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Genotypes assessment for developing varieties on multi-canopy rice cultivation system

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Abstract. *Khamid MBR, Junaedi A, Purnamawati H, Aswidinnoor H, Prasetyo LB. 2023. Genotypes assessment for developing varieties on multi-canopy rice cultivation system. Biodiversitas 24: 1175-1185.* The Multi-Canopy Rice Cultivation (MCRC) system is a promising cultivation technique that adopts the advantages of cultivar mixture with different canopy vertical dispersion. This system may increase productivity by optimizing vertical space and more efficient input resources. This study aimed to assess the genotype derived from the IPB breeding line for suitability in the MCRC system by combining the short and the tall rice plants. Seed material used four genotypes of the short plants and four genotypes of the tall plants as promising breeding lines of IPB University and three released varieties as the control for productivity evaluation. The results showed morphological and physiological performance as good as in the mono-genotype on the variables of the flag leaf shape, plant height, Soil Plant Analysis Development (SPAD) value, and Crop Growth Rate (CGR). Some genotype combinations achieved productivity higher than 1.00 Land Equivalent Ratio (LER) compared to the mono-genotype, indicating that increasing rice productivity is possible using the MCRC system. The result indicates that the suitable combination of the short-tall genotypes in the MCRC system may be considered to deal with the criteria of plant height, grain yield, and LER in the MCRC, as well as grain index and related grain quality.

Keywords: High productivity, intensification, resources efficiency, rice canopy, vertical space

INTRODUCTION

Rice (*Oryza sativa* L.) is the most essential and major food crop globally. Rice is the staple food for nearly 4 billion people worldwide (Fukagawa and Ziska 2019). Meanwhile, the rice farming system is the largest consumer of freshwater resources (Nawaz et al. 2022) and land users in the food sector production (Becker and Angulo 2019). Land availability has been the main limiting factor for rice production over the last 50 years in several countries, such as Indonesia (Becker and Angulo 2019). In line with the increase in population and the decrease in agricultural land (Wei et al. 2020) and its quality, it is necessary to continue to increase the production of food crops, especially rice. Increasing rice yield potential is the main objective of breeders and cultivators engaged in rice improvement programs (Makino et al. 2021). Theoretically, increasing rice production can be achieved by adopting technological innovations correctly and adequately, site-specific production strategies, and breeding new high-yielding varieties. The multi-canopy rice cultivation (MCRC) system is one of the potential technological innovations to increase rice production.

The MCRC adopts the vertical agriculture system, which seeks to utilize the harvest space vertically by forming a system using tiered plants in limited lands (Beacham et al. 2019; Baumont De Oliveira et al. 2021). The utilization of vertical harvesting space is one of the approaches that can develop in rice plants because vertical agriculture has been successfully practiced on vegetable commodities through the verticulture system (Widyastuti et al. 2020). The MCRC system is designed by planting rice with different plant heights using the short and the tall genotypes on the same hill. These panicles and canopy's formation of the short and the tall genotypes mutually stratified is then referred to as multi-canopy to take advantage of the vertical harvesting space (Widyastuti et al. 2020; Hidayah et al. 2022).

The MCRC will construct the architectural canopy of rice plants that can take advantage of photosynthetic active radiation (PAR) interception, increasing the biomass and its portion in the components of rice yields, resulting in increased productivity. The potential for photosynthetic productivity in rice plants was highly dependent on the interception of PAR and the conversion efficiency of available photosynthetic radiation from radiant energy (Lu et al. 2018). The photosynthetic capacity of the leaves and the entire canopy determines the yield (Gu et al. 2014). A robust plant architectural structure could form an optimal light distribution within the canopy, increasing light energy utilization and yield (Gu et al. 2017). Stem height, leaf length, width, and angle are essential in rice plants' canopy architecture that increases the absorption of solar radiation for optimizing photosynthesis (Song et al. 2013).

MCRC system may differ from the cultivar mixture cultivation system in terms of the plant height of the combining cultivar. The cultivar mixture system generally has relatively the same canopy height, so there will be competition for light, water, nutrients, and CO_2 absorption (Aschehoug et al. 2016), which are the primary resources for plant metabolism and photosynthesis. The MCRC system may eliminate light and CO_2 competition by different canopy levels. According to Widyastuti et al. (2020) and Hidayah et al. (2022), MCRC affects several rice growth characteristics and increases the yield by 0.54 - 0.64 t ha^{-1} compared to the mono-genotype so that the plant breeding process to develop suitable varieties for the MCRC system could be a potential target. Agronomic research may contribute to assess suitable genotype combinations for the MCRC system. This study aimed to assess the genotype derived from the IPB breeding lines for suitability in the MCRC by combining the short and the tall plants.

MATERIALS AND METHODS

Time and location

The research was conducted from June to September 2021 at the Babakan Sawah field experiment station, Department of Agronomy and Horticulture, IPB University, Bogor, West Java, Indonesia (6°33'52.7"S, 106°44'06.4"E). Observations of crop yields were carried out at the Plant Production Laboratory, Department of Agronomy and Horticulture, IPB University, Dramaga, Bogor, Indonesia.

Plant materials

The genetic material consisted of eight genotypes (the short and the tall) from the rice breeding program of IPB University and three national varieties as comparisons. The seeds produce in IPB's field experiment station in the previous season. The short rice genotypes consisted of H56, H71, H88, and L39. The tall rice genotypes consisted of FK18, FK22, AR18, and AR27. Meanwhile, the comparison varieties consisted of Ciherang, IR64, and IPB 3S.

Procedures

Experimental design

This study was conducted using a randomized completely block design (RCBD). There were 27 treatments combination of genotype and their mono-genotype and three varieties as control. Each treatment was replicated three times, so there are 81 experimental units. The research was carried out in irrigated rice fields that have been processed twice by plowing and harrowing. The rice seedlings were transplanted 18 days after sowing (DAS). The seedlings were planted at 25 cm between rows and 20 cm inside the rows. Two seedlings per hill were transplanted for the mono-genotype system. The MCRC system was done by planting two seedlings per hill for each genotype (Widyastuti et al. 2020). The tall genotypes were planted in the primary row, while the short genotypes were planted on the same side (south side) as the tall genotypes and were spaced 4-5 cm apart. Plant maintenance was carried out by fertilizing three times using a basic fertilizer of 37.5 kg N ha^{-1}, 36 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1} given the first week after transplanting (WAT) and for the second and third fertilization, 37.5 kg N ha^{-1} was given at 5 and 9 WAT (Indonesian Ministry of Agriculture 2020). Pest and disease control are carried out as needed in the field. Irrigation is carried out until before harvest by maintaining the water level.

Data observation

Variables observed in this study include morphological characters consisting of plant height (cm) measured from the soil surface to the tip of the panicle in the main stem; stem length (cm) measured from the soil surface to the panicle base of the main stem; panicle length (cm) measured from the panicle base to the tip of the main stem panicle; flag leaf length (cm) measured from the ligule to the tip of the leaf; flag leaf width (cm) measured at the widest portion of the flag leaf; and flag leaf angle (º) calculated by the angle of attachment between the flag leaf blade and the main panicle axis (International Rice Research Institute 2013). Physiological characters consisting of Soil Plant Analysis Development (SPAD) values measured at 9 WAT (panicle initiation) and 13 WAT (grain filling); shoot dry weight (g), a destructive variable, was carried out when the plants were 8 WAT and 10 WAT using an oven at 80ºC for 48 hours; and CGR was determined by weighing the plant dry weight with the formula described by Gardner et al. (1985) as follows:

$$\text{CGR (g day}^{-1}) = (W_2 - W_1)/(T_2 - T_1) \quad (1)$$

Where: W_2: plant dry weight at time T_2, W_1: plant dry weight at time T_1, T_1: time unit at first sampling (8 WAT), T_2: time unit at next sampling (10 WAT).

Yield and yield components characters (harvest at 85% grain condition in yellow ripe panicle, harvest time depends on variety) consisting of grain weight per clump (g), panicle number per clump, and 1000 grains weight (g). Land Equivalent Ratio (LER) was calculated to determine land productivity and efficiency value from MCRC compared to mono-genotype (Mead and Willey 1980) As follows:

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

Where: YA: yield of A genotype grown in multi-canopy, YB: yield of B genotype grown in multi-canopy, SA: yield of A genotype grown in mono-genotype, and SB: yield of B genotype grown in mono-genotype. If the LER value is higher than 1.00, then the productivity of multi-canopy land is higher than the mono-genotype, whereas the LER value is less than 1.00, then the productivity of multi-canopy land is lower than the mono-genotype (Kamara et al. 2019).

Data analysis

The results of these observations are then processed and analyzed with Analysis of Variance (ANOVA) at an error level of 5%. If the treatment effect is significant, it is continued with Tukey's HSD test (Tukey's Honestly Significant Difference Test). Data were analyzed using SAS software version 9.0 for windows.

RESULTS AND DISCUSSION

Morphological characteristics of the MCRC system

The performance of flag leaf length, width, and angle at 10 WAT on MCRC combination genotypes, mono-genotypes, and comparison variety are shown in Table 1. MCRC treatment significantly affects the flag leaf length, width, and angle character. In general, the length, width, and angle of the flag leaf of plants in the MCRC system decreased. Only a small number of genotype combinations experienced an increase compared to the mono-genotype. Widyastuti et al. (2020) also reported that using different genotypes in MCRC affects the length and width of the flag leaf. There are differences between genotypes, whereas within the same genotype, either in combination or mono-genotype, there are no differences. This result indicates that the MCRC system does not affect the morphological characters of the flag leaves of each genotype combination when planted in a multi-canopy system. Leaves are the main structure of plants that play a role in photosynthesis (Wu et al. 2017) and make leaf morphology one of the essential traits in rice plant architecture (Zhu et al. 2020b). Rice plants with longer and erect leaves will increase yield potential per plant by decreasing shade by panicles, thereby increasing leaf light transmission and the rate of flag leaf photosynthesis (Hikosaka 2014).

The most extended leaf length and largest leaf width were observed in the H88 genotype combined with AR18 compared to other MCRC combinations, which were 39.58 cm and 2.53 cm, respectively. Although in all the combined genotype treatments, there was no significant decrease or increase in leaf size compared to the mono-genotype. Morphological characteristics such as the area of leaves could regulate plant absorptivity by changing the optical path of radiation energy. The leaf morphology of the plant will change according to the light conditions in the surrounding environment. The genetic character of the plant plays a vital role in this development. Leaf morphology development that affects the efficiency of light absorption consists of elongation, widening, and changes in leaf area. Low light reflectivity in dense populations caused light transmission to the lower layers at the beginning of the heading phase (Wu et al. 2017; Zhu et al. 2020a; Zhu et al. 2020b).

In addition to leaf size, the leaf angle is also an essential trait in the architectural structure of rice plants (Zhao et al. 2013). All genotypes in the combination treatment, mono-genotype, and comparison varieties had leaf angles that were erect or less than 45º (International Rice Research Institute 2013). The leaf angle on the H88 genotype combined with FK18 was the narrowest compared to other MCRC combinations and mono-genotype. The angle of the leaves, especially the flag leaf, greatly affects the yield because it is directly involved in capturing light and supporting the efficiency of photosynthesis. In an ideal high-yielding rice variety, the erect upper leaves reduce light saturation in the upper layers of the canopy and increase light transmission in the lower layers to reduce the loss of light energy (Zhang et al. 2013; Gu et al. 2017). Meng et al. (2018) and Wei et al. (2018) stated that a lower leaf angle delays leaf senescence in the lower canopy and maintains root activity after heading.

Table 1. Flag leaf length, flag leaf width, and flag leaf angle at 10 WAT on MCRC combination genotypes, mono-genotypes, and comparison variety

Genotypes*)	Flag leaf length **) (cm)	Flag leaf width**) (cm)	Flag leaf angle**) (º)
H56(FK18)	28.70 (77)	1.96 (87)	11.94
H56(FK22)	32.00 (86)	2.07 (92)	13.33
H56(AR18)	34.53 (93)	2.22 (99)	12.80
H56(AR27)	33.35 (90)	2.13 (95)	12.51
H56 mono	37.18 (100)	2.25 (100)	12.63
H71(FK18)	25.70 (83)	1.93 (103)	12.20
H71(FK22)	32.22 (104)	1.97 (105)	16.50
H71(AR18)	28.77 (93)	1.97 (105)	16.37
H71(AR27)	24.18 (78)	1.77 (94)	15.44
H71 mono	31.07 (100)	1.88 (100)	16.80
H88(FK18)	36.72 (81)	2.23 (87)	7.38
H88(FK22)	33.93 (75)	2.38 (93)	8.86
H88(AR18)	39.58 (87)	2.53 (98)	7.97
H88(AR27)	38.67 (85)	2.30 (89)	8.76
H88 mono	45.42 (100)	2.57 (100)	9.70
L39(FK18)	35.48 (85)	1.93 (93)	14.82
L39(FK22)	34.70 (83)	1.98 (96)	14.70
L39(AR18)	29.58 (71)	1.98 (96)	12.78
L39(AR27)	37.53 (90)	1.97 (95)	13.64
L39 mono	41.87 (100)	2.07 (100)	14.23
(H56)FK18	30.30 (94)	1.95 (100)	10.00
(H71)FK18	26.98 (84)	1.75 (90)	11.66
(H88)FK18	24.27 (75)	1.58 (81)	7.43
(L39)FK18	24.63 (77)	1.75 (90)	13.12
FK18 mono	32.18 (100)	1.95 (100)	11.01
(H56)FK22	30.87 (87)	2.10 (96)	17.73
(H71)FK22	32.03 (90)	2.05 (94)	16.71
(H88)FK22	36.70 (103)	2.25 (103)	17.37
(L39)FK22	34.58 (97)	2.17 (100)	17.42
FK22 mono	35.58 (100)	2.18 (100)	13.51
(H56)AR18	33.42 (94)	2.27 (101)	16.47
(H71)AR18	37.38 (105)	2.25 (100)	19.54
(H88)AR18	31.30 (88)	2.18 (97)	13.88
(L39)AR18	29.30 (82)	2.06 (92)	15.34
AR18 mono	35.70 (100)	2.25 (100)	15.27
(H56)AR27	25.77 (83)	2.18 (96)	14.47
(H71)AR27	35.10 (113)	2.27 (100)	17.11
(H88)AR27	34.20 (110)	2.43 (107)	13.12
(L39)AR27	34.20 (110)	2.42 (107)	16.80
AR27 mono	30.98 (100)	2.27 (100)	16.76
Ciherang	23.40	1.73	8.73
IR64	24.97	1.48	15.70
IPB 3S	37.70	2.18	11.97
HSD test	15.88	0.62	7.83

Note: *genotypes measured are written without parenthesis. The genotype in parenthesis following the first genotype is the tall plants; the genotype in parenthesis before the second genotype is the short plants; **number in the parenthesis indicates the percentage of the mono-genotype system

Table 2. Plant height, stem length, and panicle length on MCRC combination genotypes, mono-genotypes, and comparison variety

Genotypes*)	Plant height**) (cm)		Stem length**) (cm)		Panicle length**) (cm)	
H56(FK18)	110.77	(98)	82.08	(98)	28.69	(98)
H56(FK22)	110.77	(98)	81.53	(98)	29.24	(100)
H56(AR18)	110.87	(98)	83.05	(99)	27.81	(95)
H56(AR27)	109.76	(97)	81.03	(97)	28.73	(98)
H56 mono	112.80	(100)	83.61	(100)	29.19	(100)
H71(FK18)	100.44	(94)	73.11	(95)	27.33	(91)
H71(FK22)	98.56	(92)	71.40	(93)	27.16	(91)
H71(AR18)	100.75	(95)	74.44	(97)	26.31	(88)
H71(AR27)	104.61	(98)	76.25	(100)	28.36	(95)
H71 mono	106.59	(100)	76.61	(100)	29.97	(100)
H88(FK18)	103.23	(92)	73.39	(93)	29.83	(88)
H88(FK22)	106.08	(94)	77.63	(99)	28.45	(84)
H88(AR18)	104.41	(93)	75.69	(96)	28.72	(84)
H88(AR27)	105.73	(94)	75.31	(96)	30.42	(89)
H88 mono	112.70	(100)	78.71	(100)	33.99	(100)
L39(FK18)	99.09	(94)	73.01	(95)	26.08	(91)
L39(FK22)	99.88	(95)	72.95	(95)	26.93	(94)
L39(AR18)	102.63	(97)	76.40	(99)	26.23	(92)
L39(AR27)	100.90	(96)	72.89	(95)	28.01	(98)
L39 mono	105.43	(100)	76.79	(100)	28.64	(100)
(H56)FK18	118.47	(96)	91.09	(95)	27.39	(99)
(H71)FK18	116.42	(94)	90.15	(94)	26.27	(95)
(H88)FK18	119.09	(96)	93.26	(97)	25.83	(94)
(L39)FK18	109.47	(89)	83.13	(87)	26.34	(95)
FK18 mono	123.65	(100)	96.04	(100)	27.61	(100)
(H56)FK22	113.15	(93)	86.98	(94)	26.17	(90)
(H71)FK22	114.85	(94)	88.57	(96)	26.28	(90)
(H88)FK22	116.67	(96)	89.19	(96)	27.48	(95)
(L39)FK22	115.37	(95)	88.59	(96)	26.78	(92)
FK22 mono	121.59	(100)	92.54	(100)	29.05	(100)
(H56)AR18	113.21	(95)	85.94	(96)	27.27	(94)
(H71)AR18	112.35	(95)	84.39	(94)	27.96	(96)
(H88)AR18	111.97	(94)	85.38	(95)	26.59	(92)
(L39)AR18	111.81	(94)	83.88	(93)	27.93	(96)
AR18 mono	118.79	(100)	89.75	(100)	29.04	(100)
(H56)AR27	106.51	(100)	81.63	(101)	24.87	(99)
(H71)AR27	104.26	(98)	79.92	(98)	24.34	(97)
(H88)AR27	102.89	(97)	78.74	(97)	24.15	(96)
(L39)AR27	105.40	(99)	80.05	(99)	25.35	(101)
AR27 mono	106.36	(100)	81.18	(100)	25.18	(100)
Ciherang	107.79		83.74		24.05	
IR64	97.43		71.96		25.47	
IPB 3S	120.31		90.17		30.14	
HSD test	9.96		9.32		4.32	

Note: *genotypes measured are written without parenthesis. The genotype in parenthesis following the first genotype is the tall plants; the genotype in parenthesis before the second genotype is the short plants; **number in the parenthesis indicates the percentage to the mono-genotype system

One main characteristic that increases the potential for rice yields is plant height (Wang et al. 2016; Zhang et al. 2017). Plant height is a crucial agronomic character in selecting genotypes combined in the MCRC system (Hidayah et al. 2022). In our study, only plant height and stem length in genotype FK18 (109.47 cm and 83.13 cm, respectively) combined with L39 were significantly lower than in mono-genotype (123.65 cm and 96.04 cm, respectively). Likewise, with panicle length, only the H88 genotype combined with the FK22 and AR18 genotypes (28.45 cm and 28.72 cm, respectively) was significantly lower than the mono-genotype (33.99 cm) as the genotype with the longest panicle than others. However, plant height, stem length, and panicle length in other combination genotypes were not experienced a significant decrease compared to the mono-genotype (Table 2).

These results indicated that the MCRC system did not affect plant height growth, stem length, and panicle length in almost all combined genotypes. Previous research also showed no significant effect of the MCRC system on rice plant height and stem length (Widyastuti et al. 2020). The genetic differences of each genotype strongly influence plant height, stem length, and panicle length (Widyastuti et al. 2020; Hidayah et al. 2022). Another study stated that phytohormone Gibberellin and gene regulation OsMADS57 (Chu et al. 2019), OsMPH1 (Zhang et al. 2017), OsRPH1 (Ma et al. 2020) influenced plant height and stem elongation. Other researchers reported a relationship between panicle length, the number of grains per panicle, grain density, and rice quality (Wang et al. 2019).

Physiological characteristics of the MCRC system

MCRC significantly affected shoot dry weight parameters at 8 and 10 WAT (Table 3). Significant effects of MCRC were generally seen between genotypes, only slightly occurring within one genotype combined compared to their mono-genotype. Shoot dry weight varied from 11.24 to 31.66 g per plant in 8 WAT and from 22.56 to 59.39 g per plant in 10 WAT, depending on genotype. The significant decrease in shoot dry weight occurred in the L39 genotype combined with FK18 compared to the mono-genotype at both 8 and 10 WAT by 53% and 52%, respectively. At 10 WAT, there was a 58% decrease in the L39 genotype combined with AR18. In addition, in the H88 genotype at 10 WAT, the mono-genotype treatment had significantly greater shoot dry weight than the combined genotype with FK18, FK22, and AR18. Meanwhile, in the H56 genotype, the shoot dry weight of mono-genotype plants was significantly higher than that in the MCRC plants.

Each genotype increased in shoot dry weight in line with the plant growth stage. Shoot dry weight can be influenced by the genetic diversity of each genotype (Fageria et al. 2013; Ji et al. 2022) and plant growth hormones such as IAA and GA (Chang et al. 2013). Shoot dry weight can also be influenced by environmental conditions such as the physicochemical properties of the growing media (Mongon et al. 2014; Tian et al. 2017; Wang et al. 2021) and irrigation conditions (Hidayati et al. 2016; Pinta et al. 2018). This study's environmental and irrigation conditions were relatively similar, so the effect of MCRC on the same genotype was relatively lower than the differences between genotypes.

However, several combinations of genotypes grown using the MCRC system produced a higher shoot dry weight than the mono-genotypes (Figure 1). For example, combining the short genotype H88 with all the tall genotypes resulted in a higher shoot dry weight than the mono-genotype. This result indicates that the right combination of the MCRC system can maintain or increase the shoot's dry weight. A high shoot dry weight will significantly affect growth and support an increase in rice yields (Xin et al. 2021).

SPAD values ranged from 31.86-41.81 at 9 WAT and decreased to 27.74-37.97 at 10 WAT (Table 3). MCRC significantly affects SPAD parameters at 9 and 13 WAT. There are differences between genotypes, whereas within the same genotype, either in combination or mono-genotype, there are no differences. This result indicates that the MCRC system does not affect the physiological characteristics of the SPAD value of each genotype combination when planted in an MCRC system. Soil Plant Analysis Development (SPAD) is the most commonly used diagnostic tool to estimate crop chlorophyll levels (Ghosh et al. 2013) and nitrogen status (Yuan et al. 2016). The SPAD value can be used to determine the N content in rice, regulate the level of N fertilization and increase N use efficiency (Hou et al. 2021). In addition, chlorophyll content can predict the physiological condition of plant leaves (Zhao et al. 2016).

SPAD value can be influenced by several factors, such as nutrient adequacy, especially nitrogen (Singh et al. 2020), growth stadia (Ata-Ul-Karim et al. 2013), cultivar genetic differences (Barutcular et al. 2015), thickness, and observed leaf position (Yang et al. 2014). In our study, SPAD measurements were carried out at the same growth stage, leaf position, and level of nitrogen fertilization. The difference in the influence between genotypes is possible because of the genetic differences of each genotype being tested.

In this study, the MCRC treatment did not significantly affect the CGR (Figure 2). However, in some combinations of genotypes, the CGR can reach a higher value in MCRC than the mono-genotype. The combination of AR27 and H88 genotypes resulted in a CGR value of 3.61 g d^{-1}, which was greater than the mono-genotype method of AR27 and H88 genotypes (2.10 and 3.11 g d^{-1}, respectively). This result indicates that MCRC can potentially increase CGR and crop production using the right combination of genotypes. The CGR increases with LAI increment until the maximum level and determines yield formation when environmental factors are not limiting (Sandeep et al. 2016; Rajput et al. 2017).

Yield characteristic of the MCRC system

MCRC significantly affects the panicle number per clump (Table 4). When the two genotypes are planted in the MCRC, the panicle number of each genotype decreases compared to the mono-genotype. The panicle number per clump in the MCRC decreased from 19% to 56% compared to the mono-genotype. In general, genotypes grown in mono-genotype had a higher panicle number per clump than these genotypes when combined in MCRC. Several genotypes from the rice breeding program of IPB University, which were grown in mono-genotype (H71, L39, FK18, FK22, AR18), produced a higher panicle number per clump than IPB 3S as national varieties. Rice panicles and their number are closely related to estimating yield because they directly regulate the amount of grain (Duan et al. 2015). However, the total number of panicles per clump in the MCRC contributed by each short and tall genotype showed higher in some genotype combinations, indicating a potency to have higher grain yield per clump (Figure 3).

Table 3. Shoot dry weight and SPAD value on MCRC combination genotypes, mono-genotypes, and comparison variety

Genotypes*)	Shoot dry weight (g) **)				SPAD value	
	8 WAT		10 WAT		9 WAT	3 WAT
H56(FK18)	13.97	(49)	29.48	(50)	34.67	31.04
H56(FK22)	16.79	(59)	29.69	(50)	35.58	29.02
H56(AR18)	18.60	(65)	28.46	(48)	33.33	32.47
H56(AR27)	19.02	(67)	29.09	(49)	35.54	30.73
H56 mono	28.44	(100)	59.39	(100)	34.51	28.77
H71(FK18)	13.62	(59)	23.76	(49)	37.09	32.61
H71(FK22)	17.75	(77)	32.23	(66)	36.70	33.73
H71(AR18)	14.98	(65)	31.76	(65)	36.26	28.53
H71(AR27)	15.59	(68)	22.56	(46)	37.07	27.74
H71 mono	23.01	(100)	48.58	(100)	39.94	32.83
H88(FK18)	11.24	(45)	25.38	(47)	33.14	33.79
H88(FK22)	17.79	(71)	26.38	(49)	31.86	32.88
H88(AR18)	11.42	(45)	26.16	(48)	32.23	32.90
H88(AR27)	20.58	(82)	46.64	(86)	32.56	32.01
H88 mono	25.13	(100)	54.28	(100)	35.23	33.68
L39(FK18)	14.89	(47)	25.67	(48)	36.63	29.60
L39(FK22)	19.61	(62)	27.58	(51)	36.69	32.09
L39(AR18)	15.46	(49)	22.64	(42)	37.29	32.87
L39(AR27)	21.46	(68)	30.68	(57)	37.83	33.46
L39 mono	31.66	(100)	53.69	(100)	41.70	32.64
(H56)FK18	16.63	(72)	23.75	(48)	36.06	32.20
(H71)FK18	17.69	(76)	32.06	(65)	37.75	32.21
(H88)FK18	20.52	(88)	37.38	(76)	39.43	33.80
(L39)FK18	14.81	(64)	26.77	(55)	37.75	31.14
FK18 mono	23.23	(100)	49.04	(100)	41.81	35.91
(H56)FK22	13.56	(63)	30.37	(65)	32.51	31.71
(H71)FK22	15.30	(71)	25.35	(54)	33.64	33.10
(H88)FK22	19.59	(91)	34.36	(74)	33.53	34.65
(L39)FK22	17.35	(81)	29.86	(64)	33.56	32.62
FK22 mono	21.52	(100)	46.66	(100)	34.39	37.97
(H56)AR18	19.88	(91)	29.55	(67)	32.88	34.61
(H71)AR18	17.13	(78)	23.63	(54)	32.69	33.80
(H88)AR18	18.68	(85)	33.80	(77)	32.47	34.20
(L39)AR18	17.77	(81)	31.05	(70)	33.65	34.13
AR18 mono	21.91	(100)	44.16	(100)	34.18	34.31
(H56)AR27	17.28	(75)	24.46	(56)	34.76	28.84
(H71)AR27	15.68	(68)	31.77	(73)	33.03	27.82
(H88)AR27	17.81	(77)	27.52	(63)	35.32	31.17
(L39)AR27	14.94	(65)	26.27	(61)	36.65	32.68
AR27 mono	23.09	(100)	43.41	(100)	36.89	31.20
Ciherang	20.75		47.26		34.36	34.57
IR64	27.00		49.11		36.54	31.86
IPB 3S	23.81		52.07		37.34	36.12
HSD test	16.27		27.41		5.97	9.53

Note: *genotypes measured are written without parenthesis. The genotype in parenthesis following the first genotype is the tall plants; the genotype in parenthesis before the second genotype is the short plants; **number in the parenthesis indicates the percentage of the mono-genotype system

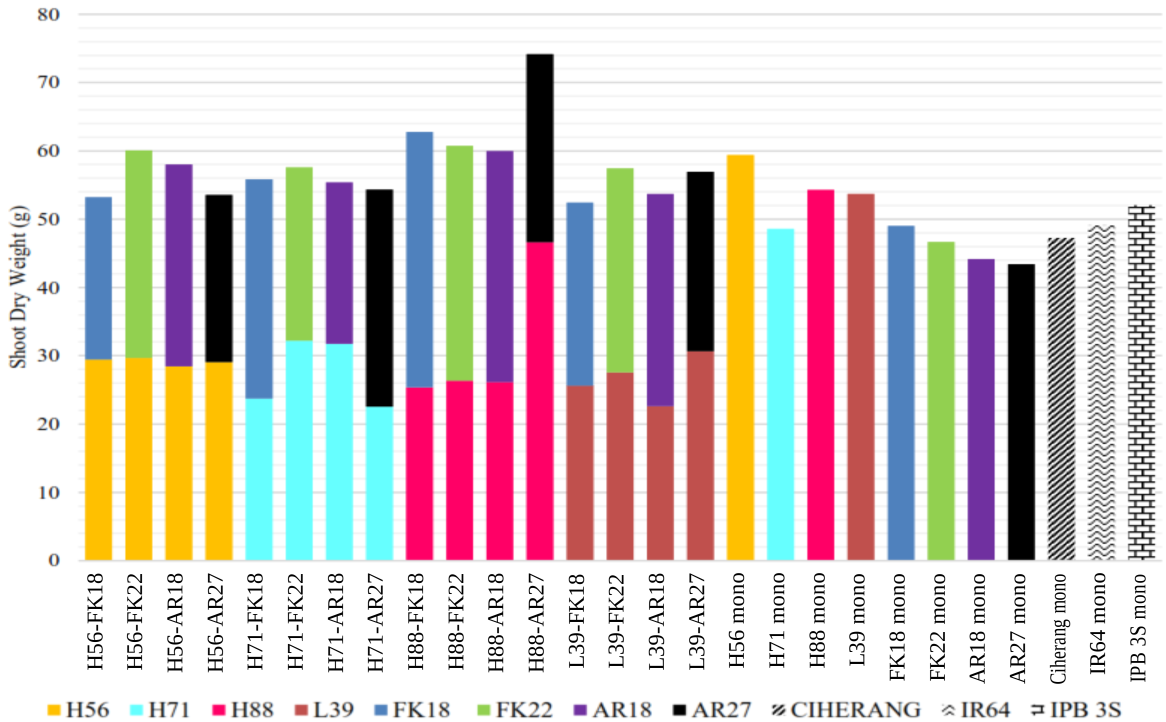

Figure 1. Shoot dry weight at 10 WAT on MCRC combination genotypes, mono-genotypes, and comparison variety (The bar image of two colors shows the data coming from the combination of the two genotypes, the short and the tall plants in the MCRC system)

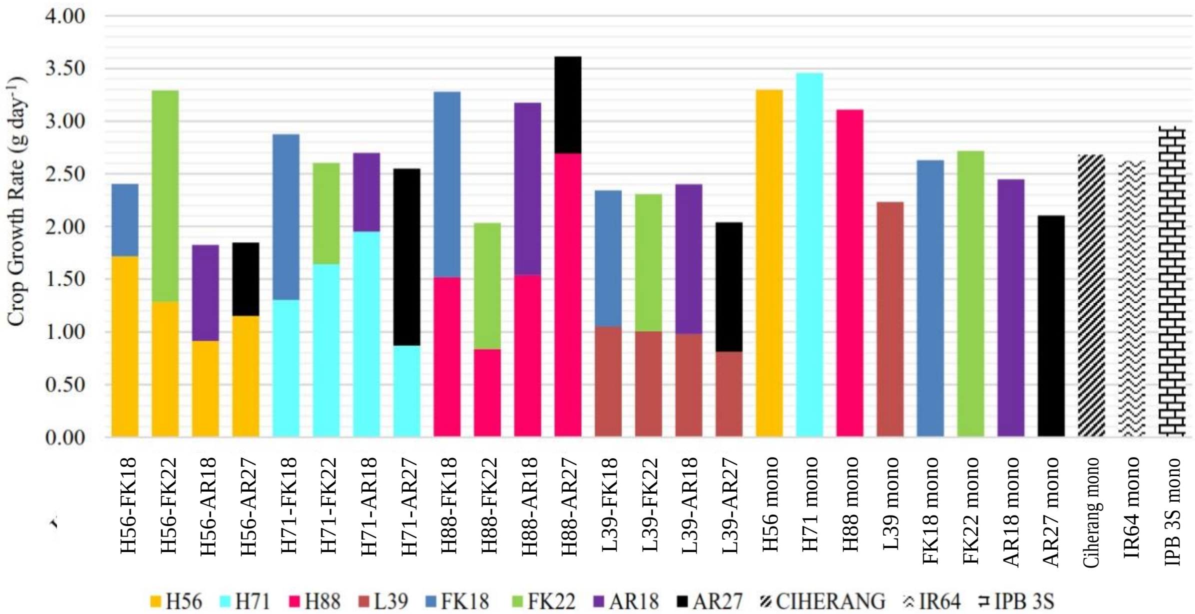

Figure 2. Crop growth rate at 8-10 WAT on MCRC combination genotypes, mono-genotypes, and comparison variety (The bar image of two colors shows the data coming from the combination of the two genotypes, the short and the tall plants in the MCRC system)

In contrast to the panicle number per clump, the MCRC system does not affect each genotype combination's yield component characteristic of 1000 grain weight or grain index compared to the mono-genotype. This fact may result in yield potency, contributed by the number of panicles per clump and the number of filled grains per panicle. Our study also found that the H56 genotype planted as mono-genotype or MCRC produced the highest 1000 grain weight compared to any other genotype, even with the three national varieties (>31 g). The H71 genotype produced the lowest 1000 grain weight when combined with FK18 (23.98 g). Li et al. (2019) stated that the size and weight of grain as a sink are influenced, among other things, by the molecular genetic mechanisms of the plant (e.g., OsALMT7 (Heng et al. 2018)). In addition, the enzyme activity level in the tissue determines the sink's strength (Zhai et al. 2020). Cultivars with heavy panicles or larger sink strength have an enormous yield potential compared with conventional cultivars (Cheng et al. 2015; Gu et al. 2017).

MCRC significantly affects the grain weight per clump (Figure 4). This parameter is one of the main traits for selecting a suitable genotype for the MCRC system. When the MCRC resulted in higher grain weight per clump compared to the mono-genotype of each short and tall, it could be the suitable combination of the two genotypes. For example, the combination of AR27 and H88 genotypes achieved a yield of 50.88 g, compared to AR27 as a mono-genotype which only reached 31.79 g, and H88 which could reach 47.76 g. This result may imply that even though the AR27 genotype has a poor mono-genotype yield, it will have a higher yield when combined with a suitable genotype in the MCRC system. Another example of genotypes that are not suitable for the MCRC system is H71 and L39, which have a low weight of 1000 grains, reflecting their relatively smaller grain size than other genotypes. This condition will cause problems when milling rice, where the grain size that is not uniform can make it difficult to set the grinder and reduce the physical quality of the rice.

The AR18 genotype combined with H56 produces a high grain weight per clump, 50.06 g. These genotypes also had high grain weight per clump when grown in mono-genotype. In addition, the FK22 genotype combined with H88 also has a grain weight per clump of 47.59 g. This result indicates that both genotype combinations have good adaptations and are suitable for planting in the MCRC system. These genotypes have a grain weight per clump greater than the three national varieties used for comparison. Rice with high grain weight and panicle length will produce a higher grain yield. The yield has a significant and positive correlation with the plant height, grain weight, filled grain percentage, filled grain number per panicle, and grain number m^{-2} (Zhao et al. 2020). Another study states that two traits determine yield in rice plants: direct and indirect. Direct traits consist of panicle number per unit area, panicle number per plant, filled grains per panicle, and 1000 grain weight. Meanwhile, indirect traits include growth stage, plant height, tillering ability, panicle length, grains number per panicle, seed setting rate, and seed length (Huang et al. 2013).

Breeding new varieties with tremendous yield potential, enhancing crop and resource (e.g., nutrient and water) management, and improving planting methods and density can increase rice grain yield (Usui et al. 2016; Das et al. 2018; Zhou et al. 2019). Efficient use of natural resources can lead to increased yields in mixed crop systems (Udhaya and Kuzhanthaivel 2015; Mugisa et al. 2020). The LER is usually used to decide which crop is suitable among the intercropping components to increase crop density or population (Habimana et al. 2019). However, in the case of MCRC, we must also consider some other characteristics, including the grain's suitable size and related character. In our result, MCRC significantly affects LER parameters (Figure 5). The AR27 genotype combined with H88 resulted in the highest LER value of 1.25. This result means that MCRC cultivation of both genotypes can produce 25% higher yields than mono-genotype cultivation. However, the seed size of AR27 is only 25.07 g per 1000 grains, whereas the seed size of H88 is 28.0 g per 1000 grains, so this combination is unsuitable by the criterion of grain quality. The FK18 genotype combined with H71 resulted in the lowest LER value of 0.78, so the genotype combination in the MCRC does not provide a better yield than mono-genotype cultivation.

Table 4. Panicle number per clump and 1000 grain weight on MCRC combination genotypes, mono-genotypes, and comparison variety

Genotypes*)	Panicle number per clump**)	1000 grain weight (g) **)
H56(FK18)	9.11 (72)	31.57 (100)
H56(FK22)	8.33 (66)	31.58 (100)
H56(AR18)	8.00 (63)	31.24 (99)
H56(AR27)	9.00 (71)	33.38 (106)
H56 mono	12.67 (100)	31.51 (100)
H71(FK18)	9.11 (50)	23.98 (88)
H71(FK22)	9.22 (50)	26.38 (97)
H71(AR18)	8.67 (47)	25.47 (94)
H71(AR27)	8.78 (48)	25.98 (96)
H71 mono	18.33 (100)	27.10 (100)
H88(FK18)	7.33 (58)	28.54 (102)
H88(FK22)	7.11 (56)	27.52 (98)
H88(AR18)	6.44 (51)	27.12 (97)
H88(AR27)	10.22 (81)	27.47 (98)
H88 mono	12.67 (100)	28.00 (100)
L39(FK18)	7.22 (49)	24.99 (99)
L39(FK22)	7.00 (47)	26.35 (104)
L39(AR18)	8.33 (56)	25.73 (101)
L39(AR27)	11.00 (74)	26.82 (106)
L39 mono	14.78 (100)	25.35 (100)
(H56)FK18	9.00 (53)	30.49 (102)
(H71)FK18	9.44 (56)	30.07 (101)
(H88)FK18	8.78 (52)	29.38 (98)
(L39)FK18	11.89 (70)	28.58 (96)
FK18 mono	16.89 (100)	29.84 (100)
(H56)FK22	8.67 (51)	30.79 (103)
(H71)FK22	7.44 (44)	29.39 (99)
(H88)FK22	9.78 (58)	30.20 (101)
(L39)FK22	10.44 (62)	29.90 (100)
FK22 mono	16.89 (100)	29.82 (100)
(H56)AR18	10.11 (66)	29.07 (100)
(H71)AR18	11.33 (74)	29.51 (101)
(H88)AR18	9.00 (59)	28.97 (99)
(L39)AR18	10.11 (66)	28.85 (99)
AR18 mono	15.33 (100)	29.14 (100)
(H56)AR27	8.78 (69)	26.29 (105)
(H71)AR27	7.33 (57)	25.35 (101)
(H88)AR27	7.67 (60)	24.83 (99)
(L39)AR27	8.44 (66)	24.73 (99)
AR27 mono	12.78 (100)	25.07 (100)
Ciherang	19.22	25.33
IR64	21.33	25.51
IPB 3S	13.89	27.13
HSD test	6.67	4.65

Note: *genotypes measured are written without parenthesis. The genotype in parenthesis following the first genotype is the tall plants; the genotype in parenthesis before the second genotype is the short plants; **number in the parenthesis indicates the percentage of the mono-genotype system

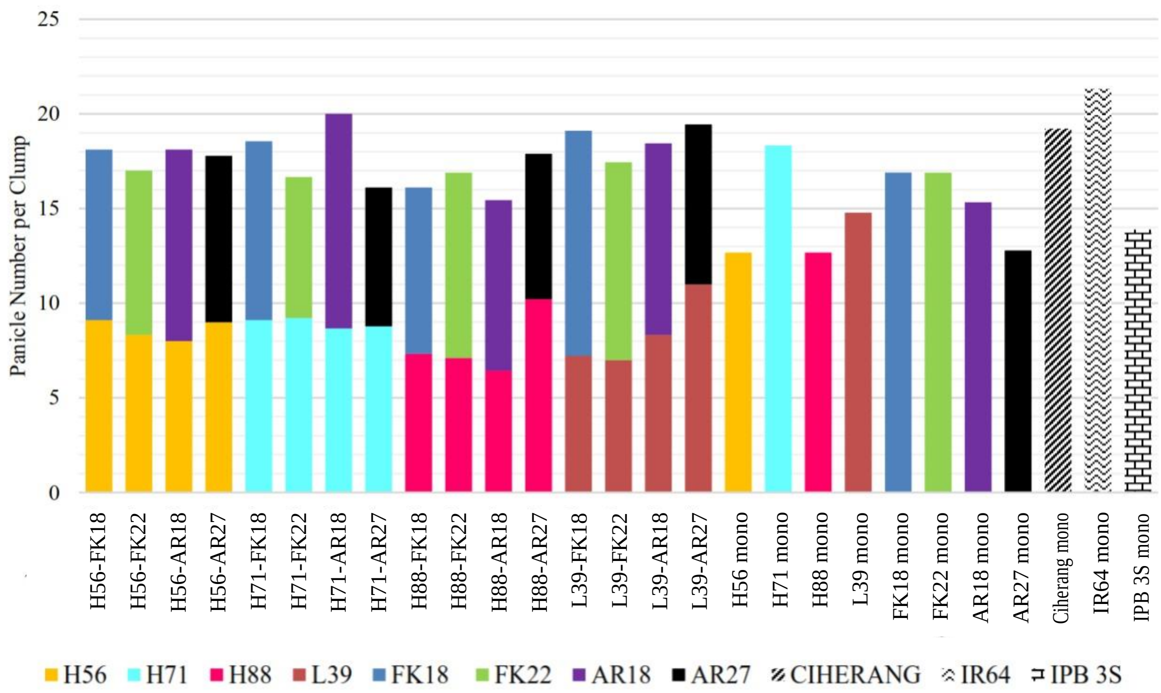

Figure 3. Panicle number per clump on MCRC combination genotypes, mono-genotypes, and comparison variety (The bar image of two colors shows the data coming from the combination of the two genotypes, the short and the tall plants in the MCRC system)

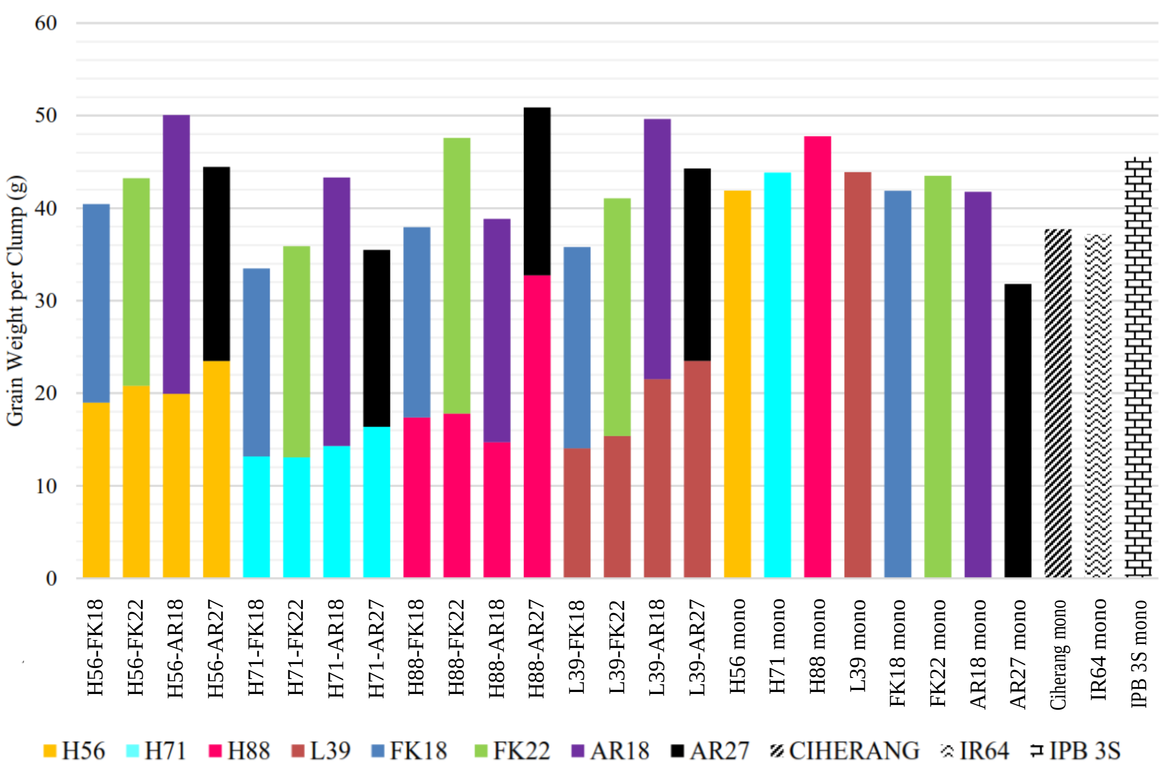

Figure 4. Grain weight per clump (g) on MCRC combination genotypes, mono-genotypes, and comparison variety (The bar image of two colors shows the data coming from the combination of the two genotypes, the short and the tall plants in the MCRC system)

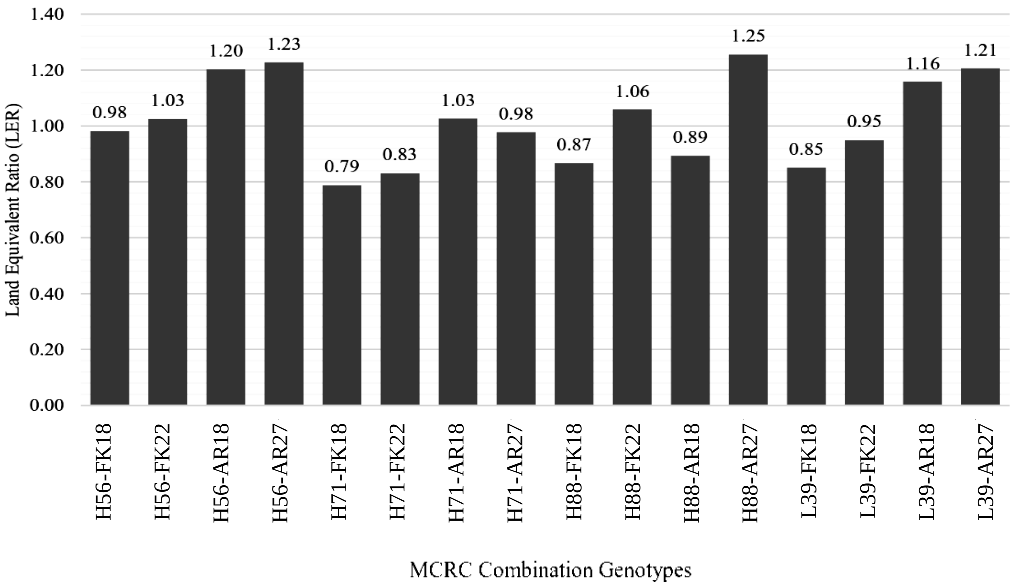

Figure 5. Land equivalent ratio on MCRC combination genotypes

Combining the height performances, grain weight per clump, LER of the MCRC, and grain index, as well as related grain quality of both genotypes, may be considered as criteria to choose a suitable combination of the short-tall genotypes in MCRC. In this research, the short genotype H56 and the tall genotype AR18 show higher grain per clump in the MCRC compared to the mono-genotype, and its combination has a LER of 1.20, as well as a suitable grain index considering the grain quality. Generally, genotypes H56 and H88 may be considered the recommended short genotypes, whereas genotypes FK22 and AR18 may be considered the recommended tall genotypes. Candidate genotypes for MCRC would be further investigated for agronomy field trials.

In conclusion, genotype assessment to select IPB's breeding lines that have good phenotyping and are suitable for planting in developing a MCRC system is promising. The result of the system showed morphological and physiological performance as good as in the mono-genotype on the variables of the flag leaf shape, plant height, SPAD value, and CGR would further imply a potency to achieve higher productivity. Our finding indicates that the suitable combination of the short-tall genotypes in the MCRC system may be considered to deal with the criteria of plant height, grain yield, and LER in the MCRC, as well as grain index and related grain quality.

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REFERENCES

Aschehoug ET, Brooker R, Atwater DZ, Maron JL, Callaway RM. 2016. The mechanisms and consequences of interspecific competition among plants. Annu Rev Ecol Evol Syst 47: 263-281. DOI: 10.1146/annurev-ecolsys-121415-032123.

Ata-Ul-Karim ST, Yao X, Liu X, Cao W, Zhu Y. 2013. Development of critical nitrogen dilution curve of Japonica rice in Yangtze River Reaches. Field Crop Res 149: 149-158. DOI: 10.1016/j.fcr.2013.03.012.

Barutcular C, Toptas I, Turkten H, Yildirim M, Koc M. 2015. SPAD greenness to estimate genotypic variation in flag leaf chlorophyll in spring wheat under Mediterranean conditions. Turkish J F Crop 20: 1-8. DOI: 10.17557/.51440.

Baumont De Oliveira FJ, Ferson S, Dyer R. 2021. A collaborative decision support system framework for vertical farming business developments. Intl J Decis Support Syst Technol 13: 34-66. DOI: 10.4018/IJDSST.2021010103.

Beacham AM, Vickers LH, Monaghan JM. 2019. Vertical farming: A summary of approaches to growing skywards. J Hortic Sci Biotechnol 94 (3): 277-283. DOI: 10.1080/14620316.2019.1574214.

Becker M, Angulo C. 2019. The evolution of lowland rice-based production systems in Asia: Historic trends, determinants of change, future perspective.. Elsevier Inc., Bonn. DOI: 10.1016/bs.agron.2019.04.003.

Chang L, Ramireddy E, Schmülling T. 2013. Lateral root formation and growth of *Arabidopsis* is redundantly regulated by cytokinin metabolism and signalling genes. J Exp Bot 64 (16): 5021-5032. DOI: 10.1093/jxb/ert291.

Cheng S, Zhan X, Cao L. 2015. Breeding strategies for increasing yield potential in super hybrid rice. Front Agric Sci Eng 2 (4): 277-282. DOI: 10.15302/J-FASE-2015081.

Chu Y, Xu N, Wu Q, Yu B, Li X, Chen R, Huang J. 2019. Rice transcription factor OsMADS57 regulates plant height by modulating gibberellin catabolism. Rice 12: 38. DOI: 10.1186/s12284-019-0298-6.

Das K, Panda BB, Shaw BP, Das SR, Dash SK, Kariali E, Mohapatra PK. 2018. Grain density and its impact on grain filling characteristic of rice: Mechanistic testing of the concept in genetically related cultivars. Sci Rep 8: 4149. DOI: 10.1038/s41598-018-22256-2.

Duan L, Huang C, Chen G, Xiong L, Liu Q, Yang W. 2015. Determination of rice panicle numbers during heading by multi-angle imaging. Crop J 3 (3): 211-219. DOI: 10.1016/j.cj.2015.03.002.

Fageria NK, Moreira A, Ferreira EPB, Knupp AM. 2013. Potassium-use efficiency in upland rice genotypes. Commun Soil Sci Plant Anal 44 (18): 2656-2665. DOI: 10.1080/00103624.2013.813031.

Fukagawa NK, Ziska LH. 2019. Rice: Importance for global nutrition. J Nutr Sci Vitaminol 65: S2-S3. DOI: 10.3177/jnsv.65.S2.

Gardner FP, Pearce RB, Mitchell RL. 1985. Physiology of Crop Plants. Iowa State University, Ames.

Ghosh M, Swain DK, Jha MK, Tewari VK. 2013. Precision nitrogen management using chlorophyll meter for improving growth, productivity and N use efficiency of rice in subtropical climate. J Agric Sci 5 (2): 253-266. DOI: 10.5539/jas.v5n2p253.

Gu J, Yin X, Stomph TJ, Struik PC. 2014. Can exploiting natural genetic variation in leaf photosynthesis contribute to increasing rice productivity? A simulation analysis. Plant Cell Environ 37 (1): 22-34. DOI: 10.1111/pce.12173.

Gu J, Chen Y, Zhang H, Li Z, Zhou Q, Yu C, Kong X, Liu L, Wang Z, Yang J. 2017. Canopy light and nitrogen distributions are related to grain yield and nitrogen use efficiency in rice. Field Crop Res 206: 74-85. DOI: 10.1016/j.fcr.2017.02.021.

Habimana S, Kalyana Murthy KN, Nanja Reddy YA, Mudalagiriyappa M, Vasantha Kumari R, Hanumanthappa DC. 2019. Impact of aerobic rice-leafy vegetables intercropping systems on weed management. Adv Hortic Sci 33 (3): 365-373. DOI: 10.13128/ahs-24266.

Heng Y, Wu C, Long Y, Luo S, Ma J, Chen J, Liu J, Zhang H, Ren Y, Wang M, Tan J, Zhu S, Wang J, Lei C, Zhang X, Guo X, Wang H, Cheng Z,Wan J. 2018. OsALMT7 maintains panicle size and grain yield in rice by mediating malate transport. Plant Cell 30 (4): 889-906. DOI: 10.1105/tpc.17.00998.

Hidayah UF, Suwarno WB, Aswidinnoor H. 2022. Genotype by environment analysis on multi-canopy cropping system in rice: Effects of different types of flag leaves. Agron J 114: 356-365. DOI: 10.1002/agj2.20959.

Hidayati N, Triadiati, Anas I. 2016. Photosynthesis and transpiration rates of rice cultivated under the system of rice intensification and the effects on growth and yield. Hayati J Biosci 23 (2): 67-72. DOI: 10.1016/j.hjb.2016.06.002.

Hikosaka K. 2014. Optimal nitrogen distribution within a leaf canopy under direct and diffuse light. Plant Cell Environ 37 (9): 2077-2085. DOI: 10.1111/pce.12291.

Hou W, Shen J, Xu W, Khan MR, Wang Y, Zhou X, Gao Q, Murtaza B, Zhang Z. 2021. Recommended nitrogen rates and the verification of effects based on leaf SPAD readings of rice. PeerJ 9: e12107. DOI: 10.7717/peerj.12107.

Huang R, Jiang L, Zheng J, Wang T, Wang H, Huang Y, Hong Z. 2013. Genetic bases of rice grain shape: So many genes, so little known. Trends Plant Sci 18 (4): 218-226. DOI: 10.1016/j.tplants.2012.11.001.

Indonesian Ministry of Agriculture. 2020. Location-Specific N, P and K Fertilizer Recommendations for Rice, Corn and Soybean Plants in Wetland (Per District), Book I Rice. Indonesian Ministry of Agriculture, Jakarta.

International Rice Research Institute. 2013. Standard Evaluation System (SES) for Rice 5th Ed. IRRI, Manila.

Ji C, Li J, Jiang C, Zhang L, Shi L, Xu F, Cai H. 2022. Zinc and nitrogen synergistic act on root-to-shoot translocation and preferential distribution in rice. J Adv Res 35: 187-198. DOI: 10.1016/j.jare.2021.04.005.

Kamara AY, Tofa AI, Ademulegun T, Solomon R, Shehu H, Kamai N, Omoigui L. 2019. Maize-soybean intercropping for sustainable intensification of cereal-legume cropping systems in Northern Nigeria. Exp Agric 55: 73-87. DOI: 10.1017/S0014479717000564.

Li R, Li M, Ashraf U, Liu S, Zhang J. 2019. Exploring the relationships between yield and yield-related traits for rice varieties released in china from 1978 to 2017. Front Plant Sci 10: 543. DOI: 10.3389/fpls.2019.00543.

Lu H, Qi X, Guo X, Towa JJ, Zhen B, Qiao D, Wang Z, Yang B, Han Y. 2018. Canopy light utilization and yield of rice under rain-catching and controlled irrigation. Water (Switzerland) 10 (10): 1-15. DOI: 10.3390/w10101340.

Ma Z, Wu T, Huang K, Jin YM, Li Z, Chen M, Yun S, Zhang H, Yang X, Chen H, Bai H, Du L, Ju S, Guo L, Bian M, Hu L, Du X, Jiang W. 2020. A novel AP2/ERF transcription factor, OsRPH1, negatively regulates plant height in rice. Front Plant Sci 11: 709. DOI: 10.3389/fpls.2020.00709.

Makino Y, Hirooka Y, Homma K, Kondo R, Liu TS, Tang L, Nakazaki T, Xu ZJ, Shiraiwa T. 2021. Effect of flag leaf length of erect panicle rice on the canopy structure and biomass production after heading. Plant Prod Sci 25 (9): 1-10. DOI: 10.1080/1343943X.2021.1908152.

Mead R, Willey RW. 1980. The concept of a 'land equivalent ratio' and advantages in yields from intercropping. Exp Agric 16 (3): 217-228. DOI: 10.1017/S0014479700010978.

Meng T, Wei H, Li X, Dai Q, Huo Z. 2018. A better root morpho-physiology after heading contributing to yield superiority of *japonica/indica* hybrid rice. Field Crop Res 228: 135-146. DOI: 10.1016/j.fcr.2018.08.024.

Mongon J, Konnerup D, Colmer TD, Rerkasem B. 2014. Responses of rice to Fe^{2+} in aerated and stagnant conditions: growth, root porosity and radial oxygen loss barrier. Funct Plant Biol 41 (9): 922-929. DOI: 10.1071/FP13359.

Mugisa I, Fungo B, Kabiri S, Sseruwu G, Kabanyoro R. 2020. Productivity optimization in rice-based intercropping systems of Central Uganda. Intl J Environ Agric Biotechnol 5: 142-149. DOI: 10.22161/ijeab.51.22.

Nawaz A, Rehman AU, Rehman A, Ahmad S, Siddique KM, Farooq M. 2022. Increasing sustainability for rice production systems. J Cereal Sci 103: 103400. DOI: 10.1016/j.jcs.2021.103400.

Pinta W, Vorasoot N, Jongrungklang N, Saingliw JL, Toojinda T, Sanitchon J. 2018. Root responses in chromosome segment substitution lines of rice 'KDML105' under early drought stress. Chil J Agric Res 78 (2): 238-254. DOI: 10.4067/S0718-58392018000200238.

Rajput A, Rajput SS, Jha G. 2017. Physiological parameters leaf area index, crop growth rate, relative growth rate and net assimilation rate of different varieties of rice grown under different planting geometries and depths in SRI. Intl J Pure Appl Biosci 5: 362-367. DOI: 10.18782/2320-7051.2472.

Sandeep K, Nayak MK, Diwan S, Anil K. 2016. Correlation study of growth, development and yield with agrometeorological indices under different planting method correlation study of growth, development and yield with agrometeorological indices under different planting method of rice. Intl J Agric Sci 8: 2682-2686.

Singh S, Mohanty DS, Sahu M, Bhaskar N, Verma B. 2020. Evaluation of SPAD meter values for estimating rice nitrogen status. Intl J Chem Stud 8 (4): 1-5. DOI: 10.22271/chemi.2020.v8.i4a.9947.

Song Q, Zhang G, Zhu XG. 2013. Optimal crop canopy architecture to maximise canopy photosynthetic CO_2 uptake under elevated CO_2-A theoretical study using a mechanistic model of canopy photosynthesis. Funct Plant Biol 40 (2): 109-124. DOI: 10.1071/FP12056.

Tian Z, Li J, He X, Jia X, Yang F, Wang Z. 2017. Grain yield, dry weight and phosphorus accumulation and translocation in two rice (*Oryza sativa* L.) varieties as affected by salt-alkali and phosphorus. Sustainability 9 (8): 1461. DOI: 10.3390/su9081461.

Udhaya ND, Kuzhanthaivel RL. 2015. Analysis of light transmission ratio and yield advantages of pigeonpea in relation to intercrop and different plant population. Afr J Agric Res 10 (8): 731-736. DOI: 10.5897/ajar2014.9122.

Usui Y, Sakai H, Tokida T, Nakamura H, Nakagawa H, Hasegawa T. 2016. Rice grain yield and quality responses to free-air CO_2 enrichment combined with soil and water warming. Glob Chang Biol 22 (3): 1256-1270. DOI: 10.1111/gcb.13128.

Wang J-X, Sun J, Li C-X, Liu H-L, Wang J-G, Zhao H-W, Zou D-T. 2016. Genetic dissection of the developmental behavior of plant height in rice under different water supply conditions. J Integr Agric 15 (12): 2688. DOI: 10.1016/S2095-3119(16)61427-2.

Wang X, Liu G, Wang Z, Chen S, Xiao Y, Yu C. 2019. Identification and application of major quantitative trait loci for panicle length in rice (*Oryza sativa*) through single-segment substitution lines. Plant Breed 138 (3): 299-308. DOI: 10.1111/pbr.12687.

Wang C, Yan Z, Wang Z, Batool M, El-Badri AM, Bai F, Li Z, Wang B, Zhou G, Kuai J. 2021. Subsoil tillage promotes root and shoot growth of rapeseed in paddy fields and dryland in Yangtze River Basin soils. Eur J Agron 130: 126351. DOI: 10.1016/j.eja.2021.126351.

Wei H, Hu L, Zhu Y, Xu D, Zheng L, Chen Z, Hu Y, Cui P, Guo B, Dai Q, Zhang H. 2018. Different characteristics of nutrient absorption and utilization between inbred *japonica* super rice and inter-sub-specific hybrid super rice. Field Crop Res 218: 88-96. DOI: 10.1016/j.fcr.2018.01.012.

Wei H-H, Yang Y-L, Shao X-Y, Shi T-Y, Meng T-Y, Lu Y, Tao Y, Li X-Y, Ding E-H, Chen Y-L, Dai Q-G. 2020. Higher leaf area through leaf width and lower leaf angle were the primary morphological traits for yield advantage of *japonica/indica* hybrids. J Integr Agric 19 (2): 483-494. DOI: 10.1016/S2095-3119(19)62628-6.

Widyastuti LPY, Suwarno WB, Aswidinnoor H. 2020. Genotype by environment analysis on multi-canopy cropping system towards vertical harvest space in rice. Agron J 112 (6): 4568-4577. DOI: 10.1002/agj2.20405.

Wu J, Qi Y, Hu G, Li J, Li Z, Zhang H. 2017. Genetic architecture of flag leaf length and width in rice (*Oryza sativa* L.) revealed by association mapping. Genes Genomics 39 (3): 341-352. DOI: 10.1007/s13258-016-0501-8.

Xin W, Liu H, Zhao H, Wang J, Zheng H, Jia Y, Yang L, Wang X, Li J, Li X, Lei L, Zou D. 2021. The response of grain yield and root morphological and physiological traits to nitrogen levels in paddy rice. Front Plant Sci 12: 713814. DOI: 10.3389/fpls.2021.713814.

Yang H, Yang J, Lv Y, He J. 2014. SPAD values and nitrogen nutrition index for the evaluation of rice nitrogen status. Plant Prod Sci 17: 81-92. DOI: 10.1626/pps.17.81.

Yuan Z, Cao Q, Zhang K, Ata-Ul-Karim ST, Tan Y, Zhu Y, Cao W, Liu X. 2016. Optimal leaf positions for SPAD meter measurement in rice. Front Plant Sci 7: 719. DOI: 10.3389/fpls.2016.00719.

Zhai L, Wang F, Yan A, Liang C, Wang S, Wang Y, Xu J. 2020. Pleiotropic effect of GNP1 underlying grain number per panicle on sink, source and flow in rice. Front Plant Sci 11: 933. DOI: 10.3389/fpls.2020.00933.

Zhang X-C, Lu C-G, HU N, Yao K-M, Zhang Q-J, Dai Q-G. 2013. Simulation of canopy leaf inclination angle in rice. Rice Sci 20 (6): 434-441. DOI: 10.1016/S1672-6308(13)60161-4.

Zhang Y, Yu C, Lin J, Liu J, Liu B, Wang J, Huang A, Li H, Zhao T. 2017. OsMPH1 regulates plant height and improves grain yield in rice. PLoS ONE 12: e0180825. DOI: 10.1371/journal.pone.0180825.

Zhao S-Q, Xiang J-J, Xue H-W. 2013. Studies on the RICE LEAF INCLINATION1 (LC1), an IAA-amido synthetase, reveal the effects of auxin in leaf inclination control. Mol Plant 6 (1): 174-187. DOI: 10.1093/mp/sss064.

Zhao B, Liu Z, Ata-Ul-Karim ST, Xiao J, Liu Z, Qi A, Ning D, Nan J, Duan A. 2016. Rapid and nondestructive estimation of the nitrogen nutrition index in winter barley using chlorophyll measurements. Field Crop Res 185: 59-68. DOI: 10.1016/j.fcr.2015.10.021.

Zhao H, Mo Z, Lin Q, Pan S, Duan M, Tian H, Wang S, Tang X. 2020. Relationships between grain yield and agronomic traits of rice in southern China. Chil J Agric Res 80 (1): 72-79. DOI: 10.4067/s0718-58392020000100072.

Zhou C, Huang Y, Jia B, Wang S, Dou F, Samonte SOPB, Chen K, Wang Y. 2019. Optimization of nitrogen rate and planting density for improving the grain yield of different rice genotypes in Northeast China. Agronomy 9 (9): 555. DOI: 10.3390/agronomy9090555.

Zhu G, Ren Z, Liu Y, Lu F, Gu L, Shi Y, Liu J, Zhou G, Nimir NEA, Mohapatra PK. 2020a. Optimization of leaf properties and plant phenotype through yield-based genetic improvement of rice over a period of seventy years in the Yangtze River Basin of China. Food Energy Secur 9 (3): e223. DOI: 10.1002/fes3.223.

Zhu Y, Li T, Xu J, Wang J, Wang L, Zou W, Zeng D, Zhu L, Chen G, Hu J, Gao Z, Dong G, Ren D, Shen L, Zhang Q, Guo L, Hu S, Qian Q, Zhang G. 2020b. Leaf width gene LW5/D1 affects plant architecture and yield in rice by regulating nitrogen utilization efficiency. Plant Physiol Biochem 157: 359-369. DOI: 10.1016/j.plaphy.2020.10.035.