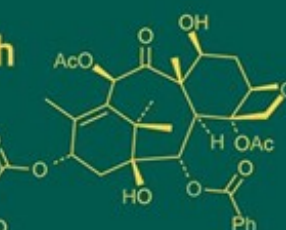


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Phenotyping of rice germplasm for physiological traits suitable for dry direct seeded rice

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ABSTRACT

Dry direct-seeded rice (DSR) offers opportunities for reducing labour and water requirements; however, successful establishment and productivity under DSR depend on the availability of genotypes possessing suitable physiological and adaptive traits. The present investigation was undertaken to phenotype rice germplasm for physiological traits associated with dry DSR and to identify promising genotypes for further evaluation. The experiment was conducted during Kharif 2025 at the Regional Agricultural Research Station, Karjat, Maharashtra, using 50 diverse rice genotypes and three checks, viz., Sahbhagi Dhan, N-22 and DRR Dhan 71, in an Augmented Block Design with five blocks. The genotypes were evaluated for germination, seedling, vegetative, reproductive, yield and physiological traits. Analysis of variance revealed substantial genetic variability for most of the traits, indicating considerable scope for selection. High genotypic and phenotypic coefficients of variation coupled with high heritability and genetic advance as per cent of mean were observed for seedling vigour index, specific leaf area, germination percentage and leaf area index, indicating their potential for selection. Grain yield showed significant positive associations with stomatal conductance, transpiration rate, absolute growth rate, net assimilation rate and other important yield-associated traits. Path coefficient analysis indicated positive direct effects of stomatal conductance, transpiration rate and net assimilation rate on grain yield, highlighting their importance as physiological selection criteria. Among the evaluated germplasm, HSAL 428, HSAL 412, G-230, G-61, G-72 and G-203 exhibited superior grain yield along with favourable expression of important physiological and yield-related traits. These genotypes may serve as promising material for further multi-environment evaluation and breeding programmes aimed at developing rice cultivars adapted to dry DSR conditions.

Keywords: Dry direct-seeded rice, Phenotyping, Physiological traits, Grain yield, Rice germplasm

Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops and a major staple in India. Conventional transplanted rice is water- and labour-intensive, whereas dry direct-seeded rice (DSR) offers advantages such as reduced labour and water requirements. However, successful crop establishment and productivity under dry DSR depend on the availability of genotypes with suitable physiological and adaptive traits. Rapid germination, vigorous seedling growth, favourable root and shoot development, efficient biomass accumulation, water relations and photosynthetic activity are important characteristics for adaptation to dry DSR conditions. Therefore, phenotyping diverse rice germplasm for these traits can help identify genotypes with superior establishment, physiological performance and yield potential under DSR conditions.

The identification of suitable physiological traits is particularly important for developing rice cultivars adapted to resource-conserving and moisture-limited production systems. Traits such as germination percentage, seedling vigour, root length, relative water content, leaf area index, growth rates, photosynthetic rate, transpiration rate and stomatal conductance can provide useful indicators of plant performance. Evaluation of genetic variability and estimation of heritability and genetic advance can assist in identifying traits amenable to selection, while correlation and path coefficient analyses can reveal traits associated with grain yield. Hence, the present study was undertaken to phenotype diverse rice germplasm for physiological traits suitable for dry DSR and to identify promising genotypes for further evaluation and use in DSR-oriented breeding programmes.

Materials and methods

The experiment was conducted during **Kharif 2025** at the **Regional Agricultural Research Station, Karjat, District Raigad, Maharashtra**, under dry direct-seeded rice conditions. The experiment comprised **50 diverse rice genotypes and three checks, viz., Sahbhagi Dhan, N-22 and DRR Dhan 71**, evaluated in

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an **Augmented Block Design with five blocks**. The plot size was **2.0 × 0.40 m (0.80 m²)** with a spacing of **20 × 10 cm**, and sowing was carried out on **1 July 2025**. Observations were recorded periodically up to physiological maturity for 27 germination, seedling, vegetative, reprod

uctive, yield and physiological traits, including germination percent-age, shoot and root length, seedling vigour index, plant height, relative water content, leaf area index, growth rates, dry matter accumulation, yield attributes, grain and straw yield, harvest index, specific leaf weight, specific leaf area, photosynthetic rate, transpiration rate, stomatal conductance and spikelet fertility.

The recorded data were subjected to **analysis of variance appropriate for the Augmented Block Design**. Genotypic and phenotypic coefficients of variation (GCV and PCV), broad-sense heritability, genetic advance and genetic advance as per cent of mean (GAM) were estimated to assess the magnitude and nature of genetic variability. Phenotypic and genotypic correlation coefficients were calculated to determine associations among traits, while path coefficient analysis was performed to assess the direct and indirect effects of component traits on grain yield. Statistical analyses were carried out following the standard procedures of **Panse et al. (1985) [1]**.

Results and discussion

The present investigation, entitled “Phenotyping of Rice Germplasm for Physiological Traits Suitable for Dry Direct-Seeded Rice (*Oryza sativa* L.)”, was carried out at the Regional Agricultural Research

Station, Karjat, Dist. Raigad, during Kharif 2025 to phenotype 53 rice genotypes (50 test entries and 3 released checks – Sahbhagi Dhan, N-22 and DRR Dhan 71) evaluated in an Augmented Block Design (five blocks) for 31 germination, seedling, vegetative, reproductive, yield and physiological traits. The results are presented and discussed under the following heads: (i) analysis of variance, (ii) mean performance and range of variability, (iii) genetic parameters of variability, (iv) correlation studies, (v) path coefficient analysis, and (vi) identification of promising genotypes.

3.1 Analysis of variance

Treatment (genotypes + checks) mean squares were significant for the great majority of the 31 traits studied – including germination percent, seedling vigour index, plant height at all three growth stages, filled grains per panicle, spikelet fertility, test weight, grain yield per plant, straw yield per plant and harvest index – confirming the presence of wide and significant genetic variability in the germplasm and its suitability for phenotypic characterisation and selection. Mean squares due to genotypes alone were significant for most traits, while the checks-vs-genotypes component was significant for several key traits, reflecting a real difference in performance between the released checks and the test entries. Traits such as harvest index, grain yield, straw yield and net assimilation rate showed non-significant or comparatively weaker genotypic differences, indicating the need for a larger, replicated trial to fully resolve genotype effects for these traits (**Table 1**).

Table 1. Analysis of variance (mean sum of squares) for germination, seedling, vegetative, reproductive, yield and physiological traits

Character	Blocks (df 4)	Treatments (df 52)	Checks (df 2)	Genotypes (df 49)	Checks vs Genotypes (df 1)	Error (df 8)
Germination percent (%)	533.956**	1138.45**	214.067*	510.637**	33750.08**	31.15
Shoot length (cm)	68.338*	56.169*	151.499**	51.486*	94.997*	15.435
Root length (cm)	25.827**	41.274*	18.394**	34.969**	62.969**	9.75
Seedling vigour index	1856420.34*	4682634.95**	1245890.394	3978541.72**	24856732.318**	512348.85
Plant height at tillering (cm)	107.822	538.061**	138.042	472.042**	4573.021**	73.924
Total tillers at tillering	1.003	7.662*	13.241*	7.47*	5.925	1.573
Total dry matter at tillering (g/plant)	3.002	12.279*	0.535	12.88*	6.325	3.087
Days to 50% flowering	42.677	89.08**	365.6**	43.87*	1751.335**	12.517
Plant height at flowering (cm)	244.33**	482.808**	708.193**	477.593**	287.578**	18.939
Total dry matter at flowering (g/plant)	142.326**	117.231**	425.765**	95.997**	540.676**	6.575
Panicle length (cm)	22.336**	14.428**	146.558**	8.608**	35.337**	1.626
Number of panicles per m ²	1649.823*	6980.648**	12092.067**	6829.013**	4187.923**	371.65
Filled grains per panicle	1471.746**	709.37**	2628.067**	592.362**	2605.393**	35.65
Spikelet fertility (%)	15.759*	22.727**	87.304**	18.899*	81.154**	3.884
Plant height at harvesting (cm)	518.99**	648.132**	469.95**	661.627**	343.224**	12.69
Total dry matter at harvest-ing (g/plant)	233.674**	147.457**	944.04**	107.627**	505.921**	10.565
Productive tillers at maturity	2.412*	5.644**	16.781**	5.206**	4.852*	0.735
Test weight (g)	40.306**	18.052**	17.679**	10.218*	12.466**	3.372
Grain yield per plant (g)	34.366**	26.099**	21.807**	18.316**	70.076*	9.169
Straw yield per plant (g)	22.107**	20.417**	18.597**	19.578**	28.168**	5.436
Harvest index (%)	41.33**	27.198**	34.447**	26.186**	49.286**	13.986
Relative water content (%)	63.872	136.337**	259.066**	133.671**	25.509**	20.124
Net assimilation rate	1.003	0.594	0.391	0.611	0.193	0.273
Photosynthetic rate	35.17	19.196	6.354	19.845	28.676	22.92
Transpiration rate (mmol)	0.769	0.614	0.772	0.62	0.002	0.747

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Stomatal conductance (mol)	0.005	0.062**	0.044*	0.069**	0.095**	0.010
Leaf area index	0.09	0.86*	0.62*	0.91**	1.25**	0.088
Absolute growth rate (g/day)	0.12	6.829*	10.839*	6.805*	2.14**	2.07
Relative growth rate (g/g/day)	0.00012	0.00036*	0.00041**	0.00031*	0.00021*	0.00005
Specific leaf weight (mg/cm ²)	0.0006	0.0058**	0.0041*	0.0062**	0.0084**	0.0008
Specific leaf area (sq cm/g)	566.104**	263.506**	346.564**	247.792**	867.409**	1.417

*Significant at $p < 0.05$; **Significant at $p < 0.01$.

3.2 Mean performance and range of variability

A wide range of expression was recorded for most characters, indicating substantial diversity in the test material (Table 2). Seedling vigour index (2030.74–8550.50), grain yield per plant (12.78–29.52 g) and filled grains per panicle (48.80–148.80) showed particularly wide ranges. Coefficients of variation were comparatively high for

seedling-stage traits (germination percent, seedling vigour index, root length) and for physiological traits (photosynthetic rate, net assimilation rate, transpiration rate), pointing to considerable scope for selection at the seedling and physiological-trait level – an outcome of particular relevance for early-stage screening under dry direct-seeded rice (DSR).

Table 2. Mean, range, standard error and coefficient of variation for 31 characters ($n = 53$ genotypes)

Sr no	Character	Mean	Minimum	Maximum	S.E.±	C.V. (%)
1	Days to 50% flowering	90.42	72.00	107.47	1.58	4.01
2	Germination percent (%)	63.92	45.00	100.00	2.50	10.75
3	Shoot length (cm)	41.85	29.00	60.00	1.76	9.28
4	Root length (cm)	18.50	11.03	27.79	1.08	12.03
5	Seedling vigour index	3893.53	2030.74	8550.50	282.94	11.76
6	Plant height at tillering (cm)	70.04	28.53	110.13	3.85	12.91
7	Plant height at flowering (cm)	94.00	44.45	129.31	1.95	6.51
8	Plant height at harvesting (cm)	111.65	63.30	162.77	1.59	4.22
9	Relative water content (%)	80.61	47.76	98.81	1.34	5.58
10	Leaf area index	3.78	1.08	5.60	0.046	12.01
11	Net assimilation rate (g/cm ² /day)	0.0341	0.0114	0.0881	0.003	5.26
12	Absolute growth rate (g/day)	0.85	0.25	1.37	0.05	11.89
13	Relative growth rate (g/g/day)	0.0194	0.0110	0.0329	0.001	7.17
14	Total dry matter at tillering (g)	13.18	4.51	22.15	0.79	13.46
15	Total dry matter at flowering (g)	35.62	20.23	64.20	1.15	7.45
16	Total dry matter at harvesting (g)	61.17	39.11	85.67	1.45	5.42
17	Panicle length (cm)	22.09	14.54	27.84	0.57	5.85
18	No. of panicles/m ²	304.24	155	515	8.62	6.41
19	Filled grains/panicle	98.29	48.80	148.80	2.67	8.92
20	Spikelet fertility (%)	85.22	66.29	91.78	0.88	5.33
21	Test weight (g)	22.86	12.87	28.96	0.82	8.05
22	Maximum tillers	11.03	6.51	17.71	0.56	11.24
23	Total productive tillers	8.77	3.69	15.5	0.38	9.64
24	Grain yield/plant (g)	20.34	12.78	29.52	1.35	6.93
25	Straw yield/plant (g)	27.74	18.38	35.60	1.04	5.48
26	Harvest index (%)	42.04	31.12	48.46	1.67	4.86
27	Specific leaf weight (g)	4.79	4.03	5.68	0.07	14.37
28	Specific leaf area (cm ² /g)	206.18	173.91	281.83	0.53	8.55
29	Transpiration rate (mmol H ₂ O m ⁻² s ⁻¹).	3.81	0.16	10.59	1.04	14.85
30	Stomatal conductance (mol H ₂ O m ⁻² s ⁻¹)	0.405	0.191	0.697	0.01	12.55
31	Photosynthetic rate (μmol CO ₂ m ⁻² s ⁻¹).	18.25	7.43	28.86	0.56	17.22

(continued on next page)

3.3 Genetic parameters of variability

Table 3. Estimates of genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), broad-sense heritability, genetic advance (GA) and genetic advance as per cent of mean (GAM)

Character	GCV (%)	PCV (%)	h ² broad sense (%)	GA	GAM (%)
Days to 50% flowering (D50)	6.343	7.503	71.47	9.751	11.046
Plant height at tillering (PHT)	29.97	32.64	84.34	37.748	56.70
Plant height at flowering (PHF)	22.57	23.04	96.03	43.234	45.57
Plant height at harvesting (PHH)	23.01	23.24	98.08	51.971	46.95
Germination percent (GP)	42.17	43.51	93.90	43.711	84.171
Shoot length (SL)	14.18	16.94	70.02	10.35	24.441
Root length (RL)	16.75	19.04	74.95	4.206	28.68
Seedling vigour index (SVI)	42.65	46.07	86.01	1750.01	78.851
Relative water content (RWC)	13.26	14.38	84.95	20.231	25.171
Filled grains/panicle (FG)	23.38	24.12	93.98	47.12	46.696
Harvest index (HI)	8.21	10.94	63.51	2.70	9.812
Total tillers at tillering (TTT)	21.76	24.49	78.94	4.444	39.827
Productive tillers (TT)	23.79	25.67	85.55	4.037	45.416
No. of panicles/m ² (NPM2)	26.70	27.46	94.56	230.969	53.492
Panicle length (PL)	12.13	14.47	81.12	4.902	22.503
Test weight (TW)	11.47	14.01	67.00	4.412	19.336
Grain yield per plant (GY)	15.19	21.49	49.94	4.403	22.111
Straw yield per plant (SY)	11.56	14.33	65.11	5.294	19.214
Net assimilation rate (NAR)	24.6	29.81	68.37	2.891	39.976
Total dry matter tillering (TDMT/P)	23.98	27.50	76.03	5.621	43.069
Total dry matter flowering (TDMF/P)	27.46	28.46	93.15	18.801	54.603
Total dry matter harvesting (TDMH/P)	16.42	17.29	90.18	19.273	32.114
Leaf area index (LAI)	14.78	18.13	66.54	0.90	23.518
Absolute growth rate (AGR)	25.56	30.64	69.59	3.739	43.92
Relative growth rate (RGR)	24.63	30.03	67.3	41.008	41.632
Specific leaf weight (SLW)	9.80	12.38	60.66	3.20	18.66
Specific leaf area (SLA)	7.558	7.579	99.43	32.242	15.524
Photosynthetic rate (PR)	13.60	16.40	69.55	3.88	27.51
Transpiration rate (TR)	11.21	15.86	56.20	0.80	21.55
Stomatal conductance (SC)	13.87	16.87	55.80	0.07	15.306
Spikelet fertility (SF)	4.572	7.129	29.45	2.11	8.394

High GCV, PCV and heritability coupled with high genetic advance as per cent of mean (GAM) were recorded for seedling vigour index, specific leaf area and germination percent, indicating that these traits are governed largely by additive gene action and are reliable for early-stage selection under dry DSR (Table 3; Fig. 1). Plant height at the three growth stages, filled grains per panicle and number of panicles per m² also combined high heritability with moderate-to-high genetic advance. In contrast, harvest index, transpiration rate, photosynthetic rate and stomatal conductance showed low estimates of heritability along with a comparatively wider gap between PCV and GCV, suggesting greater environmental influence and the need for replicated evaluation before these traits can be used as direct selection criteria.

3.4 Correlation studies

Correlation analysis was carried out to detect the association of genotype performance with grain yield through the physiological and root/seedling traits with yield.

Table 4. Phenotypic and genotypic correlation of physiological traits

Physiological trait	with grain yield per plant (GY)	
	Phenotypic r with GY	Genotypic r with GY
Stomatal Conductance (SC)	0.614**	0.552**
Transpiration Rate (TR)	0.476**	0.522**
Absolute Growth Rate (AGR)	0.331**	0.280**
Net Assimilation Rate (NAR)	0.268**	0.377**
Photosynthetic Rate (PR)	0.162**	0.290**
Leaf Area Index (LAI)	0.180**	0.125*
Relative Water Content (RWC)	0.125*	0.143**
Specific Leaf Area (SLA)	-0.083	-0.080

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Seedling Vigour Index (SVI)	0.057	0.049
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Stomatal conductance and transpiration rate emerged as the strongest physiological correlates of grain yield at both the phenotypic and genotypic levels, exceeding even photosynthetic rate itself, followed by absolute growth rate and net assimilation rate (Table 4; Fig. 2). Specific leaf area and seedling vigour index showed negligible or negative association with grain yield at the whole-trial level.

Table 5. Correlation of seedling and root traits with grain yield (GY) and straw yield (SY) ($n = 65$ genotypes)

Seedling / root trait	r with Grain Yield	r with Straw Yield
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Germination % (GP)	0.300*	0.350*
Root Length (RL)	0.720**	0.290*
Shoot Length (SL)	0.200	0.650**
Seedling Vigour Index (SVI)	0.550**	0.600**

Root length ($r = 0.720^{**}$) and seedling vigour index ($r = 0.550^{**}$) showed strong, statistically significant positive correlation with grain yield, indicating that seedling-stage root vigour is closely linked with final productivity and can be used as an early, non-destructive selection criterion under dry DSR conditions (Table 5).

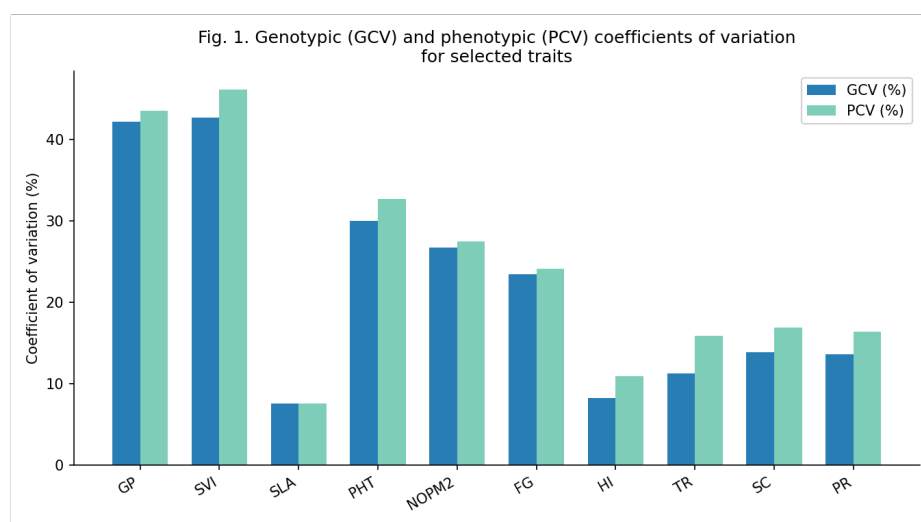


Figure 1. Genotypic (GCV) and phenotypic (PCV) coefficients of variation for selected traits with high estimates.

The complete pairwise correlation matrices among all physiological, seedling and root traits, from which Tables 4 and 5 above were de-

rived, are presented in full as Tables 6–8.

Table 6. Phenotypic correlation coefficients among seedling/root, physiological traits and grain yield per plant (GY) (*n* = 65 genotypes)

Trait	SVI	RFW	RDW	SFW	SDW	RWC	NAR	PR	TR	SC	LC	LAI	AGR	RGR	SLA	GY
SVI	SVI	1.000	0.079	0.057	0.155**	-0.217**	-0.164**	-0.007	-0.335**	0.041	0.237**	0.070	0.190**	0.087	0.035	0.534**
RFW	RFW		1.000	0.980**	0.745**	0.195**	-0.177**	0.052	-0.156**	0.150**	0.119*	-0.242**	0.054	0.266**	-0.262**	0.172**
RDW	RDW	-		1.000	0.728**	0.188**	-0.156**	0.032	-0.163**	0.142**	0.080	-0.232**	0.012	0.259**	-0.213**	0.179**
SFW	SFW	-	-		1.000	0.660**	-0.200**	0.091	-0.150**	0.175**	0.036	-0.212**	0.001	0.248**	-0.432**	0.114*
SDW	SDW	-	-	-		1.000	0.003	-0.007	0.000	0.076	-0.267**	-0.171**	-0.152**	0.159**	-0.428**	-0.089
RWC	RWC	-	-	-	-		1.000	0.140**	0.179**	-0.077	0.145**	0.394**	0.236**	-0.232**	0.123*	0.086
NAR	NAR	-	-	-	-	-		1.000	-0.173**	0.075	0.159**	-0.165**	-0.043	-0.077	0.192**	0.004
PR	PR	-	-	-	-	-	-		1.000	0.080	-0.169**	-0.058	-0.156**	0.127*	0.145**	-0.492**
TR	TR	-	-	-	-	-	-	-		1.000	0.159**	0.137**	-0.021	0.200**	0.004	-0.194**
SC	SC	-	-	-	-	-	-	-	-		1.000	0.073	0.216**	0.112*	0.182**	0.112*
LC	LC	-	-	-	-	-	-	-	-	-		1.000	0.323**	0.135*	-0.099	-0.004
LAI	LAI	-	-	-	-	-	-	-	-	-	-		1.000	-0.202**	0.204**	0.107*
AGR	AGR	-	-	-	-	-	-	-	-	-	-	-		1.000	-0.479**	-0.207**
RGR	RGR	-	-	-	-	-	-	-	-	-	-	-	-		1.000	-0.077
SLA	SLA	-	-	-	-	-	-	-	-	-	-	-	-	-		1.000
GY	GY	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

Note: The correlation matrix is symmetric; values below the diagonal are omitted (-). * Significant at *p* < 0.05; ** significant at *p* < 0.01 (two-tailed test); *n* = 65 genotypes.

Note: The correlation matrix is symmetric; values below the diagonal (two-tailed test); $n = 65$ genotypes. are omitted (-). * Significant at $p < 0.05$; ** significant at $p < 0.01$

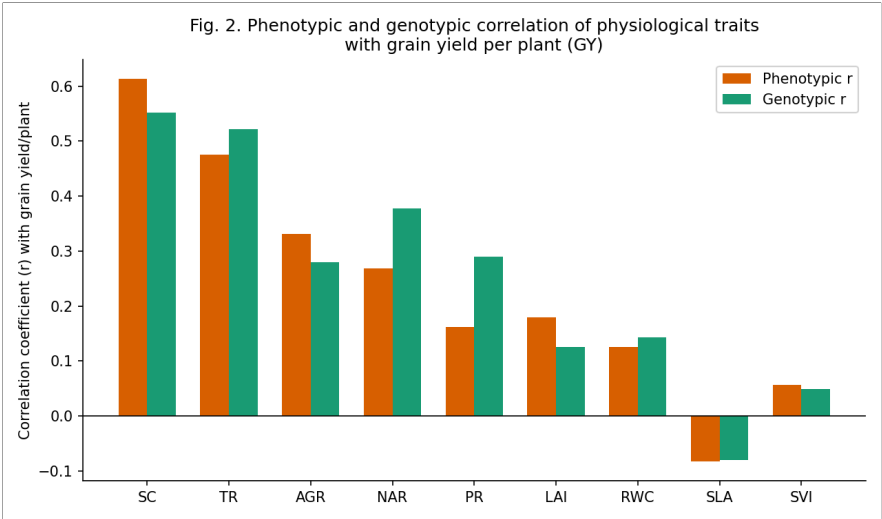


Figure 2. Phenotypic and genotypic correlation of physiological traits with grain yield per plant (GY).

Table 7. Genotypic correlation coefficients among seedling/root, physiological traits and grain yield per plant (GY) (n = 65 genotypes)

Trait	SVI	RFW	RDW	SFW	SDW	RWC	NAR	PR	TR	SC	LC	LAI	AGR	RGR	SLA	GY
SVI	SVI	1.000	-0.017	-0.039	0.143**	-0.128*	-0.127*	-0.069	-0.334**	0.046	0.294**	0.137**	0.186**	0.151**	-0.119*	0.328**
RFW	RFW		1.000	0.963**	0.576**	0.171**	-0.011	0.051	-0.015	0.053	0.038	-0.286**	0.027	0.093	-0.176**	0.206**
RDW	RDW	-		1.000	0.490**	0.073	0.016	-0.029	-0.023	0.012	0.017	-0.257**	0.007	0.082	-0.036	0.153**
SFW	SFW	-	-		1.000	0.748**	-0.072	0.069	0.049	0.154**	-0.005	-0.267**	0.045	-0.006	-0.409**	0.117*
SDW	SDW	-	-	-		1.000	-0.014	0.056	0.092	0.185**	-0.277**	-0.213**	-0.075	0.009	-0.431**	0.013
RWC	RWC	-	-	-	-		1.000	0.058	0.165**	-0.133*	0.162**	0.433**	0.310**	-0.187**	0.022	0.102
NAR	NAR	-	-	-	-	-		1.000	-0.144**	0.336**	0.166**	-0.260**	-0.106*	-0.116*	0.123*	0.139**
PR	PR	-	-	-	-	-	-		1.000	0.032	-0.146**	-0.009	-0.189**	0.278**	0.092	-0.466**
TR	TR	-	-	-	-	-	-	-		1.000	0.095	0.054	-0.155**	0.161**	-0.070	-0.027
SC	SC	-	-	-	-	-	-	-	-		1.000	0.043	0.121*	0.103	0.143**	0.116*
LC	LC	-	-	-	-	-	-	-	-	-		1.000	0.394**	0.105*	-0.104*	-0.018
LAI	LAI	-	-	-	-	-	-	-	-	-	-		1.000	-0.205**	0.197**	-0.011
AGR	AGR	-	-	-	-	-	-	-	-	-	-	-		1.000	-0.374**	-0.272**
RGR	RGR	-	-	-	-	-	-	-	-	-	-	-	-		1.000	-0.232**
SLA	SLA	-	-	-	-	-	-	-	-	-	-	-	-	-		1.000
GY	GY	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

Table 8. Correlation coefficients (r) among physiological, growth-analysis and root traits and grain yield (GY) (n = 65 genotypes; df = 63)

Trait	NAR	TDMT/P	TDMF/P	TDMH/P	PR(OUT)	TR	SC	LC	LAI	AGR	RGR	SLW (g/cm ²)	SLA (cm ² /g)	GY
NAR	NAR													
TDMT/P	TDMT/P	1.000	0.429**	0.242	0.373**	0.345**	0.468**	0.439**	0.347**	0.273*	0.636**	0.691**	-0.032	0.705**
TDMF/P	TDMF/P	0.429**	1.000	0.845**	0.832**	0.823**	0.833**	0.709**	0.855**	0.866**	0.863**	0.842**	0.368**	0.837**
TDMH/P	TDMH/P	0.242	0.845**	1.000	0.941**	0.821**	0.721**	0.641**	0.788**	0.925**	0.770**	0.616**	0.591**	0.758**
PR(OUT)	PR(OUT)	0.373**	0.832**	0.941**	1.000	0.750**	0.703**	0.565**	0.773**	0.881**	0.897**	0.698**	0.571**	0.768**
TR	TR	0.345**	0.823**	0.821**	0.750**	1.000	0.803**	0.796**	0.862**	0.762**	0.709**	0.716**	0.504**	0.822**
SC	SC	0.468**	0.833**	0.721**	0.703**	0.803**	1.000	0.875**	0.749**	0.773**	0.763**	0.814**	0.399**	0.805**
LC	LC	0.439**	0.709**	0.641**	0.565**	0.796**	0.875**	1.000	0.685**	0.637**	0.594**	0.660**	0.305*	0.765**
LAI	LAI	0.347**	0.855**	0.788**	0.773**	0.862**	0.749**	0.685**	1.000	0.708**	0.781**	0.761**	0.401**	0.832**
AGR	AGR	0.273*	0.866**	0.925**	0.881**	0.762**	0.773**	0.708**	0.708**	1.000	0.779**	0.693**	0.548**	0.708**
RGR	RGR	0.636**	0.863**	0.770**	0.897**	0.709**	0.763**	0.594**	0.781**	0.779**	1.000	0.907**	0.420**	0.850**
SLW (g/cm ²)	SLW (g/cm ²)	0.691**	0.842**	0.616**	0.698**	0.716**	0.814**	0.660**	0.761**	0.693**	0.907**	1.000	0.279*	0.860**
SLA (cm ² /g)	SLA (cm ² /g)	-0.032	0.368**	0.591**	0.571**	0.504**	0.399**	0.305*	0.401**	0.548**	0.420**	0.279*	1.000	0.360**
GY	GY	0.705**	0.837**	0.758**	0.768**	0.822**	0.805**	0.765**	0.832**	0.708**	0.850**	0.860**	0.360**	1.000
		0.228	0.863**	0.811**	0.776**	0.846**	0.830**	0.663**	0.853**	0.812**	0.744**	0.729**	0.607**	0.728**

Note: * Significant at $p < 0.05$; ** significant at $p < 0.01$ (two-tailed test).

3.5 Path coefficient analysis

Table 10. Direct effects of physiological traits on grain yield per plant (phenotypic and genotypic path analysis)

Physiological trait	Direct effect on GY – Phenotypic	Direct effect on GY – Genotypic
Seedling Vigour Index (SVI)	-0.0441	0.1383
Relative Water Content (RWC)	-0.1197	-0.2761
Net Assimilation Rate (NAR)	0.2679	0.3704
Photosynthetic Rate (PR)	0.3605	0.6581
Transpiration Rate (TR)	0.2848	0.3277
Stomatal Conductance (SC)	0.5679	0.6954

Leaf Area Index (LAI)	0.1267	0.3541
Absolute Growth Rate (AGR)	0.1753	-0.1505
Relative Growth Rate (RGR)	0.0790	-0.2823
Specific Leaf Area (SLA)	0.1674	-0.0034

Path analysis confirmed that stomatal conductance, transpiration rate and net assimilation rate exerted high positive direct effects on grain yield at both the phenotypic and genotypic levels, in agreement with their high positive correlation with yield, establishing them as reliable physiological selection markers under dry direct-seeded conditions (Table 10; Fig. 3). Photosynthetic rate also showed a sizeable positive direct effect, particularly at the genotypic level. Relative water content exerted a negative direct effect despite showing a positive simple correlation with yield in some cases, indicating that its influence on grain yield is largely indirect, mediated through other component traits.

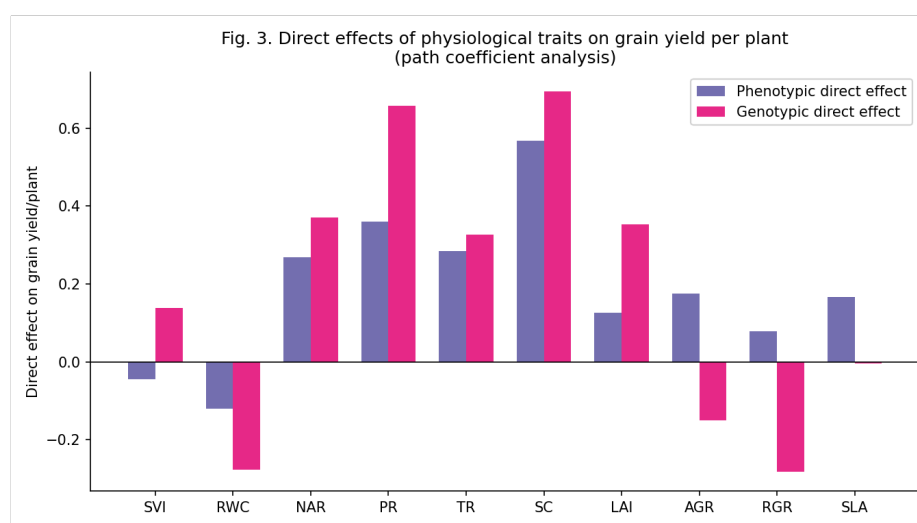


Figure 3. Direct effects (path coefficients) of physiological traits on grain yield per plant.

3.6 Identification of promising genotypes

Table 9. Genotypes combining high root vigour with high grain yield

Genotype	Root length (cm)	Seedling vigour index	Grain yield/plant (g)	Verdict
HSAL 428	27.79 (highest)	High	28.80	Best combined root vigour + yield
G-230	27.00	High	28.95	Strong alternative - best SVI
G-72	26.63	High	27.99	Also strong on germination + root traits
G-61	26.61	Moderate-high	28.92	Best on yield-side, solid root length

Table 9 highlights genotypes that combined superior seedling-stage root vigour with high final grain yield, reinforcing the value of root

length and seedling vigour index as early, non-destructive selection criteria under dry DSR.

Table 11. Best-performing genotypes ranked on grain yield per plant and cross-checked against key yield-associated traits

Genotype	Grain yield/plant (g)	Supporting traits	Remarks
HSAL 428	29.52 (highest)	High HI (48.81), high TR (3.29)	Top-ranking overall; strong harvest index and transpiration efficiency
HSAL 412	29.39	Consistently high across seedling & yield traits	Second-highest grain yield

(continued on next page)

G-230	28.95	High germination % (100), high SVI (8550.5)	Strong seedling establishment plus high yield
G-61	28.77 / 28.92*	Highest FG/panicle (147), highest AGR (13.64-14.63), high PR (28.29)	Best combination of yield components and physiological traits
G-72	27.99	Highest SC (0.67), high AGR, high germination % (100)	Strong stomatal conductance linked to yield
G-203	27.35	High germination % (100), high HI (48.08), high spikelet fertility (90.98)	Balanced performer across reproductive traits
G-34	25.72	High FG/panicle (138-139.8), high AGR (14.28), high RGR	Strong yield-component genotype
G-154	25.05	High D50 duration (105 days), high SY (33.84)	Higher-duration but high straw and grain yield

Genotypes HSAL 428, HSAL 412, G-230, G-61, G-72 and G-203 combined high grain yield with favourable expression of harvest index, filled grains per panicle, stomatal conductance, transpiration rate and absolute growth rate (Table 11), and are recommended as promising selections for further evaluation and use in the dry-DSR breeding programme.

Conclusion

Association analysis identified **root length and seedling vigour index as important early-stage traits associated with grain yield**, with root length showing a strong positive correlation with grain yield ($r = 0.720$). Among the physiological traits, **stomatal conductance and transpiration rate showed the strongest positive associations with grain yield at both phenotypic and genotypic levels**, while net assimilation rate, photosynthetic rate and absolute growth rate also contributed positively. Path coefficient analysis further highlighted **stomatal conductance as an important direct contributor to grain yield**, supporting its potential value as a physiological selection criterion under the conditions of the present study.

Based on superior grain yield combined with favourable seedling, root, physiological and yield-associated traits, **HSAL 428, HSAL 412, G-230, G-61, G-72 and G-203** were identified as promising genotypes. Among these, HSAL 428 recorded the highest grain yield (**29.52 g plant⁻¹**), while G-230 combined high grain yield with 100% germination and high seedling vigour; G-72 exhibited high stomatal conductance along with high grain yield; and G-61 showed a favourable combination of yield components and physiological performance.

Overall, the findings indicate that an integrated selection approach combining early establishment traits, root characteristics and physiological attributes can facilitate the identification of rice genotypes with potential suitability for dry DSR. The identified promising genotypes constitute valuable genetic material for further breeding and physiological studies aimed at improving DSR adaptation. Nevertheless, their performance and stability should be validated across multiple seasons, locations and moisture regimes before their

suitability for dry DSR is confirmed for broader breeding or varietal development.

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