} yielded the highest results for the yield components number of panicles per plant and total grain yield.

ACKNOWLEDGEMENT

The author would like to thank the Graduate Program of the Department of Agronomy and Horticulture, IPB University, and the Education Fund Management Institution (LPDP) for their financial support and facilities provided so that the research could be carried out properly.

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