Research Article

Multivariate Analysis in Detecting the Selection Criteria for Rice Breeding Under a Direct Seeding System

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Abstract | Rice is an essential energy source, consumed by about 90% of the world, especially in Asia. The objective of the present experiment was to study the different yields and related traits in rice under different establishment conditions and to identify the key traits that could be helpful in these conditions. The present experiment consisted of 26 genotypes under RCBD with three replications. This experiment used correlation, path analysis, and principal component analysis. Under both establishment conditions, grain yield per plant showed a significant positive correlation with plant height, panicle length, number of panicles, panicle weight, grain weight per panicle, number of grains per panicle, and spikelet fertility. In addition, under the transplanted conditions, grain yield per plant significantly correlated with flag leaf length and flag leaf area. In contrast, in dry direct seeding, it positively correlated with days to heading. Path analysis revealed that several traits directly affected grain yield at both genotypic and phenotypic levels. Additionally, some traits contributed indirectly and still significantly influenced grain yield. PCA grouped the genotypes into four major components, which accounted for most of the variation. This study revealed that, compared to transplanted rice, dry direct-seeded rice can be effectively used by leveraging the correlation and the direct and indirect effects of traits under direct-seeded conditions. Finding characteristics strongly linked with rice yield may help to create new rice varieties that are directly seeded and adapted.

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Introduction

Rice (*Oryza sativa L.*), which supplies 19% of the calories worldwide, is consumed by approximately 90 percent of the world's population, particularly in Asia (Jukanti *et al.*, 2025). It plays a crucial role in global food security and livelihood, and is a rich source of amino acids and other components (Maganti *et al.*, 2020). However climate change poses increasing threats to rice production especially coastal regions, which faces wetland loss, increased storm damage, and salinity rise owing to seawater influence since they are essential irrigation zones for rice farming (Fahad *et al*., 2019; Anshori *et al*., 2025). Currently, wetlands produce more than 70% of the world's rice, which is puddled and then transplanted (Chakraborty *et al*., 2017). To produce 1 kilogram of rough rice in a traditional transplanted rice (TPR) system, roughly 2500 litres of water are needed (Bwire *et al*., 2021). The most common technique for establishing rice in those places is transplanting. Due to the rising scarcity of these resources, these labour- and water-intensive activities are becoming less lucrative (Nawaz *et al*., 2022). Considering the urgent need to reduce expenses and boost yield efficiency, alternative production systems such as dry direct-seeded rice (DSR) have drawn the attention of researchers. Through labour and water constraints, dry direct-seeded rice (DSR) has become a viable alternative establishment technique (Saha *et al*., 2021). DSR offers several benefits, including integrating rice farming with other cropping systems and reducing early crop methane emissions from fields. However, a significant disadvantage of DSR is its lower yield when compared to TPR (Sagare *et al*., 2020). This highlights the need for continuing research efforts to optimize DSR procedures to boost yield and overcome productivity limits. DSR held 21 percent of Asia's rice-planting acreage at the start of the twenty-first century (Ramaiyan *et al*., 2023). The use of rice varieties mainly designed for irrigated circumstances in the direct seeded system has been blamed for the low production of DSR (Bandh *et al*., 2023). Plant species that are ecotypes or variations adapted for diverse ecologies differ significantly in their rhizosphere and aerial characteristics (Freschet *et al*., 2021). Therefore, there is an increasing need to produce rice types that are especially suited for direct-seeded ecologies to address this dilemma successfully. In support of this, Sarla and Swamy (2005) documented the value of *O. glaberrima* as a donor parent in Asian rice crop development, particularly for growth under challenging circumstances with limited resources. The creation of DSR cultivars must concentrate on characteristics that improve the capacity of rice plants to survive and produce when directly sown. It is also critical to understand that because yield characteristics are complex, using grain yield as the only selection criterion may result in genotypes performing inconsistently (Kephe *et al*., 2021).

Breeders have also promoted indirect selection for rice yield because of this trait's low heritability (Ashraf *et al*., 2024). Therefore, the suggestion to analyze correlations between yield and its component traits and then divide them into direct and indirect effects is a solid method for interpreting the relationships among those traits (Pushkarnath *et al*., 2022). Selection criteria are crucial in any breeding program because they help in the identification of the genotypes with desirable traits under specific environmental conditions. It helps the breeder screen genotypes for a particular trait under study conditions. This study adopted direct seeding instead of the conventional transplanting method because it is a labour and water-saving strategy. Under climate change conditions, this technique could be useful for both water conservation and environmental protection, as it reduces greenhouse gas emissions. The goals of this research were to assess the quantitative relationships among yield-attributing characteristics, evaluate the direct and indirect effects of these traits on yield, and use principal component analysis to identify traits contributing most to variation under transplanted and dry direct-seeded conditions and to determine the most effective way to develop a new variety for increased crop productivity and identify the best combinations to use as selection criteria to create genotypes of high-yielding rice that are appropriate for dry direct seeding.

Materials and Methods

Research design

During the rice-growing season of 2024, research material was grown in the research area of the Department of Plant Breeding and Genetics, Faculty of Agriculture and Environment, the Islamia University of Bahawalpur. The plant material consisted of 26 genotypes, evaluated under transplanted and dry direct-seeded conditions. The experiment followed a Randomized Complete Block Design (RCBD) with three repetitions. Distances between rows and plants were maintained at 20 cm and 10 cm during the transplanting and direct seeding. A healthy crop was maintained by adapting standard agronomic procedures, which were carried out until harvest. Plants were appropriately tagged to prevent errors in data collection.

Research procedure

The experimental field was prepared by dry ploughing with a tractor-drawn disc harrow, followed by cultivation, rotavating, and laser levelling for flawless levelling. The field was irrigated for Puddled Transplanted Rice (PTR), levelled with a wooden board, and puddled with a cage wheel. In contrast, Dry Direct-Seeded Rice (DSR) was sown using a zero-seed drill. Under transplanted conditions, 21-day-old seedlings of 26 genotypes were transplanted in late May, while three seeds of the same genotypes were directly sown, with excess plants removed after germination. Each line consisted of five plants with 20 cm spacing, with the central three plants used for yield measurements. NPK was applied at 120:60:60 kg/ha, and standard practices were followed for weed, insect, and disease management. Phenotypic data were collected on various traits, including days to heading (HD), days to maturity (DM), flag leaf length (FLL), flag leaf width (FLW), flag leaf area (FLA), plant height (PH), panicle length (PL), number of tillers (NT), number of panicle (NP), panicle weight (PW), grain weight per panicle (GW/P), number of grains per panicle (NG/P), spikelet fertility (SF), and grain yield per plant (YP). Correlation analysis helps identify optimal trait combinations for higher yield, while path analysis extends regression by examining complex models.

Table 1: *Analysis of variance of studied traits under transplanted condition*

Trait	Mean sum of square	F-value	Significance	
HD	128.24	26.43	0.000	***
DM	121.51	13.76	0.000	***
PH	397.51	7.03	0.000	***
PL	14.25	3.80	0.000	***
FLL	108.15	4.62	0.000	***
FLW	0.09	13.78	0.000	***
FLA	279.88	6.35	0.001	***
NT	11.26	2.00	0.010	*
NP	12.48	2.28	0.010	*
PW	3.54	1.69	1.000	NS
GW	1.08	4.78	0.000	***
NG	4516.60	5.42	0.000	***
SF	145.71	2.09	0.010	*
YP	152.03	1.95	1.000	NS

*Note: *** significant effect at 0.1% error level, **significant effect at 1% error level, * significant effect at 5% error level, NS: no significant, Days to heading (HD), Days to maturity (DM), flag leaf length (FLL), flag leaf width (FLW), Flag leaf area (FLA), Plant height (PH), Panicle length (PL), number of tillers per plant (NT), number of panicles per plant (NP), panicle weight (PW), Grain weight per panicle (GW/P), number of grains per panicle (NG/P), Spikelet fertility (SF), grain yield per plant (YP).*

Data analysis

Analysis of variance was performed by using R v 4.4.2 software. Linear mixed-effect models were fitted with the lmer function in the lme4v1.1-35 package. Treatment was specified as a fixed effect, and replication was treated as a random effect. Statistical analysis was performed for the correlation coefficient (Singh and Chaudhary, 1981). The protocol provided, used, and outlined by (Oladosu *et al*., 2018), is used for path analysis, direct and indirect effect were estimated from the correlation matrix with agricolae v1.3-8 using standardized partial regression coefficients During analysis grain yield was considered dependent variable while other traits were considered as independent variable.

Results and Discussion

Analysis of variance revealed that, in addition to panicle weight and grain yield per plant, all other studied traits revealed significant differences among the genotypes under the transplanted growing conditions. In dry direct-seeded conditions, all the studied characters showed significant differences among genotypes except flag leaf length, number

Table 2: *Analysis of variance of studied traits under dry direct seeded condition*

Trait	Mean sum of square	F-value	Significance	
HD	141.66	29.96	0.000	***
DM	123.06	22.40	0.000	***
PH	314.17	5.68	0.000	***
PL	10.49	4.33	0.000	***
FLL	94.92	1.77	1.000	NS
FLW	0.09	11.14	0.000	***
FLA	372.14	3.89	0.000	***
NT	9.95	1.30	1.000	NS
NP	12.51	1.32	1.000	NS
PW	1.97	5.89	0.000	***
GW	1.84	7.59	0.000	***
NG	5421.60	7.35	0.000	***
SF	430.47	3.98	0.000	***
YP	264.50	2.29	0.010	*

*Note: *** significant effect at 0.1% error level, **significant effect at 1% error level , * significant effect at 5% error level, NS: no significant, Days to heading (HD), Days to maturity (DM), flag leaf length (FLL), flag leaf width (FLW), Flag leaf area (FLA), Plant height (PH), Panicle length (PL), number of tillers per plant (NT), number of panicles per plant (NP), panicle weight (PW), Grain weight per panicle (GW/P), number of grains per panicle (NG/P), Spikelet fertility (SF), grain yield per plant (YP).*

Table 3: *Correlation coefficient genotypic (above the diagonal line) and phenotypic (below the diagonal line) under TRP*

	HD	DM	FLL	FLW	FLA	PH	PL	NT	NP	PW	GW/P	NG/P	SF	YP
HD		0.99**	0.63**	-0.08NS	0.34NS	0.71**	0.68**	0.24NS	0.29NS	0.82**	0.08NS	-0.03NS	0.44*	0.35NS
DM	0.97**		0.57**	-0.13NS	0.27NS	0.68**	0.68**	0.26NS	0.26NS	0.87**	0.04NS	-0.09NS	0.47*	0.34NS
FLL	0.52**	0.47**		0.24NS	0.79**	0.72**	0.53**	0.09NS	0.10NS	0.42*	0.37NS	0.27NS	0.41*	0.45*
FLW	-0.09NS	-0.13NS	0.22NS		0.78**	0.17NS	-0.27NS	-0.43*	-0.32NS	0.55**	0.62**	0.63**	0.06NS	0.27NS
FLA	0.29*	0.23NS	0.72**	0.73**		0.59**	0.17NS	-0.21NS	-0.14NS	0.64**	0.66**	0.61**	0.29NS	0.47*
PH	0.61**	0.58**	0.70**	0.22NS	0.62**		0.77**	0.14NS	0.21NS	0.91**	0.62**	0.42*	0.45*	0.77**
PL	0.51**	0.52**	0.57**	-0.10NS	0.33*	0.74**		0.51**	0.55**	0.51**	0.06NS	-0.04NS	0.16NS	0.53**
NT	0.16NS	0.18NS	0.16NS	-0.25NS	-0.02NS	0.18NS	0.56**		0.89 **	-0.26NS	-0.31NS	-0.15NS	-0.23NS	0.47*
NP	0.19NS	0.20NS	0.21NS	-0.22NS	0.03NS	0.20NS	0.56**	0.96**		-0.16NS	-0.23NS	-0.12NS	-0.13NS	0.51 **
PW	0.40**	0.39**	0.26NS	0.29*	0.36**	0.40**	0.24NS	0.04 NS	-0.001NS		0.95**	0.69**	0.42 **	0.74 **
GW/P	0.11NS	0.11NS	0.39**	0.52**	0.60**	0.64**	0.31*	0.10NS	0.08NS	0.51**		0.90**	0.48*	0.70**
NG/P	-0.02NS	-0.04NS	0.38**	0.54**	0.60**	0.49**	0.24NS	0.14NS	0.14NS	0.37**	0.84**		0.03NS	0.63 **
SF	0.31*	0.32*	0.08NS	0.03NS	0.06NS	0.28*	0.04NS	-0.18NS	-0.24NS	0.17NS	0.26NS	-0.12NS	1 **	0.45*
YP	0.26NS	0.27*	0.44**	0.15NS	0.42**	0.56**	0.60**	0.74**	0.75**	0.32*	0.68**	0.62 **	0.02NS	1 **

*Note: **significant correlated at 1% error level, * significant correlated at 5% error level, the results with NS are non-significant, Days to heading (HD), Days to maturity (DM), flag leaf length (FLL), flag leaf width (FLW), Flag leaf area (FLA), Plant height (PH), Panicle length (PL), number of tillers per plant (NT), number of panicles per plant (NP), panicle weight (PW), Grain weight per panicle (GW/P), number of grains per panicle (NG/P), Spikelet fertility (SF), grain yield per plant (YP)*

Table 4: *Genotypic and phenotypic direct and indirect effects of studied traits under transplanted condition*

		HD	DM	FLL	FLW	FLA	PH	PL	NT	NP	PW	GW/P	NG/P	SF
HD	G	-4.44822	3.87793	-1.55784	0.21787	1.53150	0.85965	-0.50445	0.32855	-0.10850	0.13563	0.02135	0.01415	-0.00795
	P	-0.25486	0.31678	-0.64327	0.10547	0.55926	-0.06392	0.04446	-0.02045	0.14946	-0.01284	0.06187	-0.00113	0.02165
DM	G	-4.44311	3.8824	-1.39579	0.3248	1.22281	0.82634	-0.50694	0.35825	-0.10915	0.14392	0.01236	0.03575	-0.00851
	P	-0.24933	0.32381	-0.57447	0.14745	0.43907	-0.06059	0.04474	-0.02269	0.15876	-0.01239	0.06187	-0.00207	0.02294
FLL	G	-2.83205	2.21467	-2.44686	-0.61025	3.51144	0.87359	-0.39654	0.12693	-0.04282	0.07049	0.09529	-0.10087	-0.00735
	P	-0.13416	0.15222	-1.22201	-0.24365	1.54928	-0.07271	0.04893	-0.02064	0.16753	-0.00826	0.20555	0.01845	0.00587
FLW	G	0.39522	-0.51426	-0.60895	-2.4521	3.47614	0.21133	0.20656	-0.58366	0.13010	0.09080	0.15725	-0.22986	-0.00118
	P	0.02523	-0.04482	-0.27947	-1.05526	1.38984	-0.02300	-0.00909	0.03237	-0.17447	-0.00913	0.27327	0.02622	0.00220
FLA	G	-1.54175	1.07441	-1.94449	-1.92906	4.41863	0.71222	-0.12606	-0.29801	0.05923	0.10665	0.16580	-0.22222	-0.00524
	P	-0.07554	0.07535	-1.00339	-0.78476	1.88683	-0.06448	0.02903	0.00264	0.02448	-0.01140	0.31501	0.02935	0.00459
PH	G	-3.18288	2.67035	-1.77921	-0.43132	2.61946	1.20140	-0.57537	0.19365	-0.08715	0.15024	0.15627	-0.15412	-0.00819
	P	-0.15714	0.18927	-0.85712	-0.23641	1.17361	-0.10367	0.06401	-0.02350	0.15327	-0.01273	0.33587	0.02408	0.01986
PL	G	-3.0324	2.65971	-1.31122	0.68448	0.75271	0.93415	-0.73998	0.69343	-0.22469	0.08521	0.01728	0.01796	-0.00291
	P	-0.13237	0.16925	-0.69850	0.11314	0.63983	-0.07752	0.08561	-0.07053	0.43199	-0.00762	0.16444	0.01187	0.00002
NT	G	-1.07816	1.02608	-0.22912	1.05582	-0.97144	0.17163	-0.37855	1.35552	-0.41017	-0.04325	-0.07823	0.05534	0.00420
	P	-0.04182	0.05897	-0.20236	0.27679	-0.04000	-0.01955	0.04845	-0.12462	0.73723	0.00002	0.05385	0.00713	-0.01317
NP	G	-1.1871	1.04227	-0.2577	0.78469	-0.64371	0.25754	-0.40897	1.36756	-0.40656	-0.02689	-0.05783	0.04418	0.00246
	P	-0.04995	0.06742	-0.26848	0.24376	0.06057	-0.02084	0.04849	-0.12047	0.76255	0.00006	0.04328	0.00702	-0.01691
PW	G	-3.65617	3.38615	-1.04530	-1.34922	2.85585	1.09384	-0.38210	-0.35531	0.06625	0.16501	0.23985	-0.25270	-0.02221
	P	-0.10444	0.12807	-0.32212	-0.31045	0.68681	-0.04213	0.02081	0.00007	-0.00137	-0.03133	0.26737	0.01797	0.01224
GW/P	G	-0.37837	0.19121	-0.92892	-1.53624	2.91873	0.74796	-0.05093	-0.42246	0.09366	0.15768	0.25100	-0.32642	-0.00863
	P	-0.03046	0.0387	-0.48514	-0.56231	1.14795	-0.06725	0.02719	-0.01296	0.06375	-0.01618	0.51802	0.04083	0.01866
NG/P	G	0.17397	-0.38354	-0.68201	-1.55742	2.71322	0.51163	0.03673	-0.20729	0.04964	0.11522	0.22639	-0.36190	-0.00067
	P	0.00594	-0.01389	-0.46656	-0.57829	1.14644	-0.05168	0.02102	-0.01839	0.11087	-0.01165	0.43756	0.04831	-0.00898
SF	G	-1.97541	1.84499	-1.00421	-0.16135	1.29188	0.54917	-0.12013	-0.31819	0.05591	0.20466	0.12099	-0.01352	-0.01791
	P	-0.07929	0.10673	-0.10302	-0.03367	0.12434	-0.02958	0.00003	0.02358	-0.18530	-0.00551	0.13881	-0.00623	0.06960

Days to heading (HD), Days to maturity (DM), flag leaf length (FLL), flag leaf width (FLW), Flag leaf area (FLA), Plant height (PH), Panicle length (PL), number of tillers per plant (NT), number of panicles per plant (NP), panicle weight (PW), Grain weight per panicle (GW/P), number of grains per panicle (NG/P), Spikelet fertility (SF), grain yield per plant (YP) of tillers, and number of panicles. This means that substantial variance traits could be valuable for crop improvement. A detailed analysis of the ANOVA of the studied traits is presented in Tables 1 and Tables 2.

The genotypic and phenotypic correlation coefficient of yield and its link traits under transplanted conditions are presented in the Table 3. Grain yield per plant exhibited significant positive genotypic association with, flag leaf area (0.47*), plant height (0.77**), panicle length (0.53**), number of tillers (0.47*), number of panicles (0.51**), panicle weight (0.74**), grain weight per panicle (0.70**), number of grains per panicle (0.63**) and spikelet fertility (0.42*) and a significant positive phenotypic correlation with, flag leaf area (0.42*), plant height (0.56**), panicle length (0.60**), number of tillers (0.74**), number of panicles (0.75**), panicle weight (0.32*), grain weight per panicle (0.68**) and number of grains per panicle (0.62**). The genotypic and phenotypic path coefficient of the different studied traits is presented in Table 4. In path coefficient analysis, the direct effect refers to the immediate effect of independent traits on dependent traits, without mediation by any other trait. Direct effect quantifies the strength with which a trait independently contributes to yield. The indirect effect represents the influence of an independent trait of yield that is transmitted through its correlation with other traits. Path analysis revealed that direct genotypic positive effect under the transplanted condition was exhibited by days to maturity (3.8824), flag leaf area (4.41863), plant height (1.2014), number of tillers (1.35552), panicle weight (0.16501), and grain weight per panicle (0.2510). The positive direct effect of these traits indicates that direct selection of these positively affected traits could enhance the rice grain yield. In contrast, the genotypic direct negative effect was exhibited by days to heading (-4.44822), flag leaf length (-2.44686), flag leaf width (-1.05526), panicle length (-0.73998), number of panicles (-0.40656), number of grains per panicle (-0.3619) and spikelet fertility (-0.01791). While at the phenotypic level, direct positive effects were exposed by days to maturity (0.32381), flag leaf area (1.88683), panicle length (0.08561), number of panicles (0.76255), grain weight per panicle (0.51802), number of grains per panicle (0.04831) and spikelet fertility (0.0696). However, phenotypic negative direct effect was exhibited by days to heading (-0.25486), flag leaf length (-1.22201), flag leaf width (-1.05526), plant height (-0.10367), number of tillers (-0.12462), and panicle weight (-0.03133).

The genotypic and phenotypic correlation coefficients for yield and its related traits under dry direct-seeded conditions are presented in Table 5. Grain yield per plant exhibited a significant positive genotypic association with days to heading (0.22*), plant height (0.47**), panicle length (0.67**), number

Table 5: *Correlation coefficient genotypic (above the diagonal line) and phenotypic (below the diagonal line) under DSR*

	HD	DM	FLL	FLW	FLA	PH	PL	NT	NP	PW	GW/P	GN/P	SF	YP
HD		0.99**	0.12NS	0.06NS	0.77**	0.67**	0.23*	0.90**	0.08NS	0.10NS	0.10NS	-0.11NS	0.02NS	0.22*
DM	0.96**		0.13NS	0.87**	0.10NS	0.69**	0.26NS	0.88**	0.18NS	0.26*	0.16NS	-0.97**	0.01NS	0.31NS
FLL	0.01NS	0.06NS		0.49*	0.87**	0.41**	-0.18NS	-0.66**	-0.87**	0.40**	0.14NS	0.42*	-0.68**	-0.26NS
FLW	0.09NS	0.10NS	0.34*		0.84**	0.06NS	-0.18NS	-0.85**	-0.73**	0.40*	0.37NS	0.39*	-0.06NS	0.06NS
FLA	0.44**	0.85**	0.86**	0.75**		0.38**	-0.13NS	-0.94**	-0.80**	0.39*	0.34NS	0.49*	-0.36NS	-0.02NS
PH	0.56**	0.55**	0.37**	0.16NS	0.32**		0.21NS	-0.42*	-0.24NS	0.60**	0.57**	0.40*	0.19NS	0.47*
PL	0.18*	0.25NS	0.25NS	-0.03NS	0.16NS	0.30*		0.48**	0.50**	0.14NS	0.13NS	0.07NS	-0.34*	0.67**
NT	0.70**	0.80**	-0.40**	-0.18NS	-0.19NS	-0.006NS	0.38**		0.99**	-0.27NS	-0.18NS	-0.65**	-0.63**	0.03NS
NP	0.06NS	0.09NS	-0.16NS	-0.19NS	-0.21NS	0.002NS	0.38**	0.97**		-0.02NS	-0.05NS	0.02NS	-0.42*	0.29NS
PW	0.11NS	0.15NS	0.34**	0.37**	0.31*	0.53**	0.23NS	-0.04NS	-0.04 NS		0.99**	0.87**	0.62**	0.94**
GW/P	0.11NS	0.15NS	0.13NS	0.36**	0.29*	0.53**	0.21NS	-0.05NS	-0.009NS	0.99**		0.85**	0.66**	0.93**
NG/P	-0.06NS	-0.79**	0.26NS	0.38**	0.39**	0.37**	0.22NS	-0.44**	-0.01NS	0.85**	0.83**		0.23NS	0.76**
SF	0.10NS	0.06NS	-0.35**	0.02NS	-0.22NS	0.22NS	-0.16NS	-0.05NS	-0.01NS	0.54**	0.58**	0.25NS		0.51**
YP	0.17*	0.22NS	-0.02NS	0.12NS	0.05NS	0.38**	0.40**	0.62**	0.70**	0.67**	0.67**	0.55**	0.40**	

*Note: **significant correlated at 1% error level, * significant correlated at 5% error level, the results with NS are non-significant. Days to heading (HD), Days to maturity (DM), flag leaf length (FLL), flag leaf width (FLW), Flag leaf area (FLA), Plant height (PH), Panicle length (PL), number of tillers per plant (NT), number of panicles per plant (NP), panicle weight (PW), Grain weight per panicle (GW/P), number of grains per panicle (NG/P), Spikelet fertility (SF), grain yield per plant (YP).*

of panicles (0.70**), panicle weight (0.94**), grain weight per panicle (0.93**), number of grains per panicle (0.76**) and spikelet fertility (0.51*) and a significant positive phenotypic relation with days to heading (0.17*), plant height (0.38**), panicle length (0.40**), number of tillers (0.66**), number of panicles (0.62**), panicle weight (0.67**), grain weight per panicle (0.67**), number of grains per panicle (0.55**) and spikelet fertility (0.40**). This study found a positive association between plant height and grain yield per plant under direct-seeded conditions. In contrast, under transplanted conditions, a previous study reported a negative correlation of these traits (32). In a transplanted system, the transplanted shock and vegetative phase may shift assimilate partitioning towards the vegetative organ compared to dry-seed. So there is variation in the results correlation and direct and indirect effect of TRP and DSR could be possible. At the genotypic and phenotypic levels, Path coefficient analysis under dry direct seeded condition (Table 6) showed that the number of tillers (5.79812) had the highest genotypic positive direct effect on the yield per plant, followed by flag leaf area (5.61495), grain weight per panicle (3.19872), panicle length (2.39018) and plant height (1.32224). While at the phenotypic level, the highest positive direct effect was identified for the number of panicles (0.53615), followed by grain weight per panicle (0.51219), days to maturity (0.28841), flag leaf length (0.27495), and flag leaf width (0.22335). The negative direct effects at genotypic level were found in number of panicles (-7.26228), panicle weight (-3.74974), flag leaf width (-3.58881), number of grains per panicle (-3.157), days to heading (-1.96496), flag leaf length (-1.77121) and spikelet fertility (-1.16813). However, traits such as flag leaf area (-0.39857), days to heading (-0.24816), panicle length (-0.05446), and number of grains per panicle (-0.02566) exhibited an adverse direct effect at the phenotypic level.

Table 6: *Genotypic and phenotypic direct and indirect effect of study traits under direct seeded condition*

		HD	DM	FLL	FLW	FLA	PH	PL	NT	NP	PW	GW/P	NG/P	SF
HD	G	-1.96496	-0.03471	-0.21972	-0.23313	0.43246	0.89538	0.56590	0.56033	-0.64766	-3.15769	3.69160	0.37224	-0.03072
	P	-0.24816	0.27912	0.00465	0.02060	-0.01774	0.01337	-0.01001	0.01430	0.03512	0.01983	0.06014	0.00174	0.00355
DM	G	-1.94792	-0.03501	-0.24124	-0.31456	0.57014	0.92106	0.63813	1.05601	-1.37701	-5.06294	5.82075	0.30885	-0.02000
	P	-0.24017	0.28841	0.01765	0.02350	-0.03400	0.01306	-0.01379	0.01685	0.04954	0.02647	0.07760	0.00072	0.00225
FLL	G	-0.24375	-0.00477	-1.77121	-1.77398	4.92100	0.49662	-0.45036	-5.80728	6.35492	-6.39871	4.95276	-1.34567	0.80563
	P	-0.00419	0.01852	0.27495	0.07754	-0.34568	0.00984	-0.01395	-0.02714	-0.08905	0.02419	0.06767	-0.00688	-0.01261
FLW	G	-0.12764	-0.00307	-0.87553	-3.58881	4.84783	0.09075	-0.44608	-4.93681	5.32337	-12.39153	13.34335	-1.25314	0.07840
	P	-0.02276	0.03017	0.09489	0.22335	-0.30080	0.00381	0.00210	-0.03659	-0.10385	0.06216	0.18543	-0.00984	0.00103
FLA	G	-0.15134	-0.00355	-1.55231	-3.09851	5.61495	0.34813	-0.31773	-5.46543	5.81293	-12.27714	12.19659	-1.55627	0.42368
	P	-0.01104	0.02460	0.23847	0.16958	-0.39857	0.00904	-0.00882	-0.03847	-0.11490	0.05174	0.15198	-0.01022	-0.00799
PH	G	-1.33061	-0.02439	-0.66525	-0.24630	1.47836	1.32224	0.52405	-2.47823	1.80586	-18.66171	20.26511	-1.28812	-0.22270
	P	-0.14066	0.15978	0.11474	0.03633	-0.15273	0.02358	-0.01653	-0.00147	0.00155	0.08935	0.27195	-0.00958	0.00789
PL	G	-0.46522	-0.00935	0.33373	0.66978	-0.74639	0.28990	2.39018	8.61410	-10.93949	-4.54450	4.92144	-0.23924	0.39845
	P	-0.04561	0.07300	0.07042	-0.00867	-0.06453	0.00716	-0.05446	0.07442	0.20856	0.03993	0.11182	-0.00588	-0.00575
NT	G	-0.18989	-0.00638	1.77401	3.05569	-5.29276	-0.56515	3.55102	5.79812	-7.22350	8.32703	-10.13713	0.20719	0.73789
	P	-0.01836	0.02515	-0.03863	-0.04256	0.07936	-0.00018	-0.02098	0.19320	0.52226	-0.00742	-0.02807	0.00024	-0.00200
NP	G	-0.17523	-0.00664	1.54990	2.63063	-4.49432	-0.32879	3.60040	5.76710	-7.26228	0.62668	-2.02496	-0.08537	0.49607
	P	-0.01625	0.02665	-0.04567	-0.04352	0.08541	0.00007	-0.02119	0.18819	0.53615	0.00005	-0.00466	0.00002	-0.00064
PW	G	-0.20178	-0.00576	-0.36857	-1.44622	2.24182	0.80245	0.35324	-1.57013	0.14801	-3.74970	5.21843	-2.74693	-0.73217
	P	-0.02958	0.04589	0.03998	0.08395	-0.12395	0.01266	-0.01307	-0.00862	0.00016	0.16643	0.50758	-0.02193	0.01931
GW/P	G	-0.20608	-0.00579	-0.24923	-1.36048	1.94564	0.76127	0.33420	-1.66986	0.41780	-3.76726	3.19872	-2.68916	-0.77858
	P	-0.02913	0.04369	0.03632	0.08134	-0.11826	0.01252	-0.01189	-0.01059	-0.00488	0.16486	0.51219	-0.02153	0.02075
NG/P	G	0.23169	0.00342	-0.75498	-1.42454	2.76794	0.53950	0.18113	-0.38053	-0.19637	-6.75565	9.98232	-3.15700	-0.27048
	P	0.01680	-0.00805	0.07371	0.08613	-0.15875	0.00881	-0.01247	-0.00182	-0.00032	0.14219	0.42977	-0.02566	0.00897
SF	G	-0.05168	-0.00060	1.22157	0.24088	-2.03654	0.25208	-0.81529	-3.66262	3.08410	-19.27363	23.46042	-0.73100	-1.16813
	P	-0.02492	0.01834	-0.09810	0.00654	0.09016	0.00527	0.00886	-0.01093	-0.00970	0.09093	0.30073	-0.00651	0.03534

Note: Days to heading (HD), Days to maturity (DM), flag leaf length (FLL), flag leaf width (FLW), Flag leaf area (FLA), Plant height (PH), Panicle length (PL), number of tillers per plant (NT), number of panicles per plant (NP), panicle weight (PW), Grain weight per panicle (GW/P), number of grains per panicle (NG/P), Spikelet fertility (SF), grain yield per plant (YP).

Correlation analysis alone may not accurately explain yield formation due to the complex interrelationships among traits. Therefore, path analysis was used to assess the direct and indirect effects of traits on yield (Zeleke and Worede, 2021). Positive direct effects at both genotypic and phenotypic levels under transplanted and dry direct-seeded conditions were shown by days to maturity, flag leaf area, plant height, panicle length, number of tillers, number of panicles, panicle weight, grain weight per panicle, number of grains per panicle, and spikelet fertility, indicating that selecting genotypes with these traits would be effective. The varying effects of traits between conditions suggest growth condition dependency. Negative direct effects from traits like days to heading, flag leaf length, flag leaf width, flag leaf area, plant height, panicle length, number of tillers, number of panicles, panicle weight, number of grains per panicle, and spikelet fertility contributed to yield reduction, consistent with findings by (Kayastha *et al*., 2022; Pravamanjari *et al*., 2023; Atsedemariyam, 2018; Gewer *et al*., 2021).

Table 7: *Eigenvalues, variability, and proportion under the studied condition*

	Conditions	PC1	PC2	PC2	PC4
Eigenvalue	TRP	5.7221	3.1137	2.2301	1.0999
	DSR	4.74	3.3796	2.2419	1.9591
Propor-tion%	TRP	40.90	22.20	15.90	7.9
	DSR	33.90	24.10	16.00	14.00
Cumula-tive%	TRP	40.90	63.10	79.00	86.90
	DSR	33.90	58.00	74.00	88.00

According to the component matrix, under transplanted conditions, PC1 had strong positive

All things considered, DSR's yield performance was on level with or superior to TPR. Numerous studies have shown that direct-seeded rice can be as productive as transplanted rice with the right crop management techniques, such as optimal weed and water control (Xu *et al*., 2019; Kalpande *et al*., 2024). Panicle number was linked to the yield differential when DSR out yielded TPR. According to (Kalpande *et al*., 2024), the primary cause of the comparable or even greater yield of direct-seeded rice compared to transplanted rice was the increased panicle number per m2. In this study, we found negative direct effect of days to maturity under direct seeded and positive in transplanted rice, unlike our study (Thuy *et al*., 2023) in transplanted condition found also negative direct effect of days to maturity. In this study, under direct-seeded conditions, we found a positive direct effect of panicle length and a negative effect in the transplanted condition. Similarly, Ahmed *et al*. (2025) also found the same result for TRP and opposite to DSR, which is inconsistent with our outcomes. Under DSR, we identified the negative direct effect of grain weight per panicle and a positive effect in TRP. Similarly, Bhutta *et al*. (2019) also found a positive direct effect for this trait under transplanted conditions. Similar to present finding apposite results of DSR and TRP for panicle weight, (Kumar *et al*., 2022) also revealed the same positive direct effect of panicle weight in TRP as we also revealed.

Principal Component Analysis (PCA) reduces data dimensions by identifying principal components (PCs) that capture the most variance, simplifying complex multi-trait systems (Gewers *et al*., 2021). This study applied PCA to analyze 14 yield-related traits under transplanted and dry direct-seeded rice conditions. PCA was performed to identify the key traits contributing to genotype variation. Components were retained based on Kaiser's criterion (eigenvalues>1) and visual inspection of the scree plot. Kaiser criterion is accepted in multivariate analysis, and components with eigenvalues less than 1 are considered non-significant (Valsalan *et al*., 2020). According to Devi *et al*. (2019), components explaining at least 5% of the variance with eigenvalues greater than 1 are significant. Eigenvalues indicate the variance explained by each element, while factor loadings represent correlations between original traits and derived factors. Components with high eigenvalues and factor loadings are most representative of the system.

The first of four principal components in our analysis had eigenvalues greater than one in both conditions, and together, they accounted for 86.92 percent of the variance in the transplanted condition and 88% in the dry direct-seeded condition (Table 7). It was determined that the main components with less than one eigenvalue were insignificant. Under the transplanted conditions, the first principal component accounted for 40.90 percent of the diversity among the genotypes for the traits under investigation. In contrast, the second, the third and the fourth main components showed 22.20%, 15.90%, and 7.90 percent variability, respectively (Table 7). Under dry direct seeded conditions, the 1st principal component explained 33.90, the 2nd 24.10%, the 3rd 16.00%, and the 4th 14.00% of the total variability. The first principal component explains the highest variability in the data.

Table 8: *Component loading of studied parameters under transplanted and dry direct seeded conditions*

Variable	Conditions	PC1	PC2	PC3	PC4
DH	TRP	0.281	0.197	-0.387	0.085
	DSR	0.150	-0.13	-0.383	0.491
DM	TRP	0.271	0.217	-0.393	0.018
	DSR	0.169	-0.145	-0.388	0.460
FLL	TRP	0.321	-0.007	-0.085	0.477
	DSR	0.144	0.300	-0.379	-0.240
FLW	TRP	0.142	-0.433	0.138	0.181
	DSR	0.207	0.310	-0.108	-0.106
FLA	TRP	0.306	-0.269	0.041	0.412
	DSR	0.218	0.358	-0.294	-0.229
PH	TRP	0.379	0.013	-0.096	0.038
	DSR	0.357	-0.021	-0.161	0.188
PL	TRP	0.295	0.296	-0.001	0.110
	DSR	0.162	-0.308	-0.283	-0.238
NT	TRP	0.134	0.427	0.345	-0.079
	DSR	0.008	-0.477	-0.107	-0.270
NP	TRP	0.148	0.418	0.341	-0.031
	DSR	0.040	-0.481	-0.078	-0.264
PW	TRP	0.287	-0.147	-0.164	-0.369
	DSR	0.434	0.029	0.201	-0.010
GW	TRP	0.301	-0.295	0.177	-0.302
	DSR	0.429	0.026	0.221	0.012
NG	TRP	0.248	-0.285	0.341	-0.082
	DSR	0.374	0.081	0.162	-0.240
SF	TRP	0.135	-0.090	-0.369	-0.497
	DSR	0.195	-0.057	0.459	0.349
YP	TRP	0.328	0.105	0.334	-0.248
	DSR	0.364	-0.286	0.109	-0.109

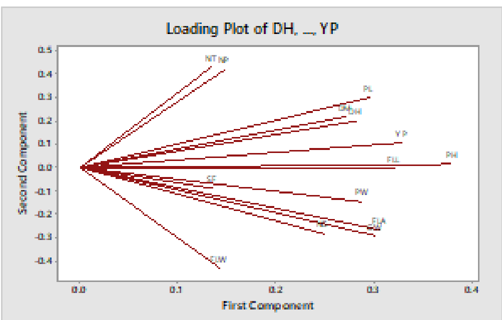

Figure 1: *Loading plot under TRP*

According to the component matrix, under transplanted conditions, PC1 had strong positive loadings for the plant height (0.3.79), grain yield per plant (0.328), flag leaf length (0.321), and flag leaf area (0.306) (Figure 1). This may suggest that PC1 capture traits associated with vegetative growth and photosynthesis activities, which are closely linked with yield potential in rice. So genotypes with higher PC1 score maybe characterized through tall plant with large flag leaves and superior grain yield per pant. High positive loading for number of tillers (0.427) was made possible by PC2, and this was followed by number of panicles (0.418), panicle length (0.296), days to maturity (0.217), and the highest negative loading was exhibited by flag leaf width (-0.433), grain weight per panicle (-0.295), number of grains (-0.285) and flag leaf area (-0.269) (Table 8). PC3 revealed the highest positive loading with the number of tillers (0.345), the number of panicles (0.341), the number of grains (0.341), and the yield per plant (0.334), in contrast this PC revealed maximum negative loading to days to maturity (-0.393), days to heading (-0.387), and spikelet fertility (-0.369). 4th PC was highly positively associated with flag leaf length (0.477) and negatively loaded to spikelet fertility (-0.497), grain weight per panicle (-0.302) and yield per plant (-0.298). Under dry direct seeded conditions, PC1 was highly positive loading for panicle weight (0.434), grain weight (0.429), number of grains per panicle (0.374), yield per plant (0.364) and plant height (0.357) and 2nd PC was highly positively loading for flag leaf area (0.358), flag leaf width (0.310), flag leaf length (0.300) and negatively loading to number of panicles (-0.481), number of tillers (-0.477), panicle length (-0.308) and yield per plant (-0.281) (Figure 2). In PC3 traits, likely spikelet fertility (0.459), grain weight (0.221), and panicle weight (0.201) were positively loading, while traits days to maturity (-0.388), days to heading (-0.387), flag leaf length (-0379) and flag leaf area (-0.294) were negatively loaded. PC4 was highly positively loading for days to heading (0.491), days to maturity (0.460), and spikelet fertility (0.349) and highly negatively loading for number of tillers (-0.270), number of panicles (-0.264), panicle length (-0.238) and flag leaf area (-0.229) (Table 8). The tendency of prominent traits that contribute the most variability and segregate in the various principal components to remain together may be considered when using these characters as donors for the associated traits in crop improvement programs.

The genotype projection on PC1 and PC2 revealed population structure and parent groups under both establishment conditions, indicating strong genotype-environment interaction. In the transplanted condition (Figure 3), genotypes G1, G2, G5, G10, G12, G16, G22, and G24 were grouped in the same box or cluster, suggesting they share similar phenotypic responses likely driven by traits with high loading on PC1 (e.g panicle weight and number of tillers) and PC2 (e.g flag leaf area). Similar performance was observed, while G6, G8, G9, and G14 were grouped separately from the main cluster, implying different expressions of traits, possibly due to lower tiller production or less efficient expression of other traits in TRP. Under dry direct-seeded conditions (Figure 4), genotypes G4, G5, G14, G20, G21, G24, and G25 were clustered together, while G3, G7, G10, G11, G15, and G26 were in another group, showing the shifting of genotypes' performance, likely influenced by the traits. The contrasting grouping between TRP and DSR emphasize condition dependent trait prioritization, for example flag leaf area which loading significantly On PC2 maybe more influence in TRP due to its effective role in higher photosynthetic activity under well water condition while in DSR traits likely panicle weight etc (contributing PC1) may dominate selection under DSR. The projections of other genotypes are also shown in Figures 3 and Figure 4.

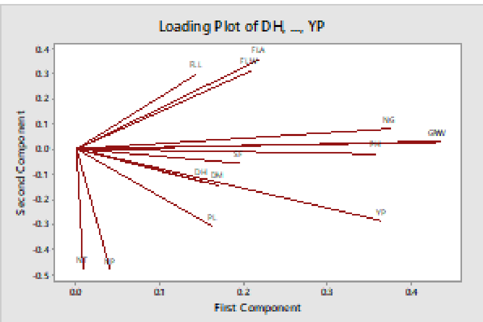

Figure 2: *Loading plot under DSR*

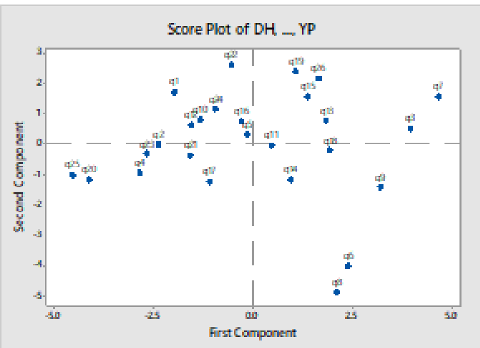

Figure 3: *Score plot under TRP*

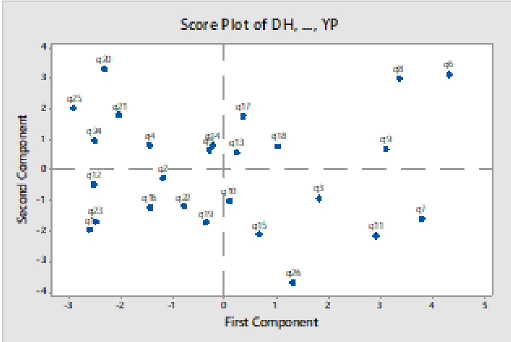

Figure 4: *Score plot under DSR*

Due to a lack of understanding of the traits' relative value and utility, the investigator attempts to incorporate every potential variable, resulting in a data matrix that is noticeably vast, complex, and unintelligible. For this reason, the investigator needs a methodical approach for reduction and summation. Principal component analysis is a multivariate statistical technique first created independently by Hotelling and later by Pearson (Al-Khayri *et al*., 2023). Finding the fewest components that can account for the most variability is the goal of principal component analysis (PCA). The first primary component accounts for the most significant percentage of the overall variance, while the other components gradually decrease it (Singh *et al*., 2020).

Ten initial connected traits were reduced to four independent principal components, contributing most to the dataset's variation. (Wang *et al*., 2022), Similarly, four significant PCs were identified. In this study, PC1 showed positive contributions from panicle weight, flag leaf area, plant height, flag leaf length, and yield per plant. This aligns with findings by (Reetisana *et al*., 2022; Christina *et al*., 2021) regarding the positive correlation between plant height and flag leaf length in the first principal component. Additionally, Anshori *et al*. (2025) and Reetisana *et al*. (2022) reported that most traits were positively associated with PC1. (Ali *et al*., 2024) found spikelet fertility positively linked to PC1, while Ali *et al*. (2024) also noted a positive association of flag leaf length in PC1. The four-group genotype classification by Ali *et al*. (2024) further supports these findings.

Conclusions and Recommendations

A correlation analysis was conducted in the present experiment to examine the relationship between various yields and their related traits under transplanted and direct-seeded conditions. Association analysis exposed those understudied conditions showed that grain yield per plant had a significant positive correlation with plant height, panicle length, number of panicles, panicle weight, grain weight per panicle, number of grains per panicle, and spikelet fertility, but in addition under the transplanted condition it had significant correlation with days to maturity, flag leaf length, flag leaf area and in direct seeded with days to heading. Hence, by selecting these traits that show a positive and significant correlation with grain yield, there is a possibility of increasing the grain yield of rice under both conditions, particularly direct-seeded conditions. Genotypic and phenotypic path coefficients of different studied traits revealed that those traits had a positive correlation and a direct effect on yield, which could be more beneficial under the studied conditions. Principal component analysis divided the entire material into four main components, the primary source of variability under the studied conditions. These results suggest that selecting these traits will directly increase the total grain yield per plant.

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Novelty statement

The novelty of this study lies in the comprehensive comparative analysis of rice yield and its associated traits under different planting conditions. It also utilizes different types of analysis, such as correlation, path analysis, and principal component analysis, to identify the main factors contributing to yield. Unlike previous studies, this study emphasizes the differential relationship of agronomic traits under direct-seeding and transplanting conditions, thus providing new insights into trait selection for breeding direct-seeding rice varieties. Under this study, we used two rice establishment techniques, which revealed that traits related to yield, such as tillers and grain weight per panicle, had a direct effect on grain yield, suggesting their vital role in yield determination under water-efficient conditions, such as dry direct seeding. The integration of traits we identified under DSR with marker-assisted selection or genomic selection could accelerate the development of yield-yielding DSR-adapted cultivars. The findings highlight the potential of direct-seeded rice as an alternative cropping system by utilizing specific trait associations to improve adaptability and yield efficiency.

Author's contribution

Zeeshan Ali: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing-original draft, Visualization, Funding acquisition, reviewed the final version and approved the manuscript before submission.
Muhammad Naeem: Conceptualization, Methodology, Investigation, Resources, reviewed the final version and approved the manuscript before submission.
Iqra Rafiq: Conceptualization, Methodology, Investigation, Resources, reviewed the final version and approved the manuscript before submission.
Abu Talha Nusrat: Conceptualization, Methodology, Investigation, Resources, reviewed the final version and approved the manuscript before submission.
Purnama Isti Khaerani: Validation, Data curation, reviewed the final version and approved the manuscript before submission.
Abd Haris Bahrun: Validation, Data curation, reviewed the final version and approved the manuscript before submission.
Achmad Kautsar Baharuddin: Data curation, reviewed the final version and approved the manuscript before submission.
Muhammad Fuad Anshori: Conceptualization, Software, Validation, Formal analysis, Data curation, Funding acquisition, reviewed the final version and approved the manuscript before submission.

Generative AI and AI-assisted technology statement
The authors declare that no generative artificial intelligence (AI) or AI-assisted technologies were used for this manuscript.

Conflict of interest
The authors declare there is no conflict of interest.

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