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MULTIVARIATE ANALYSIS OF EARLY SEEDLING VIGOUR AND ITS COMPONENT TRAITS IN A SUBSET OF RICE (*ORYZA SATIVA* L.) 3K PANEL

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ABSTRACT

Early seedling vigour is a critical trait in direct-seeded rice systems, influencing crop establishment, weed competitiveness and yield potential. This study evaluated 168 diverse accessions from the 3K rice genome panel for vigour related traits using the paper towel method. Phenotypic assessments at 7th day and 15th day post-germination included germination percentage, seedling length, dry weight and seedling vigour indices. Descriptive statistics revealed substantial variability among accessions, with germination efficiency exceeding 97% in most cases. Correlation analysis indicated strong interdependence among vigour component traits, particularly between seedling length and vigour indices. Principal component analysis identified two major dimensions of variation, elongation-based vigour and biomass accumulation. PC1, explaining 72.55% of the variance, was primarily associated with seedling length and vigour indices, while PC2 (14.27% variance) highlighted dry matter accumulation as a distinct growth strategy. These findings provide valuable insights into genetic variation in seedling vigour and offer a basis for selecting high-performing genotypes for DSR breeding programs.

Key words: Early seedling vigour, *Oryza sativa* L., Multivariate analysis.

Introduction

Rice (*Oryza sativa* L.) is a staple cereal crop and a primary source of carbohydrates across developing Asian countries, contributing approximately 23% of global caloric intake (Chauhan and Abugho, 2013; Mahender *et al*., 2015). It plays a crucial role in global food security, supporting the livelihoods of nearly 3.5 billion people (Anandan *et al*., 2016). Traditionally cultivated in semiaquatic environments through puddled transplanting, rice production now faces multiple challenges, including depleting natural resources, rising labour shortages, shrinking arable land, increasing input costs and changing climatic conditions (Kahani and Hittalmani, 2015). These constraints necessitate a shift from conventional transplanting to direct-seeded rice (DSR), a water-efficient and cost-effective alternative that eliminates the need for puddling while ensuring moisture retention throughout the growing period (Zhang *et al*., 2005). To overcome this, an alternative strategy is to go for direct seeded rice (DSR). DSR had many advantages and currently a technique in demand across the country. The success of DSR largely depends on major complex traits such as early seedling vigour (ESV), weed competitiveness, lodging tolerance, nutrient uptake ability and yield. Among these, ESV is one such imperative trait that promotes rapid and uniform emergence, particularly under moisture-limiting conditions. Improving ESV not only enhances crop establishment and yield potential but also strengthens resilience against climatic stresses and biotic constraints (Fischer *et al*., 2001; Gibson *et al*., 2003; Zhao *et al*., 2006). However, breeding for enhanced seedling vigour remains a significant challenge due to the complexity of its genetic control and the difficulty in precise measurement (Jiang *et al*., 2004). Understanding genetic variation within rice germplasm is essential to dissect the genetic basis of ESV and facilitate the development of vigorous, high-yielding rice varieties suitable for DSR systems. To achieve this, multivariate statistical tools such as trait correlation to establish the component traits and principal component analysis (PCA) to identify the divergence and trait contributions is essential. PCA simplifies complex datasets by reducing dimensionality while retaining most of the variability, allowing breeders to pinpoint the most influential traits in seedling establishment. Identifying principal components associated with ESV enables breeders to select superior genotypes with multiple desirable traits, ultimately improving crop establishment and yield stability in DSR systems. With this background, we aimed to ascertain the key traits that determine the vigour and to asses the potential of Indian subset 3K rice genome panel for seedling vigour.

Material and Methods

Experimental material and methodology

A total of 168 diverse accessions from the 3K rice genome panel were evaluated for early seedling vigour (ESV) and associated traits during 2023-24 in mid seasons of *Kharif* and *Rabi* (Table 1) at ICAR- Indian Institute of Rice Research, Hyderabad, India. Standardized phenotyping procedures outlined by Standard Evaluation System for Rice (SES) provided by IRRI, Philippines were employed to ensure accuracy and reproducibility (Table 1).

Phenotyping for early seedling vigour using the paper towel method

In order to conduct vigour test using paper towel method, the procedure outlined by Zhang *et al*., (2005) was duly employed. Uniform, well-filled grains were selected and residual dormancy was mitigated by subjecting seeds to 50°C temperature for five days. Surface sterilization was performed using 0.6% sodium hypochlorite for 15 minutes, followed by three rinses with sterile distilled water to eliminate chemical residues. Pre-germination was induced by soaking the sterilized seeds in sterile distilled water at 30°C for 36 hours. The pre-germinated seeds were then placed on moistened paper towels, which were carefully rolled to maintain uniform hydration. The rolls were secured at both ends and incubated in a growth chamber at 18°C in complete darkness. This controlled environment facilitated synchronized seedling development. At 7- and 15-days post-inoculation, representative seedlings were randomly selected for phenotypic assessment. This experiment was repeated twice in at different intervals to ensure the efficacy and accuracy. The phenotype data on vigour component traits and calculation of vigour index was done using standard procedures. Germination percentage was determined by dividing the total number of seeds germinated on the 7th day of the experiment by the total number of seeds initially placed for germination. This ratio was then expressed as a percentage.

$$\text{Germination Percentage (\%)} = \frac{\text{Total number of seeds germinated}}{\text{Total number of seeds kept for germination}} \times 100$$

Later on, seedling length was measured from the tip of the longest leaf to the root tip. Five normal and random seedlings per accession were selected and their individual lengths were recorded. The final seedling length was expressed as the average of these measurements. To determine biomass accumulation, five seedlings per accession were oven-dried at 80°C for 48 hours. The dried seedlings were then weighed and the average dry weight was recorded in milligrams at 7th and 15th day. Finally, seedling vigour indices were calculated following the formula given by Abdul Baki and Anderson (1973) to quantify early seedling performance at 7th and 15th day intervals.

Seedling Vigour Index I = Germination Percentage × Seedling Length (cm)

Seedling Vigour Index II = Germination Percentage × Total Dry Wegiht (mg)

Statistical Analysis

The perusal of the thorough data obtained was duly subjected to statistical analysis such as descriptive statistics, correlation studies and principal component analysis. All the analysis was performed using a recently developed R based package "GRAPES" developed by Gopinath *et al.*, (2021).

Results and Discussion

The analysis of seedling vigour traits across the evaluated accessions revealed substantial variability in germination efficiency, seedling growth, biomass accumulation and overall vigour indices. Descriptive

Table 1: Details of 168 germplasm accessions utilized for the study.

S. No.	Germplasm ID	IRG ID	S. No.	Germplasm ID	IRG ID	S. No.	Germplasm ID	IRG ID	S. No.	IRG ID
1	G1	3K-126	43	G43	IRG092	85	G85	IRG164	127	IRG240
2	G2	3K-130	44	G44	IRG093	86	G86	IRG166	128	IRG241
3	G3	3K-273	45	G45	IRG094	87	G87	IRG168	129	IRG243
4	G4	3K-328	46	G46	IRG096	88	G88	IRG170	130	IRG244
5	G5	3K-362	47	G47	IRG098	89	G89	IRG171	131	IRG245
6	G6	3K-423	48	G48	IRG100	90	G90	IRG172	132	IRG250
7	G7	3K-631	49	G49	IRG101	91	G91	IRG175	133	IRG251
8	G8	IRG033	50	G50	IRG102	92	G92	IRG178	134	IRG252
9	G9	IRG036	51	G51	IRG104	93	G93	IRG180	135	IRG253
10	G10	IRG038	52	G52	IRG105	94	G94	IRG181	136	IRG255
11	G11	IRG039	53	G53	IRG106	95	G95	IRG184	137	IRG273
12	G12	IRG040	54	G54	IRG112	96	G96	IRG187	138	IRG276
13	G13	IRG041	55	G55	IRG114	97	G97	IRG189	139	IRG281
14	G14	IRG043	56	G56	IRG115	98	G98	IRG190	140	IRG285
15	G15	IRG045	57	G57	IRG116	99	G99	IRG191	141	IRG289
16	G16	IRG046	58	G58	IRG120	100	G100	IRG193	142	IRG292
17	G17	IRG047	59	G59	IRG122	101	G101	IRG194	143	IRG293
18	G18	IRG048	60	G60	IRG124	102	G102	IRG197	144	IRG299
19	G19	IRG049	61	G61	IRG129	103	G103	IRG198	145	IRG301
20	G20	IRG050	62	G62	IRG133	104	G104	IRG201	146	IRG303
21	G21	IRG051	63	G63	IRG135	105	G105	IRG203	147	IRG305
22	G22	IRG052	64	G64	IRG138	106	G106	IRG204	148	IRG306
23	G23	IRG053	65	G65	IRG139	107	G107	IRG205	149	IRG308
24	G24	IRG056	66	G66	IRG140	108	G108	IRG206	150	IRG309
25	G25	IRG060	67	G67	IRG141	109	G109	IRG210	151	IRG310
26	G26	IRG061	68	G68	IRG142	110	G110	IRG211	152	IRG312
27	G27	IRG064	69	G69	IRG143	111	G111	IRG212	153	IRG314
28	G28	IRG067	70	G70	IRG145	112	G112	IRG213	154	IRG317
29	G29	IRG068	71	G71	IRG146	113	G113	IRG214	155	IRG319
30	G30	IRG069	72	G72	IRG147	114	G114	IRG215	156	IRG322
31	G31	IRG070	73	G73	IRG148	115	G115	IRG216	157	IRG323
32	G32	IRG073	74	G74	IRG150	116	G116	IRG217	158	IRG326
33	G33	IRG075	75	G75	IRG152	117	G117	IRG222	159	IRG328
34	G34	IRG078	76	G76	IRG153	118	G118	IRG223	160	IRG332
35	G35	IRG079	77	G77	IRG154	119	G119	IRG224	161	IRG344
36	G36	IRG081	78	G78	IRG155	120	G120	IRG225	162	IRG348
37	G37	IRG082	79	G79	IRG156	121	G121	IRG227	163	IRG349
38	G38	IRG084	80	G80	IRG157	122	G122	IRG234	164	IRG351
39	G39	IRG086	81	G81	IRG158	123	G123	IRG235	165	IRG353
40	G40	IRG089	82	G82	IRG160	124	G124	IRG237	166	IRG357
41	G41	IRG090	83	G83	IRG161	125	G125	IRG238	167	IRG360
42	G42	IRG091	84	G84	IRG163	126	G126	IRG239	168	IRG375

statistics provided insights into the extent of variation, while normality assessments highlighted deviations in specific traits. Correlation analysis established interrelationships among measured parameters and principal component analysis (PCA) identified major axes of variation, distinguishing elongation-based vigour from biomass accumulation as two independent dimensions of seedling vigour.

Descriptive statistics

Germination percentage (GP) exhibited a higher mean value of 97.20% considering all the accessions. Among the 168 accessions considered, 86.30% yielded complete germination. This suggests that, there was uniform germination efficiency attained. Seedling length showed progressive growth over time, with mean values of 21.02 cm at 7th day (SGL_7) and 31.01 cm at 15th day (SGL_15). Biomass-related traits displayed higher variability, particularly at early growth stages, as reflected by the variation for total dry weight at 7th day with a mean of 11.66 mg and 22.74 mg at15th day. This indicated that, there has been accumulation of biomass over the

Table 2: Phenotypic descriptive statistics of distinct ESV traits considered for the study.

Variables	Mean	Minimum	Maximum	Standard Deviation	Skewness	Kurtosis
GP	97.2	70	100	7.34	-2.5	4.99
SGL_7	31.01	19.12	39.89	3.75	-0.15	0.28
TDW_7	21.02	11.12	27.5	3.13	-0.45	0.2
SGL_15	3064.52	1624.17	3988.34	428.29	-0.49	0.51
TDW_15	2078.69	988.5	2750	354.77	-0.76	0.45
SVII_7	2244.53	1395.84	2763.34	238.65	-0.65	0.54
SVIII_7	1142.96	457.83	2626	274.07	1.07	6.38
SVII_15	22.74	16.68	27.63	1.95	-0.16	0.01
SVIII_15	11.66	5.48	31.05	2.98	2.5	13.69

* Note: GP: Germination Percentage, SGL_7: Seedling Length at 7th Day, TDW_7: Total dry weight at 7th Day, SVII_7: Seedling Vigour Index -I at 7th Day, SVIII_7: Seedling Vigour Index -II at 7th Day, SGL_15: Seedling Length at 15th Day, TDW_15: Total dry weight at 15th Day, SVII_15: Seedling Vigour Index -I at 15th Day and SVIII_15: Seedling Vigour Index -II at 15th Day

time interval, which in turn relates to the vigour of the seedlings. Among vigour indices, seedling vigour index-I at 7th day (SVII_7) exhibited a mean of 2078.69. Meanwhile, seedling vigour index-II at 7th day (SVIII_7) displayed a mean of 1142.96. During the second stage i.e., at 15th day, SVII_15 has attained an average of 3064.52 and SVIII_15 had a mean of 2244.53. Considering the complete germination obtained across most of the accessions, it can be inferred that, the increase in vigour indices from 7th day to 15th day is majorly based on the increase in seedling length for index I and dry weight for index II respectively (Table 2).

Germination percentage is a key element of seed quality, early seedling vigour and crop establishment. It plays a crucial role in improving resistance to pests and diseases while minimizing weed competition. In DSR systems, particularly in rainfed lowlands with limited moisture and nutrients, rapid germination and efficient nutrient uptake are vital traits (Yamane *et al.*, 2018). Studies have reported significant variability in germination percentage among rice accessions (Wang *et al.*, 2011; Septiningish *et al.*, 2013; Baltazar *et al.*, 2014). Additionally, Tejaswi (2012) and Suneetha Madhuri (2014) identified QTLs associated with this trait in cultivated rice genotypes. Lower germination percentages in some cases may be linked to seed dormancy, affecting uniform and rapid germination. On the other hand, seedling length is a key trait influencing early seedling vigour in direct-seeded rice and is widely used as an indicator of vigour (Zhang *et al.*, 2017). Studies have reported significant variability in seedling length among cultivated rice genotypes (Akshaya *et al.*, (2020), Koshle *et al.*, (2020) and Bharamappanavara *et al.*, (2023)). Cordero-Lara *et al.*, (2016) highlighted that seedling length is influenced not only by shoot length (SHL) but also by root length (RL), suggesting that their combined effect determines overall seedling growth. Variability in seedling length across environments may range from low to moderate due to these interactions. Additionally, early-stage slow growth could result from poor germination and low temperatures.

Dang *et al.*, (2014) outlined that, seedling dry weight serves as a crucial index for assessing early seedling vigour, reflecting the efficiency of photosynthesis and nutrient accumulation in the initial growth stages. They emphasized that high total dry weight is a reliable selection criterion for identifying vigorous rice genotypes. Studies on early seedling vigour in rice by Diwan *et al.*, (2013) and Dang *et al.*, (2014) reported significant variability in total dry matter among mapping populations and their parents, highlighting the genetic diversity associated with this trait. Similarly, Tejaswi (2012), Roy and Bhadra (2014) and Suneetha Madhuri (2014) observed substantial variation in cultivated rice genotypes, supporting the importance of seedling dry weight as a key indicator of vigour. Dang *et al.*, (2014) further noted that efficient nutrient accumulation in both the shoot and root is vital for early seedling establishment, as it influences subsequent resource allocation to leaves and overall leaf area development. Barik *et al.*, (2019) suggested that a rapid increase in dry weight by 15th day indicates effective resource partitioning from initial seedling establishment to active vegetative growth.

SVI-I is defined as the product of GP and SGL, is a vital trait that determines a genotype's ability to produce high-quality seedlings by efficiently utilizing resources such as light, moisture and nutrients. This index plays a vital role in ensuring rapid germination and early seedling growth under field conditions. Diwan *et al.*, (2013) reported significant variability for SVI-I in different rice populations, highlighting its importance in early seedling establishment. Similarly, SVI-II, which measures dry matter accumulation in normal seedlings, serves as an indicator of seed vigour and food reserve availability. Sanghmitra *et al.*, (2021) suggested that seeds with higher

Table 3: Correlation coefficients among and for the ESV and its component traits.

Variables	GP	SGL_7	TDW_7	SGL_15	TDW_15	SVII_7	SVIII_7	SVII_15	SVIII_15
GP	1								
SGL_7	0.65**	1							
TDW_7	0.456**	0.59**	1						
SGL_15	0.505**	0.74**	0.39**	1					
TDW_15	0.433**	0.681**	0.334**	0.919**	1				
SVII_7	0.737**	0.991**	0.598**	0.735**	0.674**	1			
SVIII_7	0.593**	0.726**	0.869**	0.514**	0.472**	0.742**	1		
SVII_15	0.664**	0.786**	0.44**	0.978**	0.895**	0.805**	0.58**	1	
SVIII_15	0.68**	0.765**	0.421**	0.907**	0.951**	0.792**	0.581**	0.945**	1

* Note 1: GP: Germination Percentage, SGL_7: Seedling Length at 7th Day, TDW_7: Total dry weight at 7th Day, SVII_7: Seedling Vigour Index -I at 7th Day, SVIII_7: Seedling Vigour Index -II at 7th Day, SGL_15: Seedling Length at 15th Day, TDW_15: Total dry weight at 15th Day, SVII_15: Seedling Vigour Index -I at 15th Day and SVIII_15: Seedling Vigour Index -II at 15th Day
Note 2: *: Significant at 95% confidence interval and **: Significant at 99% confidence interval

macromolecular reserves exhibit improved dry matter accumulation, leading to better early-stage growth. Addanki *et al*., (2018) further noted that seedlings with high vigour tend to establish more robust plants, making them more resilient to biotic and abiotic stresses. These inferences can be corroborated to the current study results, where in the increase in dry matter accumulation and seedling length have contributed to the increase in vigour.

Trait distribution and normality assessment

The normality of trait distributions was assessed using Quantile – Quantile Plots (QQ), revealing differences in skewness and kurtosis across traits (Table 2 and Fig. 1). GP followed a near-normal distribution, with a slight negative skew (skewness = -2.50, kurtosis = 4.99), while SGL at 15th day exhibited minimal deviation from normality (skewness = -0.15, kurtosis = 0.28). In contrast, TDW at 7th day showed substantial deviation from normality, with strong positive skewness (skewness = 2.50) and a heavy-tailed distribution (kurtosis = 13.69), indicating the presence of extreme values. A similar trend was observed for SVI-II at 7th day, which exhibited high kurtosis (6.38), suggesting large variability among accessions in early biomass accumulation. While most traits approximated normal distributions, the presence of outliers and non-normality in specific traits such as TDW_7 and SVIII_7 might suggest the potential influence of genetic variation or environmental factors affecting early seedling growth. Usually, in mapping populations, the distributions tend to be almost normal. However, when germplasm in consideration, there could be potential accessions with higher values or lower values, which could bring the deviation in the distributions. From

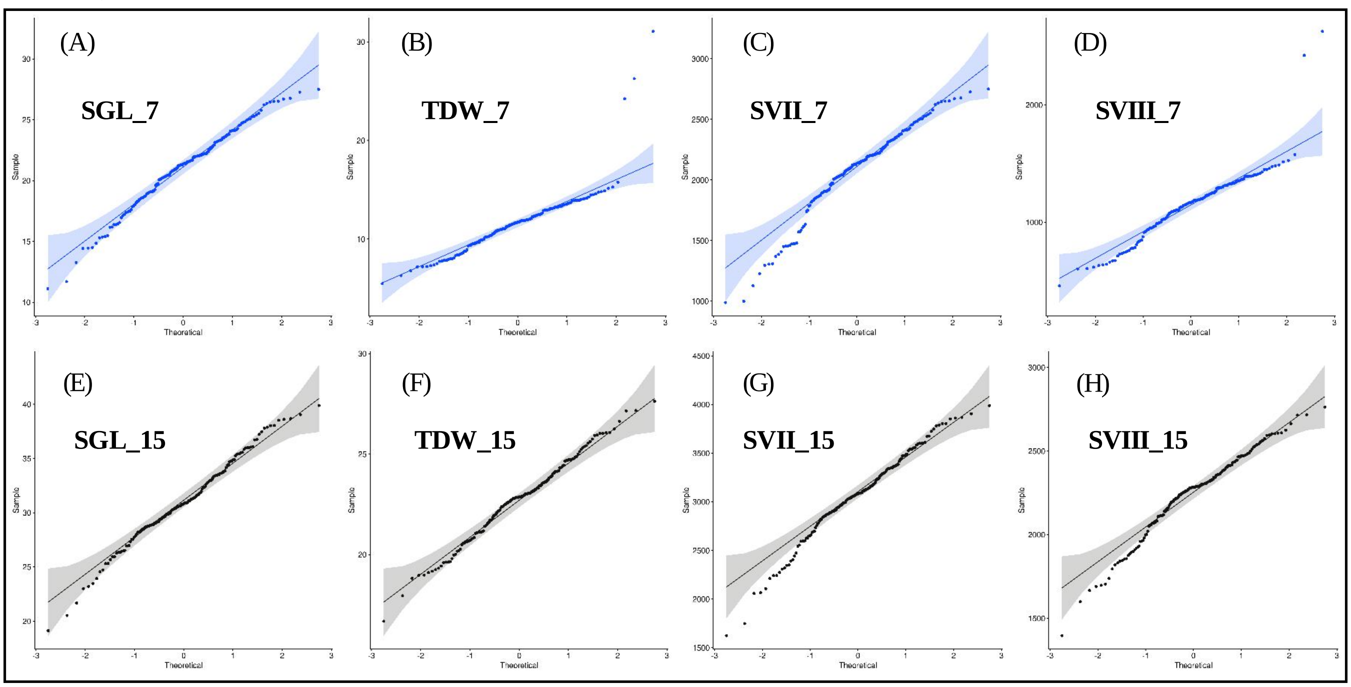

Fig. 1: Depiction of Quantile-Quantile plots to represent phenotype normality at 7th and 15th days in ESV traits.

Table 4: Eigen values and percent variance explained by principal components to the divergence.

Principal Components	Eigen Value	Percentage of Variance	Cumulative Percentage of Variance
PC1	6.529	72.547	72.547
PC2	1.284	14.266	86.813
PC3	0.585	6.503	93.316
PC4	0.358	3.981	97.297
PC5	0.137	1.523	98.82
PC6	0.099	1.1	99.92
PC7	0.006	0.072	99.992
PC8	0	0.004	99.996
PC9	0	0.004	100

*Note: PC: Principal Components

the figures, it can be inferred that, most of the values are in alignment with the expected line, with only few stretching away.

Correlation analysis among traits

Correlation analysis revealed significant associations among seedling vigour traits, highlighting the interdependence of early growth and vigour indices (Table 3; Fig. 2). A strong positive correlation was observed between SGL at 7th day and 15th day, indicating that early seedling growth is a reliable predictor of later-stage vigour. Similarly, TDW at 15th day exhibited a strong correlation with SVI-II at 15th day, confirming the significant role of biomass accumulation in seedling vigour. Early vigour traits showed strong interdependence, with SVI -I at 7th day and SVI-II at 7th day being highly correlated, reflecting their shared reliance on GP and early biomass accumulation. GP exhibited the highest correlation with SVI-I at 7th day, reinforcing its influence on early seedling vigour. In contrast, TDW at 7th day and 15th day showed weaker correlations with GP.

Attainment of positive correlation pertaining considered traits, it can be inferred that, the components traits measured compliment each other and are highly effective in ascertaining early vigour. These above findings indicated a strong positive association among most of the traits, suggesting they might be under common genetic control. Notably, SVI-I and SVI-II exhibited

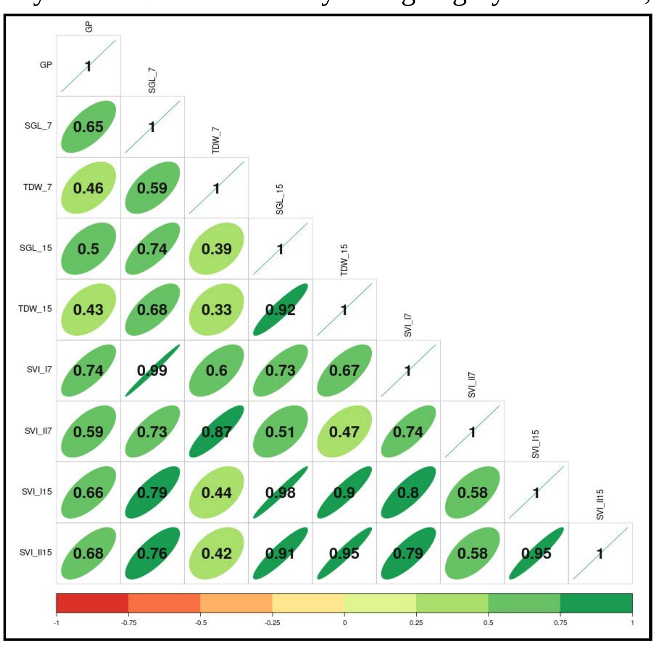

Fig. 2: Depiction of magnitude and direction of correlation among seedling vigour component traits considered in the study.

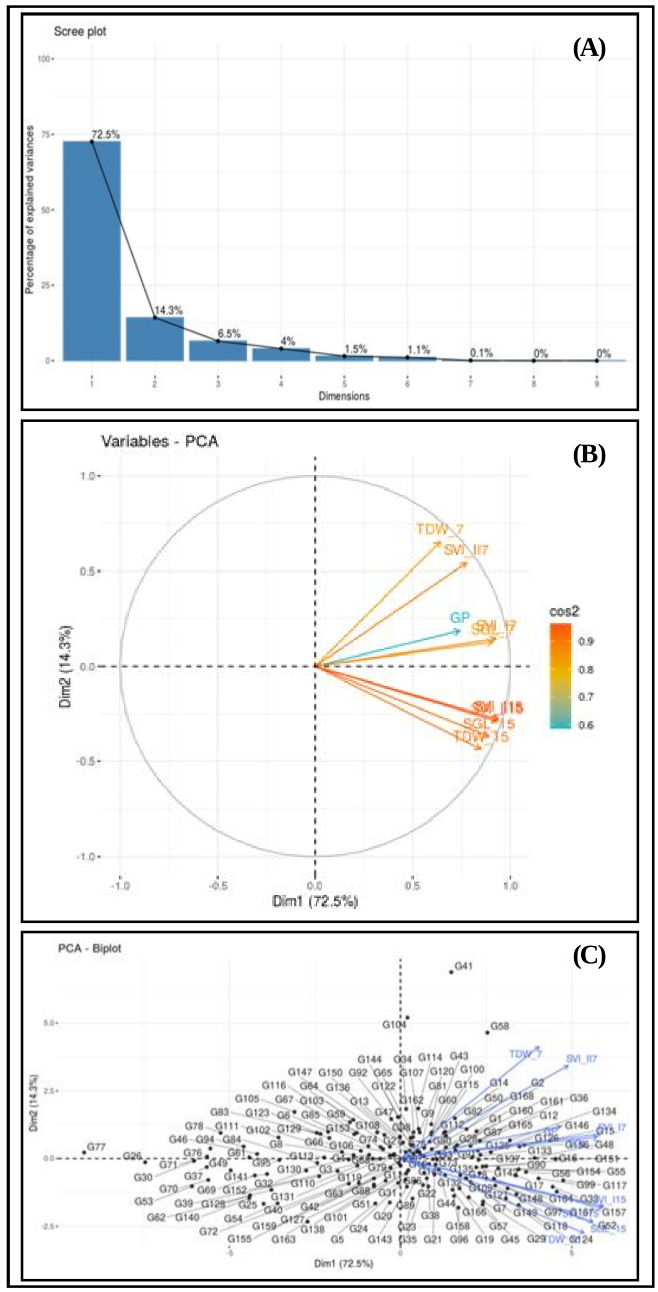

Fig. 3: A) Scree Plot; B) Trait Contributions and C) Biplots representing contributions of traits and accessions for total divergence

Table 5: Correlation of ESV component traits with the principal components obtained.

Variables	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
GP	0.743	0.188	-0.583	0.27	0.013	0.021	0.025	0
SGL_7	0.911	0.127	-0.088	-0.381	-0.003	0.026	0.022	-0.011
TDW_7	0.641	0.655	0.318	0.139	0.104	0.172	-0.001	0
SGL_15	0.891	-0.37	0.163	0.021	0.188	-0.078	0.028	0.006
TDW_15	0.85	-0.435	0.225	0.055	-0.169	0.073	0.035	0.002
SVII_7	0.928	0.145	-0.172	-0.294	-0.009	0.028	-0.024	0.013
SVIII_7	0.777	0.544	0.173	0.079	-0.13	-0.219	0.001	0
SVII_15	0.941	-0.279	0.008	0.083	0.156	-0.062	-0.035	-0.007
SVIII_15	0.934	-0.289	-0.011	0.134	-0.144	0.066	-0.04	-0.002

* Note: GP: Germination Percentage, SGL_7: Seedling Length at 7th Day, TDW_7: Total dry weight at 7th Day, SVII_7: Seedling Vigour Index -I at 7th Day, SVIII_7: Seedling Vigour Index -II at 7th Day, SGL_15: Seedling Length at 15th Day, TDW_15: Total dry weight at 15th Day, SVII_15: Seedling Vigour Index -I at 15th Day and SVIII_15: Seedling Vigour Index -II at 15th Day

significant positive correlations with all component traits. Similar trends were reported by Sangamitra *et al*., (2021), where GP showed a strong positive correlation with vigour indices and dry weight. Likewise, Padmashree *et al*., (2022) observed a positive association between germination percentage and vigour indices using the paper towel method, though its relationship with dry weight was minimal.

The consistent pattern of significant positive associations among traits highlights their interconnected nature in rice breeding and genetic improvement programs. Tejaswi (2012) and Addanki *et al*., (2018) also reported significant positive correlations among key seedling vigour parameters, reinforcing this conclusion. Further, studies by Bordoloi D Sarma (2018), Barik *et al*., (2019), Jan and Kashyap (2019), Beerelli *et al*., (2020), Katiyar *et al*. (2019) and Bharamappanavara *et al*., (2023) have consistently demonstrated the same. These associations suggest that genetic factors influencing one trait may simultaneously affect others, supporting the value of considering multiple traits when assessing seedling vigour in rice.

Principal Component Analysis (PCA)

Principal component analysis was conducted to identify major sources of variation among the seedling vigour traits (Table 4; Fig. 3). The first two principal components (PC1 and PC2) accounted for 86.81% of the total variance, effectively summarizing complex trait interactions into two dominant dimensions. PC1 explained 72.55% of the total variance, primarily influenced by SGL at 7th day, SGL at 15th day, SVI-I at 7th day, SVI-I at 15th day and SVI -II at 15th day. The dominance of these traits in PC1 suggests that elongation-based vigour across growth stages is the primary determinant of variation in seedling vigour. PC2 accounted for 14.27% of the total variance, with major contributions from TDW at 7th day and SVI-II at 7th day, indicating that biomass accumulation represents a secondary but distinct axis of variation.

The contribution of traits to principal components confirmed the differentiation between elongation-based vigour and biomass accumulation. SGL at 7th day (12.70%) and SVI -I at 7th day (13.19%) were the most influential contributors to PC1, followed closely by SGL at 15th day (12.16%) and SVI-II at 15th day (13.35%). The dominance of these traits underlines the importance of seedling elongation across time points in defining overall vigour. In contrast, TDW at 7th day made the highest contribution to PC2 (33.37%), emphasizing the role of early biomass accumulation in explaining additional variation. The biplot of PCA loadings revealed a distinct separation between early-stage and late-stage vigour traits, further supporting the differentiation between elongation-based and biomass-driven vigour dimensions (Fig.). Genotypes positioned at the extreme positive end of PC1, such as G41, G35, G154 and G117, displayed high values for seedling length and vigour indices. Conversely, those on the negative end of PC1 exhibit

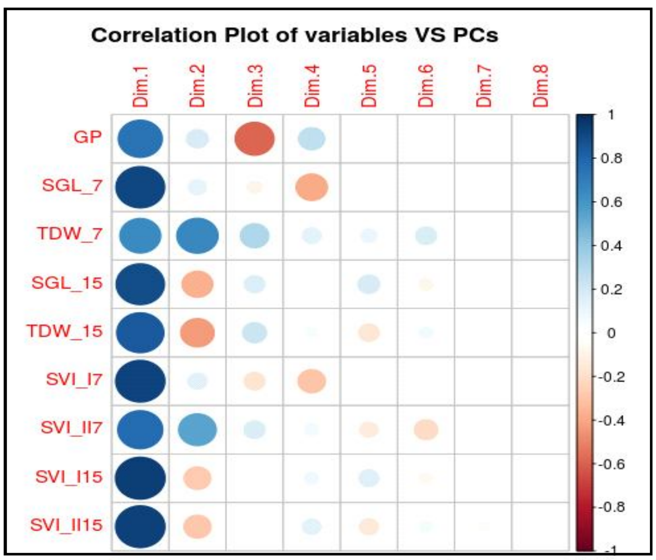

Fig. 4: Inter-Correlations among vigour component traits, vigour indices and principal components attained in the study.

lower vigour potential. Along PC2, genotypes diverge based on total dry weight and germination percentage, suggesting that biomass accumulation significantly influenced early seedling performance. The distinct clustering of these genotypes highlights inherent variation in early growth strategies, with some favouring rapid elongation and others highlighting biomass accumulation. This differentiation is critical for selecting suitable accessions for direct-seeded rice systems, where both emergence speed and seedling robustness play crucial roles in establishment and yield potential.

Inter-component correlations provided further insights into the relationships among major axes of variation (Table 5; Fig. 4). A significant correlation was observed between PC1 and PC3, suggesting that vigour shared some variance with later-stage biomass accumulation. Conversely, PC2 and PC4 exhibited weak correlations, indicating that early biomass accumulation follows an independent trajectory distinct from elongation-driven growth. These findings highlight two complementary but independent dimensions of seedling vigour, one driven by seedling length growth and the other by dry matter accumulation. The distinct clustering of traits in PCA confirms that both aspects should be considered in breeding programs aimed at improving early vigour in rice accessions.

The current PCA results align with the findings of Uzair *et al*., (2022), who analysed 190 rice accessions from the 3K rice genome panel and reported that SGL and grain yield-related traits were the primary contributors to total divergence. Similarly, Anandan *et al*., (2020) observed a comparable distribution pattern of vigour traits in first and second quadrants, supporting the genetic basis of early seedling growth variation. The PCA-based divergence analysis provides valuable genetic insights into the multivariate distribution of early seedling vigour traits. The clear separation of genotypes along the principal components suggests that specific seedling traits are under strong genetic control, which can be leveraged for selection in breeding programs. Since PC1 captures the maximum variance, the traits contributing to it such as seedling length, seedling vigour indices and total dry weight are likely governed by major effect quantitative trait loci (QTLs).

However, in contrast to our findings, Rudresh *et al*., (2021) reported that days to 50% flowering (DFF) and days to maturity (DM) were the most influential traits in PC1, whereas seedling vigour traits dominated PC2, indicating differential trait prioritization based on genetic background and environmental conditions. These insights align with previous genomic studies indicating that early vigour traits in rice are polygenic and exhibit moderate to high heritability. Understanding such genetic divergence is crucial for selecting superior genotypes for direct-seeded rice (DSR) systems.

Conclusion

This study highlights the genetic diversity available for early seedling vigour among existing rice accessions, emphasizing the role of seedling length and dry matter accumulation as independent yet complementary dimensions of vigour. The strong correlations among vigour indices suggest that selection for early growth traits can significantly enhance crop establishment in DSR systems. The distinct clustering of accessions in PCA highlights inherent variation in seedling growth strategies, offering potential targets for breeding resilient, high-vigour rice varieties. These results provide a foundation for identifying promising genotypes for direct-seeded cultivation, ultimately contributing to improved adaptation and productivity under changing agronomic conditions.

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