

Agronomic Performance and Light Interception in a Multi Canopy Rice Cultivation System

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Abstract

Vertical space optimization through a multi-canopy system can potentially increase rice production. This research aims to evaluate the agronomic performance, light interception, and production of rice plants cultivated with a multi-canopy system. This research was conducted at the Sawah Baru Experimental Farm, IPB University. Rice varieties used two common height plants ("Inpari 30" and "Inpari 32") and the taller plants ("IPB 9G"). This research consisting of nine treatment combinations of cultivation system: mono-variety ("Inpari 30", "Inpari 32", and "IPB 9G"), combination of two varieties in one hill multi-canopy ("Inpari 30"- "IPB 9G" and "Inpari 32"- "IPB 9G"), inter-variety one-insertion multi-canopy ("Inpari 30"- "IPB 9G" and "Inpari 32"- "IPB 9G"), and inter-variety two-insertion multi-canopy ("Inpari 30"- "IPB 9G" and "Inpari 32"- "IPB 9G"). The results showed morphological and physiological performance as good in a multi-canopy system (inter-variety one insertion) on the variables of the plant height, number of panicles per clump, panicle length, number of grains per hill, weight of grains per hill, photosynthetic rate and land equivalent ratio (LER). The percentage of light interception in the multi-canopy system decreased by 19.13-61.54%. The inter-variety one-insertion multi-canopy with the "Inpari 30"- "IPB 9G" combination increases yield potential by 10.18%, and the "Inpari 32"- "IPB 9G" combination increases by 13.81% compared to the mono-variety. The combination of the "Inpari 30"- "IPB 9G" and "Inpari 32"- "IPB 9G" variety in an inter-variety one-insertion multi-canopy system produces an LER value of 1.75 and 1.64; this shows that the inter-variety one insertion multi-canopy system is promising to increase rice production.

Keywords: high productivity, land use efficiency, rice canopy, vertical space

Introduction

Rice is a staple food crop and a crucial commodity, with demand steadily increasing in line with population growth (Fadhilah et al., 2021). Therefore, continuous efforts are required to enhance the quality and yield potential of rice (Makino et al., 2021). Rice yields are determined by several factors, including environmental conditions and cultivation techniques (Yang and Hwa., 2008). Theoretically, increasing rice production can be achieved by implementing technological innovations appropriately, adequately, and specifically (Khamid et al., 2023b). According to Widyastuti et al. (2020), vertical farming is one method to increase rice yields. One approach to implementing vertical farming in food crop cultivation is the multi-canopy cultivation system, which involves growing two rice cultivars-one with tall stems and the other with short stems-on the same plot of land, creating a layered canopy structure.

The multi-canopy system causes competition between plants, including competition for light reception by plants (Hidayah et al., 2022). Rice plants with a higher canopy structure have a higher yield potential when compared to rice plants with a lower canopy structure, due to the ability of plants to absorb light in more significant amounts (Lu et al., 2010). Multi-canopy can potentially increase light interception by plants, which will be utilized in photosynthesis to increase biomass and yield components that increase rice productivity (Khamid et al., 2023b). Increased plant productivity is greatly influenced by light interception and the efficiency of available energy use (Lu et al., 2018).

Plants subjected to shade stress adapt by modifying their morphological and physiological characteristics to optimize light absorption. Differences in plant height, serving as an indicator of a complex canopy structure (Liu et al., 2022), have been utilized in

previous studies to assess the impact of leaf area on plant productivity by altering light competition patterns (Yi et al., 2022). Munda et al. (2019) reported that competition among rice plants can influence tiller growth and lead to reductions in biomass and yield. Therefore, research is essential to evaluate plant responses in terms of morphology, physiology, production, and land equivalency ratios within multi-canopy cultivation systems.

Materials and Methods

This research was conducted at the Sawah Baru Experimental Farm, Babakan Dramaga, Departement of Agronomy and Horticulture, IPB University, Bogor, West Jawa, Indonesia (6°33'52.7"S, 106°44'06.4"E) from November 2023 to April 2024. The materials used were two common rice seeds ("Inpari 30" and "Inpari 32") and taller rice seeds ("IPB 9G"), fertilizers (Urea, SP-36, and KCl), and Plant growth-promoting Rhizobacteria (PGPR). The tools used were LI-COR 6800 photosystem, LI-COR 1500, LI-190R Quantum Sensor, SPAD chlorophyll meter, scales, and cameras.

The experimental design was a one-factor randomized complete block design. This study consisted of nine treatments: a mono-variety cultivation system (A, B, C), combining two varieties in one hill multi-canopy (AC, BC), inter-variety one-insertion multi-canopy (AC1, BC1), and inter-variety two-insertion multi-canopy (AC2, BC2). Each treatment was repeated four times, totaling 36 experimental units.

Experimental Procedures

Land cultivation was carried out two weeks before planting. Planting used the 4:1 rows (known as the "legowo" planting system in Indonesia) with a planting distance of 15 cm x 30 cm when the seedlings were

21 days after sowing (DAS). The first fertilization used 150 kg.ha⁻¹ urea, 150 kg.ha⁻¹ SP-36 and 100 kg.ha⁻¹ KCl at 1 WAP (weeks after planting), and the second fertilization used 100 kg.ha⁻¹ urea at 5 weeks after planting. The plants are harvested when the panicles of 90% of the total population have turned yellow.

Measurements were made on morphological characters: plant height (cm), number of tillers, productive tillers (%), physiological characters: Soil Plant Analysis Development (SPAD) Value, photosynthetic rate (μmol.m⁻².s⁻¹), light interception (%), yield components: grain weight per hill (g), panicle length (cm), number of panicles per hill, number of grains per panicle (grain), percentage of filled grain (%), production: yield potential per hectare (ton), and Land Equivalent Ratio (LER).

The light interception was calculated using the following formula:

$$\text{Light interception (\%)} = (\text{RAFac} - \text{RAFbc} / \text{RAFac}) \times 100 \quad (1)$$

Where

RAFac: photosynthetic active radiation light above the canopy

RAFbc: photosynthetic active radiation light below the canopy.

The land equivalent ratio was calculated using the following formula:

$$\text{LER} = (\text{YA}/\text{SA}) + (\text{YB}/\text{SB}) \quad (2)$$

Where

YA: yield of A varieties grown in multi-canopy

YB: yield of B varieties grown in multi-canopy

SA: yield of A varieties grown in mono-variety

SB: yield of B varieties grown in mono-variety.

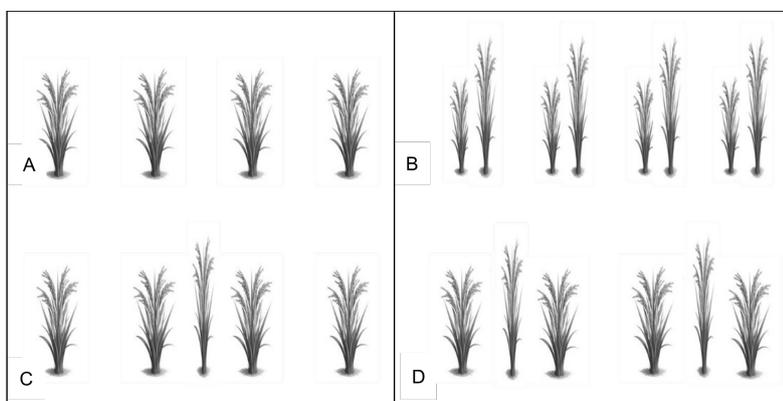


Figure 1. Rice cultivation systems, A; mono-variety, B; combinations of two varieties in one hill multi-canopy, C; inter-variety one-insertion multi-canopy, D; inter-variety two-insertion multi-canopy.

Data Analysis

The observation data for each variable were analyzed using analysis of variance (ANOVA) at $\alpha=0.05$ and continued with the Duncan multiple range test (DMRT) if the means between treatments were significant. Statistical analysis was performed using Statistical Tool for Agricultural Research (STAR) from International Rice Research Institute (IRRI).

Results and Discussion

Rice Morphological Characteristics

The height of “Inpari 30” and “Inpari 32” in the multi-canopy system showed no significant differences compared to the mono-variety system. However, the number of tillers of “Inpari 30” and “Inpari 32” in the combination of two varieties in one hill multi-canopy system decreased by 54.64% and 52.17%. The number of panicles per clump decreased by 60.41% and 54.74% compared to the mono-variety system (Table 1). The cultivation system did not significantly affect the character of plant height, number of tillers, number of panicles per clump, and productive tillers of “IPB 9G” in the multi-canopy system (Table 2).

The panicle length of “Inpari 30” in the combination of two varieties in one hill multi-canopy system decreased

by 13.68%, the number of grains per panicle of “Inpari 30” and “Inpari 32” in the combination of two varieties in one hill multi-canopy system decreased by 32.29% and 22.57%, respectively. In comparison, the weight of grain per clump of “Inpari 30” and “Inpari 32” in the combination of two varieties in one hill multi-canopy system decreased by 73.08% and 65.60%, respectively, compared to the mono-variety system. The grain weight per clump of “Inpari 30” and “Inpari 32” in the inter-variety one-insertion multi-canopy system was similar to the mono-variety system. The grain weight per clump of Inpari 30 in the combination of two varieties in one hill multi-canopy system decreased by 73.08%, and the inter-variety two-insertion multi-canopy system decreased by 42.37% compared to the mono-variety system. The grain weight per clump of “Inpari 32” combined with two varieties in one hill multi-canopy system decreased by 65.60%. In contrast, the inter-variety two-insertion multi-canopy system decreased by 41.87% compared to the mono-variety system (Table 3).

The percentage of filled grain of “IPB 9G” in the combination of two varieties in one hill multi-canopy system decreased by 16.33% when combined with “Inpari 30” and by 16.93% when combined with “Inpari 32”. In contrast, the inter-variety two-insertion multi-canopy system decreased by 22.38% when combined with “Inpari 30” and 24.66% with “Inpari 32”. The weight of grain per clump of “IPB 9G” in the

Table 1. Plant height, number of tillers, number of panicles per clump, and productive tillers of “Inpari 30” and “Inpari 32” in mono-variety and multi-canopy cultivation systems

Cultivation system	Plant height (cm)	Number of tillers	Number of panicles per clump	Productive tillers (%)
Mono-variety				
“Inpari 30”	79.48abc	24.25b	14.22a	65.20
“Inpari 32”	71.67e	28.75a	13.72a	59.32
Combination of two rice varieties in one hill multi-canopy				
“Inpari 30” (“IPB 9G”)	77.64bcd	11.00e	5.63d	57.17
“Inpari 32” (“IPB 9G”)	73.70de	13.75de	6.21d	53.97
Inter-variety one-insertion multi-canopy				
“Inpari 30” (“IPB 9G”)	82.10a	18.25c	10.97bc	65.85
“Inpari 32” (“IPB 9G”)	73.68de	22.50b	12.55ab	60.87
Inter-variety two-insertion multi-canopy				
“Inpari 30” (“IPB 9G”)	80.66ab	16.75cd	10.41bc	63.92
“Inpari 32” (“IPB 9G”)	75.50cde	17.25cd	9.72c	60.71

Notes: measurements were conducted on the rice variety without parenthesis; values followed by the same letter in the same column are not significantly different according to the DMRT at $\alpha=0.05$.

Table 2. Plant height, number of tillers, panicles per clump, and productive tillers of “IPB 9G” in mono-variety and multi-canopy cultivation systems

Cultivation system	Plant height (cm)	Number of tillers	Number of panicles per clump	Productive tillers (%)
Mono-variety				
“IPB 9G”	102.48	13.25	8.74	66.52
Combination of two varieties in one hill multi-canopy				
(“Inpari 30”) “IPB 9G”	99.59	11.00	6.57	65.77
(“Inpari 32”) “IPB 9G”	99.38	11.75	6.89	67.68
Inter-variety one-insertion multi-canopy				
(“Inpari 30”) “IPB 9G”	99.32	11.50	7.25	71.06
(“Inpari 32”) “IPB 9G”	91.69	12.75	8.19	67.92
Inter-variety two-insertion multi-canopy				
(“Inpari 30”) “IPB 9G”	93.98	11.50	6.44	66.50
(“Inpari 32”) “IPB 9G”	97.83	12.75	7.72	67.00

Notes: measurements were conducted on the rice variety without parenthesis.

Table 3. Panicle length, number of grains per panicle, percentage of filled grains, and weight of grains per clump of “Inpari 30” and “Inpari 32” in mono-variety and multi-canopy cultivation systems

Cultivation system	Panicle length (cm)	Number of grains per panicle	Percentage of filled grains (%)	Weight of grains per clump (g)
Mono-variety				
“Inpari 30”	29.53a	120.00ab	48.03	22.14a
“Inpari 32”	24.75bc	103.00c	54.75	20.35a
Combination of two varieties in one hill multi-canopy				
“Inpari 30” (“IPB 9G”)	25.49bc	81.25d	41.03	5.96c
“Inpari 32” (“IPB 9G”)	23.39c	79.75d	46.06	7.00c
Inter-variety one-insertion multi-canopy				
“Inpari 30” (“IPB 9G”)	29.33a	123.25a	49.16	18.87a
“Inpari 32” (“IPB 9G”)	25.50bc	104.00c	48.19	17.87a
Inter-variety two-insertion multi-canopy				
“Inpari 30” (“IPB 9G”)	27.94ab	106.75bc	40.57	12.76b
“Inpari 32” (“IPB 9G”)	25.96bc	103.00c	39.13	11.83b

Notes: measurements were taken on the rice variety without parenthesis; values followed by the same letter in the same column are not significantly different according to the DMRT at $\alpha=0.05$.

combination of two varieties in one hill multi-canopy system combined with Inpari 30 decreased by 36.11% and 31.05% when combined with “Inpari 32”. In contrast, in the inter-variety two-insertion multi-canopy system decreased by 44.90% and 29.26%, respectively, compared to the mono-variety system (Table 4).

Physiological Characteristics

The cultivation system significantly affects the photosynthesis rate but does not statistically significantly affect SPAD values “Inpari 30” and “Inpari 32” (Table 5). The photosynthetic rate of “Inpari 32” in a combination of two varieties in one hill multi-canopy system increased by 50.90% compared to the mono-variety system. The multi-canopy system did not affect SPAD value and photosynthetic rate of “IPB 9G” compared to the mono-variety (Table 6).

“Inpari 32-IPB 9G” in a combination of two varieties in one hill multi-canopy system decreased the percentage of light interception at heights of 20 cm (57.59%), 40 cm (54.01%), and 60 cm (27.05%), the combination of “Inpari 30-IPB 9G” in an inter-variety one-insertion multi-canopy system decreased the percentage of light interception at heights of 20 cm (43.04%), 40 cm (41.87%), and 60 cm (29.56%), and the combination of “Inpari 32-IPB 9G” in an inter-variety two-insertion multi-canopy system decreased the percentage of light interception at heights of 20

cm (61.54%), 40 cm (26.10%), and 60 cm (19.13%), compared to the mono-variety system (Figure 2).

Yield Potential

The combination of two varieties in one hill multi-canopy system increased the yield potential per hectare by 4.58% (“Inpari 30-IPB 9G”) and 25.42% (“Inpari 32-IPB 9G”) compared to the mono-variety system. In comparison, the combination of varieties in an inter-variety one-insertion multi-canopy system increased the yield potential hectare by 10.18% (“Inpari 30-IPB 9G”) and 13.81% (“Inpari 32-IPB 9G”), compared to the mono-variety system (Figure 3).

Land Equivalent Ratio (LER)

The multi-canopy system produces LER values >1, which range from 1.19-1.75. The combination of two varieties in one hill multi-canopy system is a cultivation system with the lowest LER values, namely 1.19 (“Inpari 32-IPB 9G”) and 1.22 (“Inpari 30-IPB 9G”), significantly different from the inter-variety one-insertion multi-canopy system and the inter-variety two-insertion multi-canopy system. The inter-variety one-insertion multi-canopy system produces LER values of 1.75 (“Inpari 30-IPB 9G”) and 1.64 (“Inpari 32-IPB 9G”) (Figure 4).

Table 4. Panicle length, number of grains per panicle, percentage of filled grains, and weight of grains per clump of “IPB 9G” in mono-variety and multi-canopy cultivation systems

Cultivation system	Panicle length (cm)	Number of grains per panicle	Percentage of filled grains (%)	Weight of grains per clump (g)
Mono-variety				
“IPB 9G”	31.42	182.40	53.03a	26.86a
Combination of two varieties in one hill multi-canopy				
(“Inpari 30”) “IPB 9G”	29.58	175.00	44.37b	17.16bc
(“Inpari 32”) “IPB 9G”	30.05	179.09	44.05b	18.52bc
Inter-variety one-insertion multi-canopy				
(“Inpari 30”) “IPB 9G”	27.75	196.88	47.00ab	21.84ab
(“Inpari 32”) “IPB 9G”	30.00	174.50	46.69ab	21.26ab
Inter-variety two-insertion multi-canopy				
(“Inpari 30”) “IPB 9G”	28.41	168.51	41.16b	14.80c
(“Inpari 32”) “IPB 9G”	31.61	181.22	39.95b	19.18bc

Notes: measurements were taken on the rice variety without parenthesis; values followed by the same letter in the same column are not significantly different according to the DMRT test at $\alpha=0.05$.

Table 5. SPAD value and photosynthetic rate of “Inpari 30” and “Inpari 32” in mono-variety and multi-canopy cultivation systems

Cultivation system	SPAD value	Photosynthetic rate ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$)
Mono-variety		
“Inpari 30”	40.72	23.34bc
“Inpari 32”	40.55	21.18bc
Combination of two varieties in one hill multi-canopy		
“Inpari 30” (“IPB 9G”)	38.54	20.93bc
“Inpari 32” (“IPB 9G”)	36.51	31.96a
Inter-variety one-insertion multi-canopy		
“Inpari 30” (“IPB 9G”)	40.70	16.54bc
“Inpari 32” (“IPB 9G”)	42.12	18.80bc
Inter-variety two-insertion multi-canopy		
“Inpari 30” (“IPB 9G”)	46.41	23.94b
“Inpari 32” (“IPB 9G”)	39.90	17.64c

Notes: measurements were taken on the rice variety without parenthesis; values followed by the same letter in the same column are not significantly different according to the DMRT test at $\alpha=0.05$.

Table 6. SPAD value and photosynthetic rate of “IPB 9G” in mono-variety and multi-canopy cultivation systems

Cultivation system	SPAD value	Photosynthetic rate ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$)
Mono-variety		
“IPB 9G”	39.02	21.09
Combination of two varieties in one hill multi-canopy		
(“Inpari 30”) “IPB 9G”	43.60	23.16
(“Inpari 32”) “IPB 9G”	39.05	19.34
Inter-variety one-insertion multi-canopy		
(“Inpari 30”) “IPB 9G”	37.38	28.62
(“Inpari 32”) “IPB 9G”	37.63	20.23
Inter-variety two-insertion multi-canopy		
(“Inpari 30”) “IPB 9G”	37.69	17.90
(“Inpari 32”) “IPB 9G”	38.91	17.09

Notes: Measurements were taken on the rice variety without parenthesis.

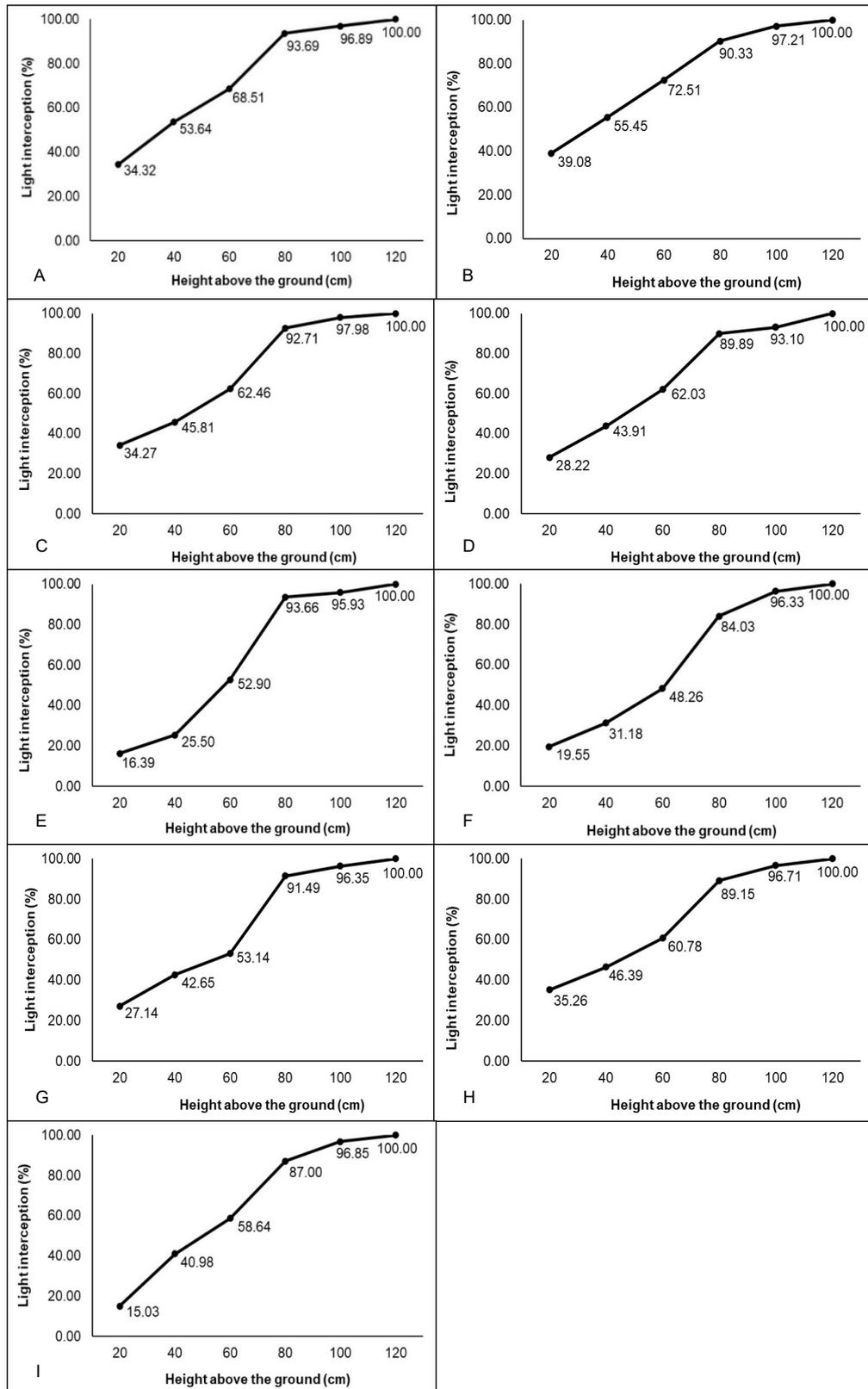


Figure 2. Light interception of rice plants in mono-variety and multi-canopy systems, A: mono-variety (“Inpari 30”), B: mono-variety (“Inpari 32”), C: mono-variety (“IPB 9G”), D: combination of two varieties in one hill multi-canopy (“Inpari 30-IPB 9G”), E: Combination of two varieties in one hill multi-canopy (“Inpari 32-IPB 9G”), F: Inter-variety one-insertion multi-canopy (“Inpari 30-IPB 9G”), G: Inter-variety one-insertion multi-canopy (“Inpari 32-IPB 9G”), H: Inter-variety two-insertion multi-canopy (“Inpari 30-IPB 9G”), I: Inter-variety two-insertion multi-canopy (“Inpari 32-IPB 9G”).

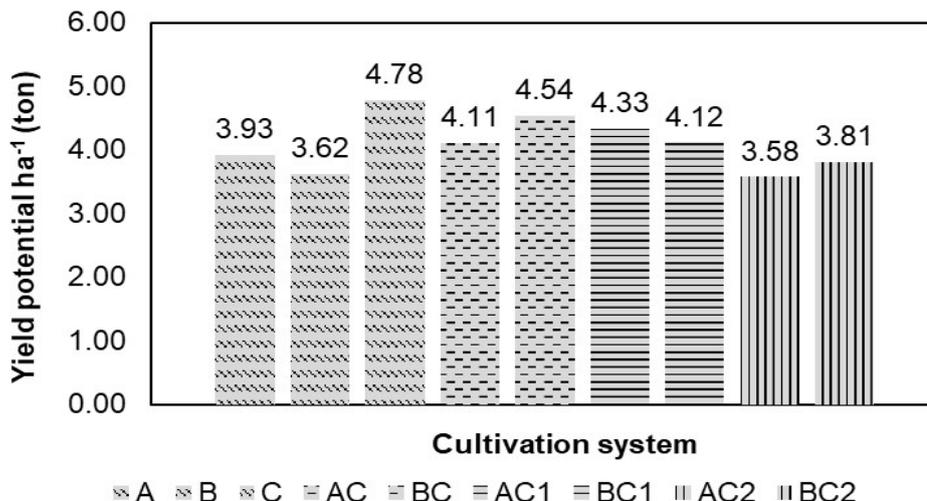


Figure 3. Yield potential per ha of rice in mono-variety and multi-canopy systems, A; mono-variety (“Inpari 30”), B; mono-variety (“Inpari 32”), C; mono-variety (“IPB 9G”), AC; Combination of two varieties in one hill multi-canopy (“Inpari 30-IPB 9G”), BC; Combination of two varieties in one hill multi-canopy (“Inpari 32-IPB 9G”), AC1; Inter-variety one-insertion multi-canopy (“Inpari 30-IPB 9G”), BC1; Inter-variety one-insertion multi-canopy (“Inpari 32-IPB 9G”), AC2; Inter-variety two-insertion multi-canopy (“Inpari 30-IPB 9G”), BC2; Inter-variety two-insertion multi-canopy (“Inpari 32-IPB 9G”).

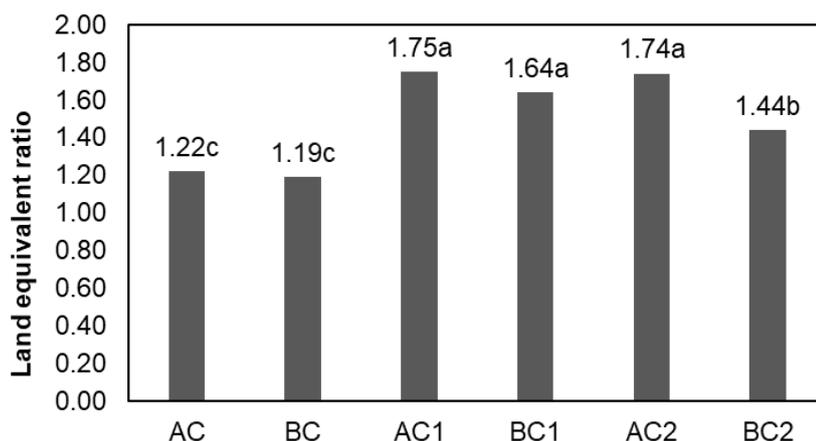


Figure 4. Land equivalent ratio on multi-canopy systems, AC; Combination of two varieties in one hill multi-canopy (“Inpari 30-IPB 9G”), BC; Combination of two varieties in one hill multi-canopy (“Inpari 32-IPB 9G”), AC1; Inter-variety one-insertion multi-canopy (“Inpari 30-IPB 9G”), BC1; Inter-variety one-insertion multi-canopy (“Inpari 32-IPB 9G”), AC2; Inter-variety two-insertion multi-canopy (“Inpari 30-IPB 9G”), BC2; Inter-variety two-insertion multi-canopy (“Inpari 32-IPB 9G”).

Discussion

The cultivation system has different effects between rice varieties; it did not affect the height of “Inpari 30”, “Inpari 32”, and “IPB 9G” in the multi-canopy system, but affected the number of tillers and the number of panicles of the main plant in several treatment combinations. In general, the number of panicles of genotypes planted with mono-genotypes has a higher number of panicles per clump when compared to the genotypes planted with a multi-canopy system (Khamid et al., 2023b). The combination of several specific genotypes in the multi-canopy system did not

experience a significant decrease in plant height and panicle length when compared to mono-varieties. This shows that the multi-canopy system does not affect plant height growth and panicle length in most genotype combinations (Khamid et al., 2023b). Plant height is a significant agronomic character in selecting appropriate genotypes in the multi-canopy system (Hidayah et al., 2022). It is essential in increasing yield potential (Zhang et al., 2017). The decrease in tillers and panicles is caused by intraspecific competition between plants (Widyastuti et al., 2020) in the form of light, nutrients, and growing space (Sinarmata et al., 2023).

Panicle length, number of grains per panicle, and grain weight per hill of short varieties in the single-hill multi-canopy system significantly decreased compared to the mono-variety system. Grain weight per hill of tall varieties significantly decreased in the single-hill multi-canopy and inter-variety two-insertion multi-canopy systems. Panicle size in rice plants shows great diversity between varieties due to the type of panicle branching, density, and total number of grains in the panicle (Ma et al., 2023). Several studies have confirmed the significant contribution of photosynthesis to grains/panicles during grain filling (Sanchez-Bragado et al., 2016) and yield (Merah et al., 2017). Other studies have shown that the effect of shading on the grain-filling phase significantly reduces rice yield by reducing the number of panicles, the number of grains per panicle, the grain-filling rate, and the grain weight (Deng et al., 2023). Grain weight per hill is one of the main characteristics of selecting suitable genotypes in a multi-canopy system. When the combination of short and tall genotypes produces higher grain weight per hill than mono-genotypes, it can be concluded that the combining them is suitable for a multi-canopy system (Khamid et al., 2023a).

Several factors, especially leaf nitrogen content, influence the SPAD value (Singh et al., 2020). The SPAD value of short varieties ranges from 36.51-46.41, while the SPAD value of tall varieties ranges from 37.38-43.60. The average SPAD value in the booting phase ranges from 20-50 (Liu et al., 2023). The SPAD value can be used to select the right plants in a multi-canopy system (Khamid et al., 2023a) and estimate plant chlorophyll levels, N content, and N use efficiency (Hou et al., 2021). The multi-canopy system does not affect the physiological characteristics of the SPAD value in each genotype combination (Khamid et al., 2023b).

The multi-canopy system is one of the efforts to regulate the architectural pattern of the plant canopy so that plants can maximize the efficiency of absorption and use of sunlight. The architecture of the plant canopy is greatly influenced by plant height, number of leaves, number of tillers, and length and width of leaves (Burgess et al., 2017). The difference in plant height between short and tall varieties causes a decrease in competition for light and carbon dioxide absorption, so the resulting assimilate can be more optimally distributed to other organs (Bassuonv and Zsembeli, 2020). Optimal canopy structure can increase light interception, thus increasing photosynthetic capacity (Cao et al., 2021), an essential factor in plant biomass production (Kondo et al., 2022). Light interception is greatly influenced by plant population density during tillering, panicle initiation, flowering, maturation (Kumar et al., 2019),

and seed filling (Moroyoqui-Parra et al., 2023).

Light is vital to plant productivity (Du et al., 2015). The availability of light to plants is influenced by plant population, plant distribution, and canopy structure (Zhi-qiang et al., 2018). Changes in light availability are caused by differences in the structural characteristics of leaves and plant canopies (Zhang et al., 2016), which are related to crop yield and production. Yield is positively correlated with plant height, grain weight, percentage of filled grain, number of filled grains per panicle (Zhao et al., 2020), panicle length, and grain weight per hill (Khamid et al., 2023a).

The potential yield and yield gap are crucial to evaluating cultivar development and appropriate cultivation practices, intending to accelerate the sustainable intensification of rice production systems in various regions (Cui et al., 2018). The magnitude of rice yield gaps worldwide varies, with an average ranging from 20-80%. Previous studies have evaluated factors affecting rice yield potential and gaps, including cultivars, planting time, fertilization, and irrigation management. These factors are closely related and interact with genotype, environment, and agronomic management practices (Zhang et al., 2019).

The primary goal of breeders and farmers is to improve rice yield potential (Makino et al., 2021). It is necessary to develop high-yielding cultivars suitable for climate conditions and cultivation practices, where the interaction between genotype, environment, and cultivation practices must be optimally designed and adjusted to create appropriate planting systems (Zhang et al., 2019). Reduced solar radiation is one of the primary factors causing yield potential decline (Chen et al., 2017); thus, regulating leaf structure and rice plant canopy structure is essential. Plants with longer and more upright leaves will increase yield potential by reducing shading percentage from panicles, thereby improving light transmission by leaves and increasing flag leaf photosynthesis rate (Hikosaka, 2014).

The yield potential of "IPB-9G" in a mono-variety system as one of the upland rice varieties shows a good response when cultivated like a lowland variety. That may be due to the plant's adaptability to environmental changes. Cell walls are crucial in the plant's adaptive mechanisms against abiotic stresses (Novaković et al., 2018). Gene mutations affect the composition or structure of cell walls, which can alter adaptation to drought or other abiotic stresses (Xu et al., 2020). Plants require continuous cell division to promote growth (Sun et al., 2022) to produce tillers, panicles, and grains, thereby increasing yield potential.

The efficiency of the multi-canopy system to increase rice yields through vertical farming systems can be evaluated by calculating the LER value. Based on the experimental results, the multi-canopy system produced an LER value >1 ranging from 1.19-1.75. LER is the primary indicator used to evaluate the superiority of crop yields based on land area or number of plants from the multi-crop system compared to mono-variety (Deb and Dutta, 2022), and a factor in determining the appropriate combination of plants to increase plant population (Habimana et al., 2019).

Conclusions

The combination of varieties in the inter-variety one-insertion multi-canopy system gave an excellent response to the character of plant height, number of panicles per hill, panicle length, number of grains per panicle, weight of grains per hill, photosynthesis rate, and LER value. The multi-canopy system reduced the percentage of light interception, ranging from 19.13-61.63%. The yield potential of the inter-variety one-insertion multi-canopy system increased by 10.18% in the combination of "Inpari 30" and "IPB 9G" varieties. It increased by 13.81% in the combination of "Inpari 32" and "IPB 9G" varieties. The combination of "Inpari 30" and "IPB 9G" varieties in the inter-variety one-insertion multi-canopy system produced the highest LER value of 1.75, indicating that the system has the potential to increase productivity.

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