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Research Paper

AGRONOMIC AND GRAIN YIELD TRAITS OF RICE VARIETIES UNDER SEASONAL VARIATION IN TROPICAL LOWLANDS

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ARTICLE HIGHLIGHTS

- Planting time in the wet season changed rice growth and grain yield.
- Mid rainy season planting reduced grain yield in all tested rice varieties.
- Hybrid Intani 602 recorded the highest yield in late rainy season planting.
- Grain yield increased with greater plant biomass and faster crop growth.
- Longer flowering and maturity were associated with lower grain yield.

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ABSTRACT

Rice (*Oryza sativa L.*) is a strategic crop in Southeast Asia, where seasonal variation strongly influences its growth, physiology, and yield. This study evaluated the agronomic performance and yield components of three rice genotypes representing local (Pandan Wangi), improved (Inpari 32), and hybrid (Intani 602) types across three planting periods within the wet season (early, mid, and late rainy season) in tropical lowland fields of East Java, Indonesia, during 2023 – 2024. The experiment was arranged in a randomized complete block design within each planting period, and data were analyzed using combined ANOVA, correlation analysis, and genotype by trait (GT) biplot. Results indicated that genotype and planting period significantly affected most agronomic and yield traits, with significant genotype × planting period interactions observed for several key variables. Grain yield was positively associated with biomass accumulation and growth efficiency (DW and CGR) and supported by canopy development (LAI), whereas phenological duration (DTF and DTM) showed negative associations with yield under the tested wet season conditions. GT biplot analysis explained 77.95% of the total variation (PC1 = 64.48%, PC2 = 13.47%) and indicated that hybrid combinations in the late rainy season planting period were closely associated with major yield and biomass traits, while Inpari 32 in the early rainy season planting period was more closely associated with radiation use indices (EPA and RUE) and tiller related traits. Pandan Wangi combinations were positioned nearer to phenological and vegetative traits with lower yield levels. Overall, the findings provide a site-specific basis to interpret varietal suitability and planting period sensitivity within the wet season in tropical lowland rice systems.

Keywords: agronomic traits, planting period, rice genotypes, tropical lowlands

INTRODUCTION

Rice (*Oryza sativa L.*) is the principal staple across Southeast Asia, including Indonesia, and it is strategic for national food security. In Indonesia, rice cultivation in tropical lowland agroecosystems is largely concentrated in the wet season, which is dynamic, with rainfall intensity typically progressing from the onset phase to a peak phase and then to a late phase that transitions toward the dry season. Each phase creates a distinct agroclimatic regime that strongly influences the expression of agronomic and physiological traits. During the wet season, reduced radiation and elevated humidity often extend vegetative growth, increase pest and disease pressure, and constrain panicle filling, which results in a higher proportion of empty spikelets. In the transitional period, weather fluctuations, irregular rainfall, and temperature anomalies can disrupt flowering and grain filling, thereby elevating the risk of yield loss (Cosentino *et al.* 2016; Gao *et al.* 2024; Duc *et al.* 2025). In this study, the within-season variability was evaluated using three planting periods within the wet season (early, mid, and late rainy season).

Variation in planting periods in tropical climates is a practical lever to maintain rice yield stability and to match genotypes to specific calendars. We compared the responses of local landraces, high-yielding inbred varieties (locally termed VUB), and hybrids under distinct wet-season planting periods. Local landraces typically tolerate low soil fertility and irregular water supply, with tradeoffs of longer crop duration, taller stature, and modest yield potential (Ibrahim *et al.* 2024). High-yielding inbred varieties generally combine shorter duration with an agronomically desirable ideotype and higher yield potential (Lal *et al.* 2023). Hybrids express heterosis, including larger numbers of spikelets per panicle, longer panicles, and greater biomass, although performance is often less stable in fluctuating environments such as transitional seasons (Huang *et al.* 2021). Beyond genetic and seasonal main effects, quantitative traits, including panicle length, the number of filled and unfilled spikelets, the weight of 1,000 grains, plant height, and tiller number, are shaped by genotype-by-environment interaction linked to the planting period (Hidayah *et al.* 2022).

Planting season is a critical determinant of yield stability and varietal adaptability in tropical rice systems. Prior studies have examined environmental influences on agronomic performance, but many primarily contrasted the wet season versus dry season and therefore, did not compare genotype performance across wet-season planting periods, namely early, mid, and late rainy season, in tropical lowlands (Tsujimoto *et al.* 2021; Wang *et al.* 2024). Moreover, many investigations focused on yield endpoints without evaluating multi trait relationships using simultaneous multivariate approaches. These gaps leave an incomplete understanding of how genotype by planting period interactions shape agronomic trait expression yield formation under tropical lowland conditions.

Complex growth responses require further evaluation to determine the stability of agronomic trait expression across contrasting wet-season planting periods. This, in turn, calls for analytical frameworks that integrate multiple agronomic traits with environmental covariates in a single assessment. The Genotype by Trait (GT) biplot offers such capability, since it visualizes, in one display, relationships among traits and genotype trait profiles across wet-season planting periods. Although this approach has been applied to several crops, including wheat, soybean, maize, and sunflower (Abu *et al.* 2019; Purwati *et al.* 2022; Shojaei *et al.* 2022). Its use in tropical rice production systems remains limited, especially when planting period are explicitly contrasted (Khan *et al.* 2023). Building on this rationale, the present study characterizes genotype by environment interactions for local landraces, high-yielding inbred varieties (locally termed VUB), and hybrids under tropical lowland conditions in East Java, Indonesia, using GT biplot analysis. Accordingly, this study aimed to determine whether planting period contrasts within the wet season modify grain yield, agronomic trait expression, and the consistency of genotype performance within this site year in an irrigated tropical lowland system, while identifying trait networks and key trait combinations associated with yield formation under wet season constraints. This study provides a trait-based and site-specific interpretation of how within-season variability influences yield formation and genotype performance during the wet season in tropical lowland rice systems.

MATERIALS AND METHODS

Experimental Site and Design

The field experiment was conducted in lowland tropical rice fields located in Sidoarjo District, East Java, Indonesia (7°27' S, 112°43' E; ± 5 m asl) during the 2023 – 2024 growing season. The study evaluated three planting periods within the wet season, i.e., early rainy season (S1: sowing in November), mid rainy season (S2: sowing in January), and late rainy season (S3: sowing in March) (Table 1).

In each planting period, the trial was arranged in a randomized complete block design (RCBD) with three replications (blocks), with genotype as the treatment factor. The genotype factor consisted of three types: a local genotype (Pandan Wangi/ V1), a newly released improved variety (Inpari 32/ V2), and a commercial hybrid (Intani 602/ V3). These genotypes were selected as contrasting, farmer relevant benchmarks, and were evaluated under the same irrigated lowland environment rather than for altitudinal adaptation screening. Each plot measured 5 m × 5 m with a spacing of 25 cm × 25 cm. The site soil had pH 6.80, total nitrogen 0.14%, available phosphorus (P_2O_5) 67.03 ppm, and exchangeable potassium (K-dd) 1.09 me 100/g. Crop management, including fertilization, irrigation, and pest and disease control, followed the national rice production technology recommendations.

Observed Parameters

Observed parameters were grouped into: a) agronomic and phenological traits; b) yield and yield component traits; and c) radiation related indices. Agronomic and phenological traits included tiller number (NT), leaf number (NL), leaf area (LA), leaf area index (LAI), productive tiller number (PT), days to flowering (DTF), and days to maturity (DTM). Yield and yield component traits included panicle number per hill (NP), grain number per main panicle (NG), thousand seed weight (TSW), and grain yield measured per plot (GY_plot), per hill (GY_hill), and per panicle (GY_panicle), with average grain yield (GY) used as an integrative measure. Biomass accumulation was quantified as total dry weight (DW) and crop growth rate (CGR). Radiation absorption efficiency (EPA) and radiation use efficiency (RUE) were treated as radiation related indices derived from crop growth and radiation data. Observations were taken from five randomly selected sample plants per plot.

Table 1 Meteorological conditions during three planting periods within the 2023 – 2024 wet season

Sowing	Month	Tn	Tx	Tavg	RH_avg	RR	SS
S1	Nov-23	26.24	35.24	30.22	72.82	0.18	7.35
	Dec-23	25.79	34.54	29.46	78.13	1.63	6.42
	Jan-24	25.41	33.54	28.40	82.55	11.56	4.66
	Feb-24	25.21	33.30	28.29	83.48	15.38	5.02
	Mar-24	25.38	33.05	28.49	84.27	6.45	4.43
Mean		25.60	33.93	28.97	80.25	7.04	5.58
S2	Jan-24	25.41	33.54	28.40	82.55	11.56	4.66
	Feb-24	25.21	33.30	28.29	83.48	15.38	5.02
	Mar-24	25.38	33.05	28.49	84.27	6.45	4.43
	Apr-24	25.87	33.37	29.19	82.27	11.80	5.73
	May-24	25.68	33.55	29.48	76.46	0.04	8.07
Mean		25.51	33.36	28.77	81.81	9.05	5.58
S3	Mar-24	25.38	33.05	28.49	84.27	6.45	4.43
	Apr-24	25.87	33.37	29.19	82.27	11.80	5.73
	May-24	25.68	33.55	29.48	76.46	0.04	8.07
	Jun-24	25.10	32.70	28.68	76.96	0.47	7.24
Mean		25.51	33.17	28.96	79.99	4.69	6.37

Notes: Tn = Minimum temperature (°C); Tx = Maximum temperature (°C); Tavg = Average temperature (°C); RH_avg = Average relative humidity (%); RR = Rainfall (mm); SS = Sunshine duration (h).

Data Analysis

Data obtained were analyzed using a combined analysis of variance (ANOVA) to evaluate the effects of planting period, genotype, and their interaction on each parameter. When significant effects were detected, means were compared using the Least Significant Difference (LSD) test at the 5% significance level. Analysis of variance and LSD were performed using the SAS 9.0 software version.

To further explore the relationships among physiological and agronomic traits and their contribution to grain yield, correlation analysis and Genotype by Trait (GT) biplot analysis were performed. The analyses were conducted using R Studio version 4.2.2 with the GT Biplot package (Weikai & Istvan 2002) and the metan package (Olivoto & Lúcio 2020). This approach allowed visualization of interaction patterns between genotypes and agronomic traits simultaneously, supported the identification of traits with the strongest contribution to yield, and facilitated indirect selection for genotype improvement.

RESULTS AND DISCUSSION

Combined Analysis of Variance for Agronomic Traits and Yield Components of Rice

The combined analysis of variance revealed that the environmental factor (wet-season planting period) had a significant to highly significant effect on all observed variables related to both growth and yield traits. The genetic factor also showed significant and highly significant effects ($P < 0.01$) on all measured parameters, indicating that genotypic variation contributed to differences in the expression of agronomic and yield traits according to the characteristics of each variety. The interaction between planting period and genotype had a significant effect ($P < 0.05$) on traits such as NT, LA, CGR, EPA, NP, NG, GY-plot, and GY, and a highly significant effect ($P < 0.01$) on LAI, DW, RUE, DTF, and DTM (Table 2).

These results indicate that the response of growth and yield components varied among genotypes across wet-season planting periods. The genotype × environment (G × E) interaction represents the adaptability of a variety under specific seasonal conditions. The coefficients of variation for agronomic and yield traits ranged from 3.6% to 17.9%. Thus, the presence of significant G × E interactions highlights the importance of evaluating genotypes not only for yield potential but also for the consistency of agronomic trait expression across wet-season planting periods within this site year.

The LSD mean comparisons in Table 3 showed that genotype by wet-season planting period combinations differed significantly in grain yield (GY) and yield components. The highest GY was recorded in V3S3 (9.5 tonnes/ha) and was not significantly different from V3S1 (8.8 tonnes/ha) and V2S1 (8.7 tonnes/ha). These results indicate that early and late wet-season planting periods can maintain high productivity for specific genotypes within this site year.

Table 2 Recapitulation of observed characters based on analysis of variance

Plant characters	Treatment and interaction			
	Season	Genotype	Sea X Gen	CV (%)
Number of tillers (NT)	24.5 *	68.9 **	20.9 *	8.6
Number of leaves (NL)	1,175.6 **	1,610.7 **	184.7ns	17.9
Leaf area (LA)	2,212,927.0 **	547,260.1 **	85,846.7 *	8.1
Leaf area index (LAI)	5.6 **	1.3 **	0.2 **	8.1
Dry weight (DW)	65,600.8**	2,922,725.5 **	25,509.6 **	3.7
Crop growth rate (CGR)	0.4 **	3.2 **	0.6 *	3.6
Radiation use efficiency (RUE)	0.5 *	0.3 **	0.2 **	7.2
Radiation absorption efficiency (EPA)	2,219.9 *	3,315.4 **	1,490.9 *	8.9
Days to flowering (DTF)	76.93 **	155.81 **	11.81 **	0.8
Days to maturity (DTM)	309.6 **	338.5 **	10.37 **	1.06
Productive tillers (PT)	443.4 **	58.1 *	1.6 ns	5.4
Number of panicles (NP)	26.0 **	113.8 *	10.4 *	7.6
Number of grains (NG)	5,352.3 **	14,674.5 **	1,264.9 *	12.8

Plant characters	Treatment and interaction			
	Season	Genotype	Sea X Gen	CV (%)
Grain yield per harvested plot (GY-plot)	73,231.0 **	139,542.9 **	13,481.3 *	8.5
Grain yield per hill (GY-hill)	1,141.4 **	2,277.3 **	20.9 ns	12.9
Grain yield (GY)	7.2 **	14.1 **	1.4 *	8.4
1,000 seed weight (TSW)	14.0 *	198.5 **	1.8 ns	5.0

Notes: *Significant at the 0.05 probability level; **Significant at the 0.01 probability level.

Table 3 LSD mean comparison of yield and yield component traits of rice genotypes across wet-season planting periods

Treatment	NP	NG	GY-plot (g/m2)	GY (tonnes/ha)
V1S1	23.7 a	124.7 cde	653.3 bc	6.5 bc
V1S2	16.3 d	116.3 e	538.1 d	5.4 d
V1S3	20.3 bc	134.0 cde	648.5 bcd	6.4 c
V2S1	19.7 bc	130.0 cde	875.6 a	8.7 a
V2S2	18.3 d	121.3 de	601.3 cd	6.0 d
V2S3	21.0 abc	154.0 bcd	703.7 bc	7.0 bc
V3S1	22.3 ab	187.0 b	876.9 a	8.8 a
V3S2	21.3 ab	159.3 bc	755.7 b	7.5 b
V3S3	22.3 ab	252.0 a	953.5 a	9.5 a
LSD 5%	**2.79**	**34.86**	**111.4**	**1.09**

Notes: NP = Panicle number per hill; NG = grain number per main panicle; GY-plot = yield per plot; GY = grain yield. Means followed by the same letter in the same column were not significantly different based on LSD at 0.05.

Table 4 LSD mean comparison of growth traits (NT, LA, LAI, DW, CGR, EPA, and RUE) of rice genotypes across wet season planting periods

Treatment	NT	LA (cm2)	LAI	DW (g/m2)	CGR (g/m2/day)	EPA (%)	RUE (g/MJ)
V1S1	29.3 ab	1,448.1 d	2.3 d	1,939.4 cd	18.5 cd	2.2 cd	2.5 b
V1S2	21.7 c	1,122.6 e	1.8 e	1,826.9 de	17.4 de	2.3 bcd	2.7 ab
V1S3	26.3 b	1,773.5 c	2.9 c	1,782.8 ef	16.9 ef	1.9 d	2.1 c
V2S1	32.3 a	1,445.7 d	2.3 d	1,997.6 c	19.0 c	2.8 a	2.8 ab
V2S2	32.0 a	742.6 f	1.2 f	1,689.1 f	16.0 f	2.1 cd	2.1 c
V2S3	28.3 ab	2,049.7 b	3.3 b	1,817.4 de	17.3 de	2.2 bcd	2.2 c
V3S1	30.7 ab	1,800.6 c	2.8 c	2,154.2 ab	20.5 ab	2.4 bc	2.7 ab
V3S2	29.3 ab	1,375.9 d	2.2 d	2,063.0 bc	19.7 bc	2.3 bcd	2.9 a
V3S3	31.3 a	2,392.0 a	3.8 a	2,245.7 a	21.4 a	2.5 ab	2.5 b
LSD 5%	**4.43**	**227.8**	**0.36**	**127.5**	**1.2**	**0.36**	**0.32**

Notes: NT = Tiller number; LA = leaf area; LAI = leaf area index; DW = total dry weight; CGR = crop growth rate; EPA = radiation absorption efficiency; RUE = radiation use efficiency. Means followed by the same letter in the same column were not significantly different based on LSD at 0.05.

In contrast, the mid wet-season planting period (S2) tended to be yield limiting, as reflected by lower yields in V1S2 (5.4 tonnes/ha) and V2S2 (6.0 tonnes/ha) and a decline in V3S2 (7.5 tonnes/ha). In V1, V1S1 (6.5 tonnes/ha) and V1S3 (6.4 tonnes/ha) were comparable, indicating greater yield consistency between early and late wet-season planting periods despite moderate yield levels. Yield shifts across planting periods tracked changes in NG more consistently than NP, suggesting that across wet-season planting periods, yield variation was driven more by panicle sink size than by panicle number (Tsujimoto *et al.* 2021). Table 4 further shows that yield differences were supported by differences in growth traits across genotype by planting period combinations.

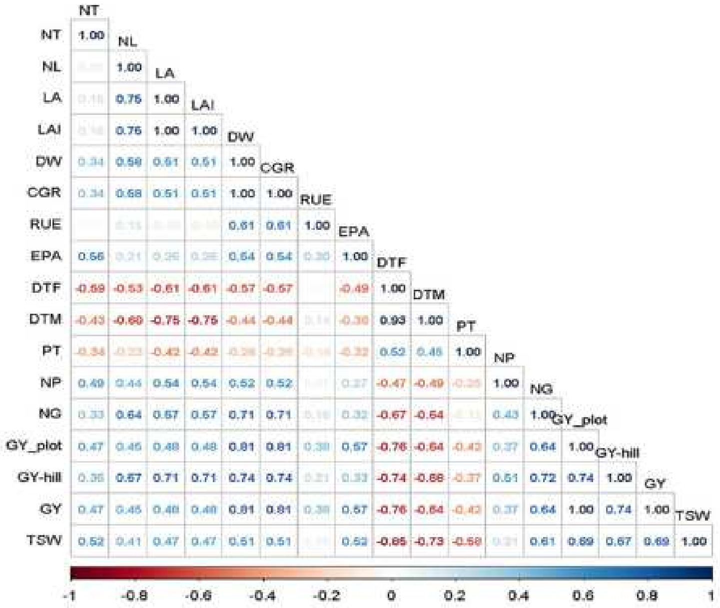
In V3S3, NT, LA, LAI, DW, CGR, and EPA reached the highest values (31.3, 2392.0, 3.8, 2245.7, 21.4, and 2.51), reflecting greater canopy capacity and biomass accumulation in a high yielding combination. In contrast, the highest RUE occurred in V3S2 (2.9) but did not coincide with maximum yield, indicating that radiation use efficiency during the wet season may not translate directly into yield when sink formation and grain filling are constrained by humid conditions and frequent low radiation episodes (Wang *et al.* 2024).

Correlation Analysis

The correlation analysis showed that grain yield measured at plot and overall scales (GY_plot and GY) was strongly and positively associated with biomass accumulation and growth rate, particularly dry weight (DW; r = 0.81 for both GY and GY_plot) and crop growth rate (CGR; r = 0.81 for both GY and GY_plot) (Fig. 1).

In contrast, leaf area index (LAI) showed a moderate correlation with GY and GY_plot (r = 0.48), but a stronger association with yield per hill (GY_hill; r = 0.71), indicating that canopy size was more consistently reflected at the plant unit yield scale. Positive correlations were also observed with NG (r = 0.64) and TSW (r = 0.69), confirming that increases in leaf area, biomass accumulation, and grain size were associated with rice productivity. Li *et al.* (2021), emphasized that "grain number per panicle and thousand seed weight were the most important determinants of final grain yield," which aligns with the pattern observed in this study.

Conversely, phenological traits (DTF and DTM) exhibited moderate to strong negative correlations with yield and key yield components, including GY (r = -0.76 for DTF; r = -0.64 for DTM) and TSW (r = -0.85 for DTF; r = -0.73 for DTM), suggesting that prolonged flowering and maturity duration were not associated with higher productivity under rainy season conditions. Vegetative traits, including NL, LA, and NP, showed positive but weaker correlations with yield (r = 0.44 – 0.54). Wang *et al.* (2024), noted that moderate canopy and sink related development can be beneficial for yield, whereas excessive vegetative growth under humid conditions may reduce reproductive efficiency. Importantly, productive tiller number (PT) showed a negative correlation with yield (r = -0.42) and did not appear to be compensated by heavier grains, because PT was also negatively correlated with thousand seed weight (TSW) (r = -0.58), indicating that higher tillering intensity coincided with reduced grain mass rather than improved grain filling in this dataset; such a negative tillering yield relationship is consistent with compensatory trade-offs under excessive tillering, including greater tiller abortion and reduced panicle/grain filling due to within-plant competition for assimilates (Kalaitzidis *et al.* 2025). This mechanism is especially plausible under wet season conditions characterized by frequent low light episodes, where reduced radiation constrains canopy photosynthesis and assimilate supply during reproductive development, leading to lighter grains and lower yield despite greater vegetative proliferation.



	NT	NL	LA	LAI	DW	CGR	RUE	EPA	DTF	DTM	PT	NP	NG	GY_plot	GY-hill	GY	TSW
NT	1.00																
NL	[illegible]	1.00															
LA	0.15	0.75	1.00														
LAI	0.16	0.76	1.00	1.00													
DW	0.34	0.58	0.61	0.51	1.00												
CGR	0.34	0.58	0.51	0.51	1.00	1.00											
RUE	[illegible]	0.11	[illegible]	[illegible]	0.61	0.61	1.00										
EPA	0.56	0.21	0.35	0.35	0.54	0.54	0.30	1.00									
DTF	-0.59	-0.53	-0.61	-0.61	-0.57	-0.57	[illegible]	-0.49	1.00								
DTM	-0.43	-0.60	-0.75	-0.75	-0.44	-0.44	0.14	-0.30	0.93	1.00							
PT	-0.34	-0.23	-0.42	-0.42	-0.26	-0.26	-0.14	-0.32	0.52	0.45	1.00						
NP	0.49	0.44	0.54	0.54	0.52	0.52	[illegible]	0.27	-0.47	-0.49	-0.25	1.00					
NG	0.33	0.64	0.67	0.67	0.71	0.71	0.16	0.32	-0.67	-0.64	[illegible]	0.43	1.00				
GY_plot	0.47	0.45	0.48	0.48	0.81	0.81	0.38	0.57	-0.76	-0.64	-0.42	0.37	0.64	1.00			
GY-hill	0.35	0.57	0.71	0.71	0.74	0.74	0.21	0.33	-0.74	-0.68	-0.37	0.51	0.72	0.74	1.00		
GY	0.47	0.45	0.48	0.48	0.81	0.81	0.38	0.57	-0.76	-0.64	-0.42	0.37	0.64	1.00	0.74	1.00	
TSW	0.52	0.41	0.47	0.47	0.51	0.51	[illegible]	0.52	-0.85	-0.73	-0.58	0.21	0.61	0.69	0.67	0.69	1.00

Figure 1 Correlation coefficient among traits of rice varieties across wet-season planting periods

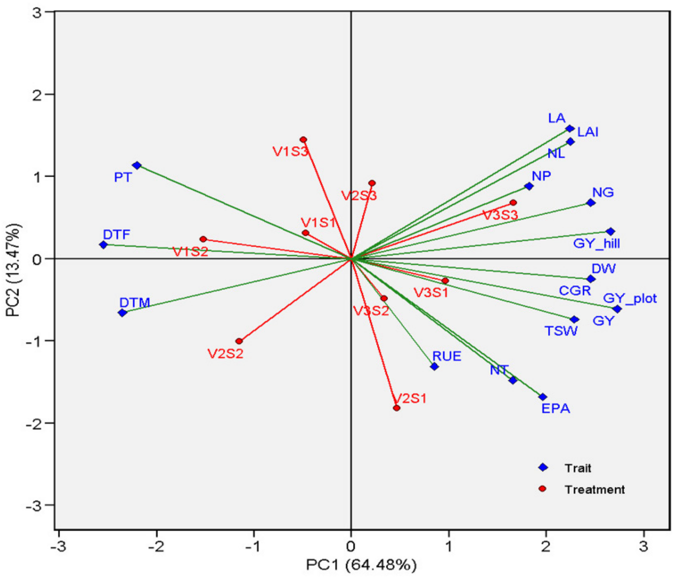


Figure 2 Genotype by trait biplot vector view

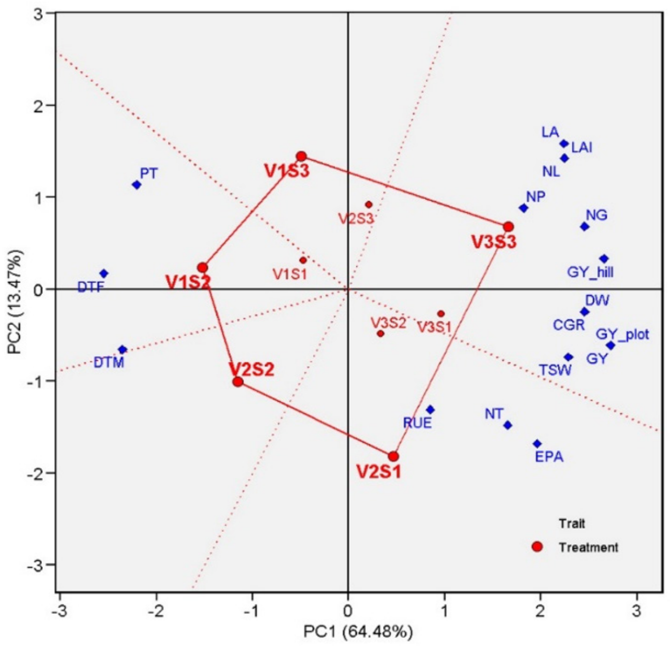


Figure 3 Polygon view

Genotype by Trait Evaluation

The genotype by trait (GT) biplot based on 17 measured traits explained 77.95% of the total variation (PC1 = 64.48% and PC2 = 13.47%), indicating that the multivariate structure was captured mainly by two biological dimensions (Fig. 2).

Along PC1, yield and biomass related traits (GY, DW, CGR, TSW, and associated yield measures) were positioned on the positive side with acute vector angles, reflecting strong positive associations and indicating that the primary axis of differentiation among genotype × planting period combinations was closely linked to productivity and biomass accumulation (Sharifi & Ebadi 2018). In contrast, phenological traits (DTF and DTM) projected in the opposite direction, suggesting negative relationships with the yield-biomass complex under the tested wet-season lowland conditions.

Importantly, GT biplot indicate that treatment differentiation was driven only by production traits. PC2 provided additional and meaningful separation associated with agronomic and canopy development attributes. Traits describing canopy vigor and plant architecture (e.g., LA, LAI, NL, and NT) showed distinct projections along PC2, indicating that variation in vegetative development contributed substantially to the multivariate structure and helped discriminate treatments beyond the productivity axis. Radiation related indices (EPA and RUE) were located on the positive side of PC1 but were not collinear with the main yield vectors and diverged along PC2, implying that radiation capture and utilization were associated with productivity in a more nuanced manner rather than acting as a single dominant yield driver across planting periods (Mousavi *et al.* 2021). Taken together, the biplot provides a compact summary showing that genotype × planting period responses were shaped jointly by productivity related traits (PC1) and agronomic/vegetative traits (PC2), supporting physiological interpretation of yield formation under wet-season variability in tropical lowlands (Phapumma *et al.* 2020; Khan *et al.* 2023).

Polygon View Biplot for Genotype by Planting Period Combination

The biplot, which explained 77.95% of the total variation (PC1 = 64.48%; PC2 = 13.47%), illustrated sectoral divisions representing the relationships between genotype × season combinations and groups of agronomic traits (Fig. 3).

The V3S3 combination occupied a vertex position in the right sector and was closely associated with key yield traits (GY, GY_plot, GY_hill, DW, CGR, LAI, TSW, NG). This indicates that the hybrids were more consistently to grain productivity. These findings are in agreement with Sabouri *et al.* (2022), who emphasized that GT biplot analysis can reveal associations between yield indices and morphophysiological traits, with vertex genotypes identified as superior candidates for selection.

Conversely, V2S1 was located in the lower sector, closer to traits related to radiation efficiency (EPA, RUE) and tiller number (NT), high lighting a physiological orientation distinct from direct yield traits. Genotypes located at the polygon vertices (apex) represent the most responsive combinations for the trait group within each sector, thereby indicating specific trait advantages across sectors (Stansluos *et al.* 2023). In the left sector, V1S2 was associated with phenological traits (DTF, DTM), indicating that the performance of local varieties was more influenced by flowering and maturity duration than by yield components. This is consistent with Heravizadeh *et al.* (2022), who reported that the stability of local varieties was often more dependent on phenological traits than on biomass accumulation. Meanwhile, V1S3 was positioned in the upper sector, in closer proximity to vegetative traits (PT, NL, LA), suggesting that leaf and tiller growth played a major role in varietal performance during that season. Overall, the polygon view biplot highlighted that hybrids were more consistently associated with productivity related traits, Inpari 32 was more strongly linked to radiation efficiency in the early season, and local varieties were more closely related to phenological and vegetative traits.

Evaluation using multiple analytical approaches provides an integrated understanding of treatment interactions and agronomic trait networks, which underpins site-specific genotype recommendations across the three wet-season planting periods. For November sowing, Inpari 32 produced grain yield statistically comparable to Intani 602; however, the yield component balance differed. Inpari 32 was characterized by stronger tiller formation supporting panicle number, whereas Intani 602 relied more on sink strengthening, particularly higher grains per panicle. Consistent with the polygon view, V2S1 occupied the vertex of the sector defined by NT, EPA, and RUE, supporting the recommendation of Inpari 32 as a competitive inbred option for the early wet-season planting period at this site. For January sowing, the climatology table indicated the most constraining conditions, with high rainfall accompanied by reduced sunshine duration or solar radiation, such that yield formation was more dependent on maintaining canopy efficiency and sink reinforcement. In line with the ANOVA, Intani 602 showed the strongest performance in this period and is therefore, recommended for the mid wet-season planting period. For March sowing, Intani 602 is recommended as the primary option for the late wet-season planting period, with productivity reaching 9.5 tonnes/ha, supported by concurrent improvements in canopy development, biomass accumulation, and sink enlargement.

Wet-season environments can vary substantially among years; therefore, these recommendations should be interpreted as site-specific within this site-year. Further research should evaluate additional locally relevant genotypes, including more inbred and hybrid cultivars, and repeat the study across wet-season planting periods over multiple years to strengthen stability inference and improve the robustness of genotype recommendations.

CONCLUSION

This study provides clear evidence that wet-season planting period strongly determines the agronomic performance and yield of rice genotypes in tropical lowlands. Grain yield was strongly associated with biomass accumulation, crop growth rate, and leaf area index, while phenological traits showed negative associations. The GT biplot effectively visualized genotype, trait, and planting period interactions, showing that hybrid in the late rainy season were closely associated with major yield and biomass traits, Inpari 32 in the early rainy season was more closely associated with radiation use indices and tiller related traits, and Pandan Wangi combinations were positioned nearer to phenological and vegetative traits with lower yield levels.

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