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Genetic Diversity and Stability of Rice Genotypes under Semi-Deep Water (SDW) Ecology in Coastal Sundarbans

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Semi - deep ecology for rice cultivation comprised of waterlogged situation (50-100 cm) for >2 months in field during vegetative and reproductive phases. Coastal low-lying areas are affected with high erratic rainfall and are affected by such conditions. The present study was carried out to find stable and high performing genotypes for varietal release pipeline as well as for finding suitable parents for generating better adapted rice germplasms. Based on seven consecutive years of phenotypic evaluation for days to 50% flowering, plant height, number of tillers per hill and number of panicles per plant, grain yield, straw yield, biomass and harvest index (HI), stable and high performing genotypes were identified. Manas Swarobor, Swarna-sub1, Purnendu, and Tilak Kesari are the underperforming genotypes, whereas Geetanjali and Najani have been the top achievers over the years. The yield of all 25 genotypes in each of the seven seasons was analyzed using a genotype and genotype-environment (GGE) biplot. 44.06% and 18.91% of the phenotypic variability (a total of 62.97%) could be explained by the two primary principal components. The seven environments were divided into two clusters: Cluster-1 (2015 and 2016), Cluster- 2 (2020, 2017, 2021, 2018), and one (2019) at a different node. In most situations, Geetanjali, CSRC(D)12- 8 -12, and CSRC(D)13 -16 -19 were found to perform better. In 2015 and 2016, CSRC(D)7- 5- 4 performed better. Grain yield in the current study was a clear indication of how sowing date and regional characteristics affect varietal performance. In breeding programs, varieties like Geetanjali can be excellent parents and are best suited for all seasons. It is possible to push advanced breeding lines like CSRC(D)13 -16 -19, CSRC(D)12- 8 -12, and CSRC(D)7- 5 -4 to the varietal evaluation pipeline (AICRIP) for release.

(***Key words:*** *Biplot analysis, Coastal rice ecologies, Diversity analysis, GGE, Semi-deep rice, Stability analysis*)

Rice is a prime staple for coastal areas across the world and is primarily affected by climatic vagaries such as erratic rainfall, flood situations, scanty rainfall, saltwater intrusion, and cyclonic disturbances in these areas (Bhowmick *et al.,* 2020). Being a high rainfall zone, rice crops in these regions are being grown under different rainfed crop ecologies, such as low land (<30 cm of standing water), semi-deep water (50-100 cm of standing water for >2 months during crop period), and deep water (>100 cm of standing water for >2 months during crop period) (Das *et al.,* 2005). Generally, coastal regions are comprised of low-lying river beds with shallow altitude harbouring crop fields inundated with rainwater and characterized by flash floods (Gao *et al.,* 2022).

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Therefore, large acreage in coastal regions are under semi- deep water ecology across the world (Das *et al.,* 2005). Apart from this, the popularization of Rice-Fish Integrated Farming System (RF-IFS) in different parts of world has highlighted the importance of genotypes that can thrive 50 -100 cm of standing water throughout their crop duration (Maiti *et al.,* 2020). The Sundarbans region is the integrated delta of the Ganga and Brahmaputra rivers spanning the Indian state of West Bengal and Bangladesh. This area is unique in having a heavy rainfall zone as well as salt-affected coastal soils, impairing rice yield and production (Bhowmick *et al.,* 2020). The region is home to several tall, photosensitive, salt-tolerant, and flood-resistant landraces such as Nona Bokra, Talmugur, Hamilton, Matla, Chamarmani, Gheuse, Dudheswar, and Bengal, which are still under cultivation in some areas because of their un-paralleled adaption to semi-deep conditions conferring on-par or better yield than modern bred cultivars under salt and flood stress (Bhambure and Kerkar, 2016). Therefore, it is very important to breed varieties suited for this ecosystem to benefit resource-poor farmers in these regions, whose sustenance relies on rice farming.

Naturally, genotypes adapted for semi-deep and deep-water conditions exhibit characteristics such as kneeing and elongation ability (Das *et al.,* 2005). Traditionally, these genotypes were grown either under transplanted condition or direct seeding on standing water (Bhambure and Kerkar, 2016). These genotypes possess excellent anaerobic germination potential (ability to germinate and elongate its coleoptile under submergence during seed germination) and early vigour (faster growth during seedling stage) (Barik *et al.,* 2019; Chamara *et al.,* 2018). Therefore, ideal plant type suited for semi-deep water (SDW) ecology must have tall stature (>150 cm), strong and thick culm (for lodging resistance), capacity for under-water photosynthesis (when half of plant part is under water), high early seedling vigour (for faster growth and capacity to beat increasing water level), capacity of anaerobic germination, more number of tillers, increased panicle length and width, higher number of grains per panicle, enhanced yield, excellent cooking and grain qualities, mild salt tolerance (EC~6 dS m^{-1}), and tolerance to various pest and diseases (Snehi *et al.,* 2022). Although low-yielder, traditional cultivars such as Dudheswar are still very popular in Sundarbans because of its excellent cooking and grain qualities as well as moderate level of tolerance to salt stress (Deb, 2021). Therefore, it is very much required to identify stable and high yielding genotypes under semi-deep water ecologies with their proper inclusion in breeding program.

Genotype × Environment (G × E) interaction analysis is key to understand stable performance of rice genotypes and their popularization among farmers (Devasena, 2025). A stable genotype generally performs stably under varying levels of climatic variations (drought or salinity), changes in the availability and application of inputs, and uniform plant stature (Debsharma *et al.,* 2024; Lokeshkumar *et al.,* 2025). Genotype-Genotype × Environment (GGE) Biplot is a graphical approach to identify stable as well as high-performing genotypes across locations or years (Debsharma *et al.,* 2024). It gives inferences on stable genotypes across environment and high performing genotypes for each environment. The performance of environment based on average performance of genotypes within an environment is used to characterize the capacity of the environment. Kumar *et al.* (2025) performed GGE biplot analysis to identify high-performing and stable rice landraces collected from North-Eastern part of India and evaluated 148 rice genotypes. Ahmad *et al.* (2024) had evaluated 20 green super rice lines across 12 locations in Pakistan to identify suitable and high performing lines using GGE biplot analysis. Therefore, in the present study we performed GGE biplot analysis to identify best suitable advanced breeding lines for varietal trial under All India Coordinated Rice Improvement Project (AICRIP) as well as to identify robust parental lines for crossing program.

MATERIALS AND METHODS

In the present study, a set of semi-deep rice genotypes pertaining to Sundarbans region of West Bengal, along with advanced breeding lines at ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning Town, West Bengal were evaluated and analysed for the stability and performances across seven consecutive years (2015 to 2021).

Evaluation of genotypes

A set of 25 rice genotypes, including 9 landraces, 9 advanced breeding lines (ABLs), and 7 released high-yielding varieties (HYVs), were evaluated during seven consecutive *Kharif* (Wet) seasons of 2015 to 2021 (Table 1). The genotypes were evaluated in a plot size of 1 m^2 in an un-replicated evaluation approach. The plant-to-plant and row-to-row spacing was kept at 20 cm under normal transplant conditions. In each year, a wet nursery of rice seedlings was raised in normal upland conditions, and transplanting was done in a low-lying field with >30 cm of standing water. Throughout the season, the rainwater stagnated in the field, with a

Table 1. *Mean performance of genotypes for different traits under study and the category of genotypes*

GEN	Category	NT	EBT	F50	DTH	PH	YLD	SW	HI
Ambika	HYV	7.26	7.26	136.00	167.71	180.84	2823.36	5239.29	0.36
Asfal	Landrace	7.21	7.21	128.71	165.43	183.20	2850.33	4050.73	0.41
C300-BD-50-11	ABL	6.67	6.67	132.29	165.57	190.61	2420.57	4891.19	0.35
CSRC(D)12-8-12	ABL	6.91	6.91	131.14	166.14	184.59	3499.46	5132.70	0.41
CSRC(D)13-16-19	ABL	7.24	7.24	133.29	166.29	176.99	3462.93	4913.17	0.42
CSRC(D)2-0-8	ABL	6.79	6.69	130.29	165.86	187.17	2994.90	5026.84	0.38
CSRC(D)2-17-5	ABL	6.93	6.83	132.57	165.71	184.03	3048.26	5003.21	0.38
CSRC(D)5-2-2-2	ABL	6.72	6.52	130.43	166.86	188.91	3221.79	4361.30	0.42
CSRC(D)7-0-4	ABL	7.48	7.43	132.71	166.57	186.03	3245.09	5010.54	0.39
CSRC(D)7-12-1	ABL	7.43	7.43	132.00	166.43	186.29	2899.07	5056.63	0.37
CSRC(D)7-5-4	ABL	6.38	6.38	129.29	166.00	179.59	3116.04	3859.29	0.44
Dinesh	HYV	7.88	7.88	137.21	168.36	184.26	2729.09	5398.24	0.34
Gavir Saru	Landrace	8.81	8.67	140.71	166.00	149.49	2756.86	5239.86	0.34
Geetanjali	HYV	7.83	7.83	128.71	168.86	163.04	3549.90	4879.43	0.43
Manas Swarobor	Landrace	8.24	8.14	131.29	167.43	168.41	2183.06	4300.04	0.34
NC 678	Landrace	6.69	6.69	128.29	165.29	191.00	2916.59	4121.70	0.42
Najani	Landrace	8.24	8.19	130.86	167.14	180.11	3305.39	4770.40	0.42
Nalini	Landrace	7.48	7.33	132.71	167.57	179.61	2697.96	4904.26	0.36
Patnai-23	HYV	7.40	7.40	133.43	168.14	181.11	3009.50	4738.19	0.38
Purnendu	HYV	7.52	7.52	138.29	168.57	185.27	2373.76	5066.34	0.32
SR26B	HYV	8.71	8.67	130.86	168.57	174.59	3231.63	5167.31	0.39
Sabita	Landrace	7.81	7.76	131.86	168.43	182.01	3028.39	5049.49	0.38
Sada Mota Selection	Landrace	6.57	6.52	129.29	167.00	181.66	2520.67	3464.39	0.40
Swarna Sub-1	HYV	7.19	7.14	129.71	169.07	97.31	1751.19	2736.56	0.36
Tilak Keshari	Landrace	9.38	9.38	137.43	167.29	175.31	2370.96	5393.47	0.31

GEN - Genotype; HYV - High yielding variety; ABL - Advanced breeding line; NT - Number of tillers per hill; EBT - Number of ear bearing tillers per hill; F50 - Days to 50% flowering; DTH - Days to harvesting; PH - Plant height (cm); YLD - Grain yield per hectare (Kg ha^{-1}); SW - Straw weight per hectare (Kg ha^{-1}); HI - Harvest index.

Table 2. *Sowing and transplanting dates as well as weather parameters in each season of evaluation at ICAR-CSSRI, RRS, Canning*

ENV	DOS	DOT	Rainfall (mm)	RD
K-2015	20-06-2015	23-07-2015	1713	86
K-2016	09-06-2016	08-07-2016	1659	75
K-2017	21-06-2017	22-07-2017	1816.3	72
K-2018	21-06-2018	24-07-2018	1387.4	78
K-2019	05-07-2019	08-08-2019	1562.7	61
K-2020	18-06-2020	17-07-2020	1322.9	70
K-2021	01-07-2021	16-08-2021	2751	80

ENV - Environment; DOS - Date of sowing; DOT - Date of transplanting; RD - Number of rainy days.

water level consistently above 50 cm from August to October. After the end of the rainy season, the water receded from the field. The sowing and transplanting dates along with weather parameters are mentioned in Table 2. The standard packages of practice were followed for crop maintenance such as application of 75:40:10 of N:P:K, with all P and K applied as basal (at 10 days after transplanting) and N as 50% basal application (at 10 days after transplanting), two top-dressing of 25% N at booting and reproductive stages. The observations on days to 50% flowering (F50), days to maturity (DTM), plant height (PH), number of tillers (NT), number of effective tillers (EBT), grain yield per plot (YLD), straw yield per plot (SW) were recorded. The F50 were calculated as the days after sowing when approximately 50% of the plants in the plot had flowered. PH was measured on 10 randomly selected plants using a scale and then averaged. The NT and the number of ear-bearing tillers per hill were counted on 10 randomly selected hills per plot and averaged. YLD and SW of net sown plot (1 m^2) was measured and multiplied by 10000 to calculate per hectare grain and straw yield. DTM was calculated as days after sowing when all the plants in the plot has attained physiological maturity. HI was calculated as ratio between YLD and biomass (sum of grain and straw yield).

Analysis of experimental data

The raw data obtained were first subjected to the estimation of the mean performance of the environments, the mean performance of the genotypes across environments, variance, standard deviation, and coefficient of variation using 'agricolae' package in R_4.4.1 (de Mendiburu and de Mendiburu, 2019). Similarly, summary statistics of all the traits across genotypes and environments were also calculated. Normality of data in different years for all the traits were tested using Shapiro-Wilk, Anderson-Darling, Lilliefors, and Jarque-Bera tests. The average performance of all the traits in different years was plotted using violin plots. Before performing averaging of performance across years, the Bartlett's test was done to test the homogeneity of variances across environments. The values of the average performance of genotypes across environments were used to estimate the Pearson's correlation coefficients among all eight traits using 'Hmisc' R-package (Harrell and Harrell, 2019). The correlation among traits was visualized using 'corrplot' package in R (Wei *et al.,* 2017). The standard normal variate ($\bar{X}=0$, $\sigma=1$) of each trait for each genotype was calculated in MS-Excel 2016 from the average value of each trait for each genotype using the following formula (SNV= ($\bar{X}$-μ) ⁄σ). This SNV data was used to calculate the genetic distance between all 25 genotypes of the present study. The Euclidean genetic distance between genotypes was calculated using dissimilarity coefficients using the 'cluster' package in R (Maechler *et al.,* 2013).

Stability analysis

The stable performance of genotypes in different seasons was assessed using genotype by genotype × environment (GGE) interaction biplot analysis of grain yield per hectare (YLD). The mean yield of each genotype in different seasons was used for calculation with in 'metan' R-package (Olivoto and Lucio, 2019). Four distinct biplot graphs were created using the predicted model: 1) GGE biplot between the first two Principal Components; 2) environmental discriminativeness versus representativeness; 3) mean performance versus genotype stability; and 4) which-won-where view of biplot. This parametric approach was used to identify stable genotypes across environments, genotypes specifically tailored to certain environments, performance similarities between environments, and the ability of the environment to differentiate genotypic performance. Similarly, non-parametric Thennarasu's stability statistics were used to identify stable and high-yielding genotypes under semi-deep ecology. The calculations of all the four statistics N_1, N_2, N_3, and N_4 were performed using formula given by Thennarasu(1995) in 'metan' R-package (Olivoto and Lucio, 2019). The ranking of genotypes was done based on these statistics to identify stable and high-yielding genotypes.

RESULTS AND DISCUSSION

The present study underlined the importance of stability of genotypes as varietal performances over season as well as selection strategy of parental lines. The Sundarban region is unique niche of Gangetic delta where crop generally succumbs to climatic vagaries such as erratic rainfall leading to delay in sowing and submergence during early growth stages of rice crop along with stagnated water level throughout cropping period. The set of 25 genotypes including diverse native landraces and advanced breeding lines represent core set of breeding material for semi-deep ecology. Similarly, Lee *et al.* (2023) had performed multi-environment stability analysis to identify stable rice cultivars based on yield performances.

Mean performances of the genotypes

For the NT and EBT, CSRC(D)7-5 - 4 (6.38) had the lowest number of tillers across the environment, while Tilak Kesari (9.38) had the highest. Average F50 was maximum for Gavir Saru (140.71 days) and minimum for NC678 (128.29 days). Das *et al.* (2005) had also reported the similar variation for days to 50% flowering in rice cultivars suited for semi-deep ecology. DTM were almost same (165.29 to 169.07 days) for each genotypes. Genotypes bred for semi-deep ecologies are generally photo-sensitive and of long duration, thus they mature at same time after rainwater recedes from the field. Shalahuddin *et al.* (2019) had also reported a similar condition while developing varieties suited for semi-deep ecology in the deep-flooded ecosystem of Bangladesh. PH was lowest for Swarna-Sub1 (97.31 cm) and highest for NC678 (191 cm). As Swarna-Sub1 is a variety suited for medium land ecology with 14-day flash flood tolerance, it has a quiescent mechanism (minimising metabolic activities to stay alive) for coping with waterlogging in comparison with the escape mechanism (faster internode elongation with increased plant height) in semi-deep cultivars (Prakash *et al.,* 2024; Snehi *et al.,* 2025). Similarly, Swarna-Sub1 (1751.19 kg ha^{-1}) had lowest YLD while Geetanjali (3549.90 kg ha^{-1}) had highest yield. As varieties suited for semi-deep ecology have enhanced capacity of under-water photosynthesis, strong culm, and taller plant height, they are more capable of growth under prolonged waterlogged condition as compared to varieties such as Swarna-Sub1 which lacks such traits (Snehi *et al.,* 2025). SW was lowest in Swarna-Sub1 (2736.56 kg ha^{-1}) while highest in Dinesh (5398.24 kg ha^{-1}). HI was highest in CSRC(D)7-5-4 (0.44) and lowest in Tilak Kesari (0.31). The mean performances of each genotype across environments for all the eight traits are given in Table 1.

Mean performances of environments

Average NT was lowest during *Kharif*-2019 (6.23) and highest during *Kharif*-2021 (9.39), while average EBT was lowest during *Kharif*-2016 (6.19) and highest during *Kharif*-2021 (9.39). Yadav *et al.* (2010) reported similar trends for number of tillers per hill and effective tillers per hill in rice. Mean F50 ranged from 120.72 (*Kharif*-2019) to 143.08 (*Kharif*-2016), which is as usual for semi-deep genotypes (Das *et al.,* 2005). Average DTM was varying between 145.2 days (*Kharif*-2017) to 194 days (*Kharif*-2016). Average PH of crop ranged from 165.45 cm (*Kharif*-2021) to 185.6 cm (*Kharif*-2016). Shalahuddin *et al.* (2019) had also reported similar results in variability for PH, F50, and DTM in genotypes suited for semi-deep ecologies

Table 3. *Mean performance of environments for different traits under study*

ENV	NT	EBT	F50	DTH	PH	YLD	SW	HI
Kharif 2015	7.84	7.84	135.40	184.00	170.81	3501.67	6010.72	0.37
Kharif 2016	6.36	6.19	143.08	194.00	185.60	3021.07	7096.15	0.30
Kharif 2017	7.05	6.95	133.20	145.20	174.81	2607.12	3919.74	0.40
Kharif 2018	6.60	6.60	132.60	164.00	179.92	3092.04	4337.12	0.41
Kharif 2019	6.23	6.21	120.72	152.56	180.77	1915.50	2578.08	0.41
Kharif 2020	8.83	8.83	138.48	175.00	180.65	2108.54	4342.54	0.32
Kharif 2021	9.39	9.39	123.14	154.60	165.45	3915.94	4692.54	0.45

ENV - Environment; NT - Number of tillers per hill; EBT - Number of ear bearing tillers per hill; F50 - Days to 50% flowering; DTH - Days to harvesting; PH - Plant height (cm); YLD - Grain yield per hectare (Kg ha^{-1}); SW - Straw weight per hectare (Kg ha^{-1}); HI - Harvest index.

in Bangladesh. The lowest mean YLD was obtained during *Kharif*-2019 (1915.5 kg ha^{-1}), while it was highest during *Kharif*-2021 (3915.94 kg ha^{-1}). Similarly, SW was maximum during *Kharif*-2016 (7096.15 kg ha^{-1}) and minimum during *Kharif*-2019 (2578.08 kg ha^{-1}). HI was lowest during *Kharif*-2016 (0.30) and highest during *Kharif*-2021 (0.45). The mean value of all the traits in each season are given in Table 3. Interestingly, with significant delay in sowing (July sowing) and transplanting (August transplanting) coupled with

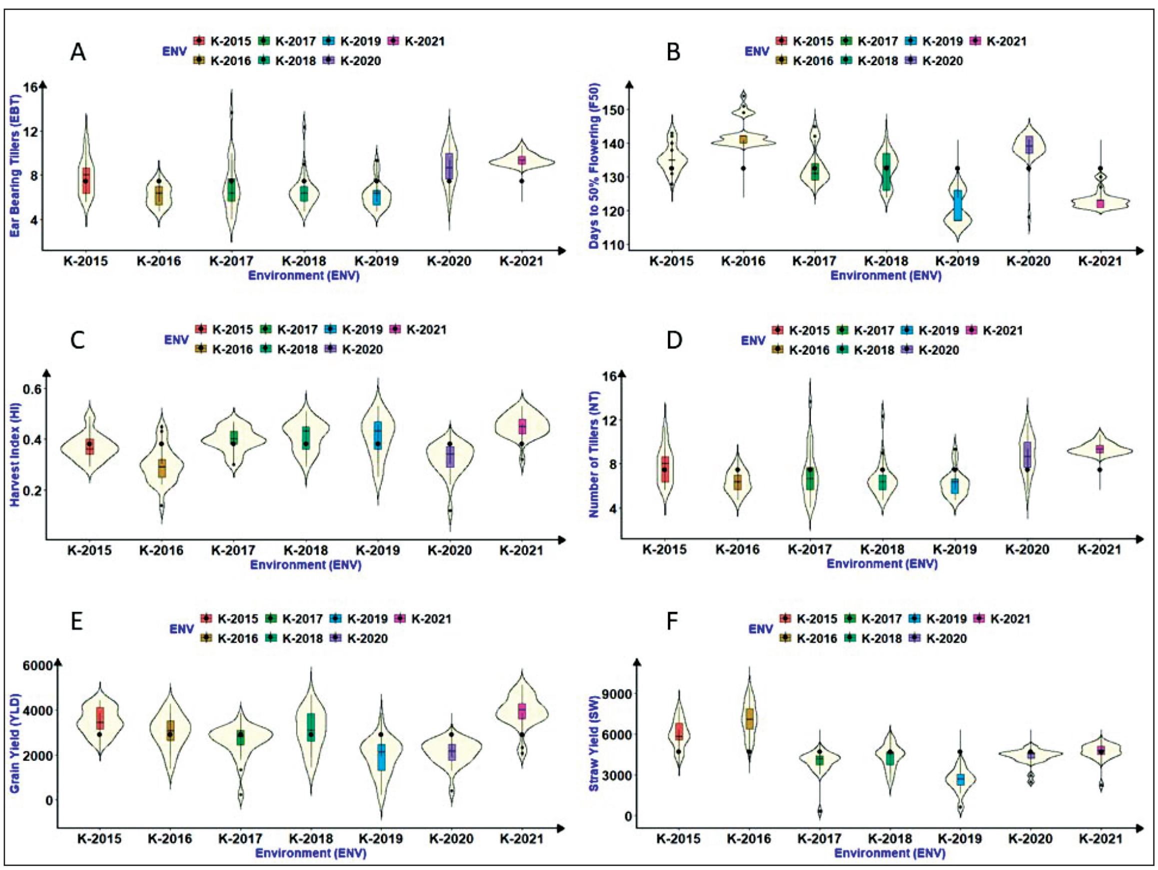

Fig. 1. *Violin plot explaining variations and summary statistics of six traits under study. (A) Ear bearing tillers; (B) Days to 50% flowering; (C) Harvesting index; (D) Number of tillers; (E) Grain yield; and (F) Straw yield*

normal rainfall during the season, there was the reduced number of tillers per hill, a lower number of ear-bearing tillers per hill, and poor grain and straw yield. However, delayed sowing during *Kharif*-2021 (July sowing) coupled with excess rainfall during the entire season was associated with highest yield and HI. Similarly, Verma and Srivastava (2004) had reported different days to flowering in different years with early or late sowing. As most of the genotypes in this set are photosensitive, the days to 50% flowering was lower during season with late sowing. It has been observed that high rainfall is suitable for better yield and productivity under semi-deep ecologies (Chattopadhyay *et al.,* 2018). The mean, variance, median, and distribution of observations for six traits are depicted in Fig.1 as a violin graph for each trait.

Summary statistics for traits

Across seasons mean F50 was 132.37 days and DM was 167.05 days which are in general displaying the inherent nature of genotypes suited for semi-deep ecologies. Average PH was 176.86 cm and it was highly required for semi-deep genotypes to sustain the >50 cm water level during cropping season and to maintain photosynthesis and survival. NT as well as EBT were 7.47 and 7.43, respectively. The vegetative growth for PH generally reduced the number of tillers per plant and it has been observed in our study that sowing dates and rainfall pattern had also impacted these traits. Pradhan *et al.* (2018) had also reported similar results while working on semi-deep rice cultivars. Average YLD across season was 2880.27 kg ha^{-1}, which is quite low as compared to other rice breeding material, but it can be also ascertained that landraces are generally low-yielding and our set of genotypes has 9 landraces and 1 non-suitable variety (Swarna-Sub1). Similarly, the average SW across seasons was 4710.98 kg ha^{-1} with an average HI of 0.38. Coefficient of variation (CV) for all the traits varied from 6.47 (F50) to 34.37 (SW). Normality test using all the four test (Shapiro-Wilk test, Anderson-Darling test, Lilliefors test, and Jarque-Bera test) was significant for DTH, PH, NT, and EBT. All the four normality test was non-significant for YLD. For HI only Shapiro-Wilk test was significant. For SW and F50 all the three test were significant (Shapiro-Wilk test, Anderson-Darling test, Lilliefors test) except Jarque-Bera Test. Test of homogeneity of variance using Bartlet's test was significant for F50, NT, EBT, SW and HI. For DTM, PH, and YLD, it was non-significant. Oladosu *et al.* (2018) had also established the normal distribution for various traits while evaluating rice genotypes under tropic conditions. Table 4 represents

Table 4. *Summary statistics and Normality test of each trait across the environments*

	F50	DTH	PH	NT	EBT	YLD	SW	HI
Summary statistics								
Mean	132.37	167.05	176.86	7.47	7.43	2880.27	4710.98	0.38
Standard error	0.65	1.28	1.60	0.14	0.14	73.77	122.39	0.01
Variance	73.42	284.92	448.80	3.52	3.59	952469.90	2621319.00	0.01
Standard deviation	8.57	16.88	21.18	1.88	1.89	975.95	1619.05	0.08
Coefficient of variation	6.47	10.10	11.98	25.10	25.51	33.88	34.37	20.36
Normality test								
Shapiro-Wilk test	0.96**	0.89**	0.79**	0.97**	0.97**	0.99ns	0.97**	0.98*
Anderson-Darling test	2.12**	7.21**	8.33**	2.11**	2.18**	0.3ns	2.14**	0.63ns
Lilliefors test	0.10**	0.20**	0.16**	0.13**	0.12**	0.037ns	0.10**	0.07ns
Jarque-Bera test	4.68ns	15.61**	533.5**	7.44*	7.17*	1.78ns	4.99ns	5.59ns
Test for homogeneity of variances								
Bartlet test	12.74*	Infinite	3.67ns	51.67**	53.14**	8.38ns	18.94**	13.05*

GEN - Genotype; NT - Number of tillers per hill; EBT - Number of ear bearing tillers per hill; F50 - Days to 50% flowering; DTH - Days to harvesting; PH - Plant height (cm); YLD - Grain yield per hectare (Kg ha^{-1}); SW - Straw weight per hectare (Kg ha^{-1}); HI - Harvest index.

summary statistics for all the traits along with normality tests and tests for homogeneity of variance.

Trait correlation under semi-deep ecology

Using mean value for all the traits across seasons, Pearson's correlation coefficients among traits were calculated. F50 has a significant positive correlation with NT (0.53) and the EBT (0.53), whereas it has a significant negative correlation with HI (-0.74). It may be noted that varieties not suited for semi-deep ecologies with lesser F50 will have less vegetative growth leading to reduced number of tillers (Chattopadhyay *et al.,* 2018). On the contrary, if there is too much vegetative growth and plant is flowering later, it may not have enough resources for development of economic part leading to HI. It concludes that an optimum duration (~ 150 days to maturity) is required while developing high yielding varieties suited for semi-deep ecologies. Tabien *et al.* (2009) had also reported similar results for grain and developmental traits with flowering related traits in rice. A significant negative correlation (-0.42) was found between DTM) and PH, while significant positive correlation for DTM was with NT (0.41) and EBT (0.42). A significant positive correlation was shown for PH with YLD (0.48) and SW (0.50). In semi-deep ecology, the more vigorous vegetative growth (plant height) represents more photosynthetic machinery above the stagnating water level and thus leading to more economic yield (Das *et al.,* 2005). NT was very highly correlated (0.99) with EBT and SW (0.46), while it was significantly negatively correlated with HI (-0.50). Similarly, EBT was significantly positively correlated with SW (0.46) and negatively correlated with HI (-0.49). YLD was significantly positively correlated with SW (0.41) and HI (0.72). Therefore, development of semi-deep genotypes should consider optimum days to flowering (which will already take care of number of tillers, days to maturity), plant height and at last yield (Gao *et al.,* 2022). A figure depicting all the significant correlation among these eight traits are is given (Fig.2).

Genetic diversity in genotypes evaluated under semi-deep ecology

Diversity among all the 25 genotypes can be a guiding factor in deciding parental combinations as well as selection of diverse lines. Hussain *et al.* (2023) had

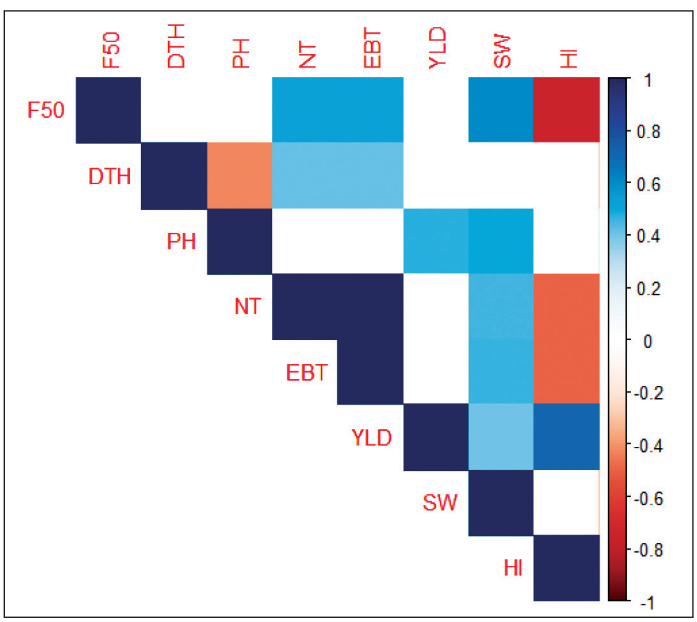

Fig. 2. *Significant correlation between all the eight traits under study based on mean values over the environments [NT - Number of tillers per hill; EBT - Number of effective tillers per hill; F50 - Days to 50% flowering; DTH - Days to harvesting; PH - Plant height (cm); YLD - Grain yield per hectare (Kg ha^{-1}); SW - Straw weight per hectare (Kg ha^{-1}); HI - Harvest index*

Table 5. *Euclidean distance matrix of all the 25 genotypes based on mean of all the eight traits over environment.*

	Ambika	Asfal	C300-BD-50-11	CSRC(D)12-8-12	CSRC(D)13-16-19	CSRC(D)2-0-8	CSRC(D)2-17-5	CSRC(D)5-2-2-2	CSRC(D)7-0-4	CSRC(D)7-12-1	CSRC(D)7-5-4	Dinesh	Gavir Saru	Geetanjali	Manas Swarobor	NC678	Najani	Nalini	Patnai-23	Purnendu	SR26B	Sabita	Sada Mota Selection	Swarna Sub-1	Tilak Keshari
Ambika	0	3.80	2.72	3.04	2.73	2.69	2.30	3.30	1.99	1.74	4.36	1.48	3.88	3.83	3.19	4.13	3.18	1.22	1.41	1.98	3.43	1.93	3.98	6.78	4.36
Asfal		0.00	2.92	2.51	2.54	2.12	2.26	2.04	2.48	2.48	1.93	4.80	5.74	3.92	3.72	1.11	2.91	3.08	3.10	5.20	4.44	3.44	2.21	6.58	6.30
C300-BD-50-11			0.00	3.24	3.47	1.77	1.81	3.18	2.83	2.04	3.65	3.79	5.25	5.26	3.64	2.88	4.30	2.38	3.14	3.66	5.17	3.69	3.15	6.97	5.71
CS-RC(D)12-8-12				0.00	1.07	1.60	1.54	1.64	1.50	2.21	2.56	4.22	5.60	3.24	4.75	2.42	2.70	2.98	2.60	4.95	4.08	2.91	3.64	7.78	6.43
CS-RC(D)13-16-19					0.00	2.14	1.75	1.96	1.21	2.14	2.78	3.80	4.84	2.94	4.35	2.79	2.15	2.77	2.23	4.61	3.61	2.59	3.69	7.39	5.86
CSRC(D)2-0-8						0.00	0.79	1.89	1.77	1.55	2.61	3.94	5.48	4.00	4.01	1.96	3.26	2.32	2.56	4.32	4.42	2.99	2.95	7.21	6.09
CSRC(D)2-17-5							0.00	2.07	1.41	1.33	2.81	3.56	4.87	4.01	3.90	2.30	3.09	2.16	2.35	4.00	4.27	2.88	3.19	7.21	5.70
CSRC(D)5-2-2-2								0.00	2.21	2.65	1.41	4.55	6.26	3.39	4.57	1.71	3.11	3.00	2.52	4.97	4.51	3.07	2.29	7.02	6.92
CSRC(D)7-0-4									0.00	1.08	3.26	2.92	4.39	2.98	3.52	2.88	1.84	1.84	1.56	3.75	3.01	1.81	3.58	7.27	4.99
CSRC(D)7-12-1										0.00	3.56	2.62	4.23	3.56	2.86	2.92	2.41	1.22	1.70	3.22	3.22	1.94	3.41	6.93	4.57
CSRC(D)7-5-4											0.00	5.64	6.89	4.21	5.09	1.36	3.94	3.94	3.62	5.93	5.48	4.19	2.04	6.78	7.75
Dinesh												0.00	3.35	4.27	3.08	5.32	3.52	2.00	2.22	1.41	3.08	2.23	5.06	7.15	3.20
Gavir Saru													0.00	5.72	3.98	6.53	4.53	4.14	4.45	3.92	4.34	4.47	6.62	7.44	2.63
Geetanjali														0.00	4.35	4.43	2.08	3.46	2.69	5.23	2.33	2.24	4.50	6.76	6.00
Manas Swarobor															0.00	4.57	3.44	2.27	2.94	3.17	3.33	2.89	3.93	5.21	3.53
NC678																0.00	3.66	3.56	3.54	5.62	5.21	3.98	2.16	7.12	7.15
Najani																	0.00	2.75	2.25	4.57	1.85	1.82	4.19	7.16	4.77
Nalini																		0.00	1.19	2.37	3.06	1.55	3.28	6.15	4.30
Patnai-23																			0.00	2.85	2.72	1.03	3.26	6.35	4.77
Purnendu																				0.00	4.25	3.16	4.97	6.77	3.73
SR26B																					0.00	1.84	5.30	7.19	3.91
Sabita																						0.00	3.89	6.65	4.41
Sada Mota Selection																							0.00	5.50	7.06
Swarna Sub-1																								0.00	7.93
Tilak Keshari																									0.00

also analysed genetic diversity of rice genotypes suited for semi-deep ecology and characterized them for various traits to be incorporated in breeding programs. In the present study, maximum (7.93) Euclidean genetic distance was found between Swarna-Sub1 and Tilak Kesari, while minimum (0.79) was between CSRC(D)2-17-5 and CSRC(D)2-0-8. As expected, Swarna-Sub1 was at separate node with very diverse traits not suitable under semi-deep ecology. Other genotypes were clustered in two different clusters A and B. Cluster A comprised of only two genotypes Tilak Keshari and Gavir Saru, whereas cluster B comprised of other 22 genotypes. Cluster B was divided into two different sub-clusters B1 and B2. Sub-cluster B1 had 12 genotypes including all 9 advanced breeding lines (C300-BD-50-11, CSRC(D)12-8-12, CSRC(D)13-16-19, CSRC(D)2-0-8, CSRC(D)2-17-5, CSRC(D)5-2-2-2, CSRC(D)7-0-4, CSRC(D)7-12-1, and CSRC(D)7-5-4), NC678, Asfal, and Sada Mota Selection. Sub-cluster B2 was constituted by 10 genotypes including Nalini, Ambika, Sabita, Patnai-23, Purnendu, Dinesh, Manas Swarobor, SR26B, Najani, and Geetanjali. Clustering of all advanced breeding lines altogether into same sub-cluster (B1) was obvious because they are derived out of similar cross Pankaj × Najani, and Pankaj × SR26B. A table containing Euclidean genetic distances between all the 25 genotypes are given in Table 5. The phylogenetic tree depicting different clusters and sub-clusters is given in Fig. 3. The cophenetic correlation between Euclidean distance matrix and phylogenetic tree was 0.8454, therefore tree constructed truly represent the genetic distance among genotypes.

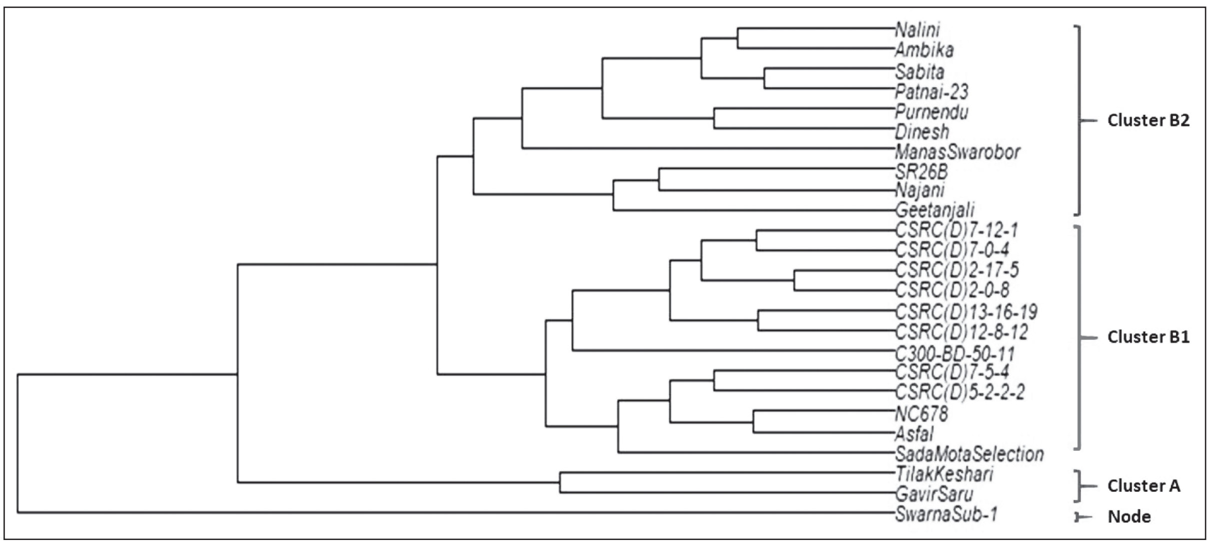

Fig. 3. *Phylogenetic tree constructed using Euclidean distance among all the 25 genotypes used in the present study employing Unweighted Pair Group Method with Arithmetic Mean (UPGMA).*

Thennarasu's stability statistics

Stability in terms of performance of a genotype along with a higher mean yield across environments is a desirable trait while selecting the best parents for crossing, as well as the best segregating progenies based on family. Based on grain yield per plant across the season, Geetanjali (3549.9 kg ha^{-1}), CSRC(D)12-8-12 (3499.5 kg ha^{-1}), and CSRC(D)13-16-19 (3462.9 kg ha^{-1}) were the top-ranking varieties. Thennarasu's non-parametric stability index rank genotypes based on mean-rank changes (N_1 and N_2) and changes in variance (N_3 and N_4). Based on the ranking of genotypes for mean absolute rank difference (N_1), CSRC(D)12-8-12 (2.71), Geetanjali (4.14), and Nalini (4.29) are the top three stable and high-yielding genotypes. Based on variance of ranks statistics (N_2), Gavir Saru, Purnendu, and Nalini are the most stable genotypes. Based on the sum of absolute rank differences (N_3), Nalini, Purnendu, and Ambika are the highly stable genotypes. Based on the

Table 6. *Thennarasu's non-parametric statistics of all the 25 genotypes and their ranking for stable performances and yield*

GEN	Y	Y_R	N1	N1_R	N2	N2_R	N3	N3_R	N4	N4_R
Ambika	2823.36	16	5.00	8	0.36	10	0.39	3	0.0453	19
Asfal	2850.33	15	5.29	11.5	0.35	8	0.46	10	0.0103	6
C300-BD-50-11	2420.57	21	7.86	22.5	0.49	15	0.51	12	0.0056	4
CSRC(D)12-8-12	3499.46	2	2.71	1	0.68	18	0.75	19	0.0000	1.5
CSRC(D)13-16-19	3462.93	3	5.43	13	1.36	25	1.12	25	0.1270	25
CSRC(D)2-0-8	2994.9	12	7.86	22.5	0.71	20.5	0.72	17	0.0675	24
CSRC(D)2-17-5	3048.26	9	5.14	9.5	0.47	12	0.57	14	0.0513	22
CSRC(D)5-2-2-2	3221.79	7	5.14	9.5	0.86	23	0.75	18	0.0258	13
CSRC(D)7-0-4	3245.1	5	6.29	18.5	1.14	24	0.80	22	0.0213	10
CSRC(D)7-12-1	2899.07	14	6.00	15.5	0.35	9	0.45	9	0.0455	20
CSRC(D)7-5-4	3116.04	8	7.86	22.5	0.79	22	0.82	23	0.0489	21
Dinesh	2729.09	18	4.43	4	0.34	6	0.45	8	0.0297	15
Gavir Saru	2756.86	17	4.71	5.5	0.26	1	0.40	5	0.0303	16
Geetanjali	3549.9	1	4.14	2	0.69	19	1.06	24	0.0082	5
Manas Swarobor	2183.06	24	7.86	22.5	0.34	7	0.44	7	0.0372	17
Najani	3305.39	4	4.71	5.5	0.67	17	0.76	20	0.0164	7
Nalini	2697.96	19	4.29	3	0.29	3	0.34	1	0.0406	18
NC678	2916.586	13	6.29	18.5	0.48	13	0.55	13	0.0226	11
Patnai-23	3009.5	11	4.86	7	0.49	14	0.58	15	0.0165	8
Purnendu	2373.76	22	6.14	17	0.28	2	0.38	2	0.0199	9
Sabita	3028.39	10	5.29	11.5	0.53	16	0.59	16	0.0533	23
Sada Mota Selection	2520.67	20	5.86	14	0.39	11	0.43	6	0.0282	14
SR26B	3231.63	6	7.14	20	0.71	20.5	0.78	21	0.0000	1.5
Swarna Sub-1	1751.19	25	8.00	25	0.32	5	0.50	11	0.0049	3
Tilak Keshari	2370.96	23	6.00	15.5	0.30	4	0.39	4	0.0227	12

GEN - Name of the genotype; Y - Grain yield per hectare; Y_R - Ranking of genotypes based on yield; N_1 - First Thennarasu's statistics; N1_R - Ranking of genotypes based on First Thennarasu's statistics; N_2 - Second Thennarasu's statistics; N2_R - Ranking of genotypes based on Second Thennarasu's statistics; N_3 - Third Thennarasu's statistics; N3_R - Ranking of genotypes based on Third Thennarasu's statistics; N_4 - Fourth Thennarasu's statistics; N4_R - Ranking of genotypes based on fourth Thennarasu's statistics.

variance adjusted stability index (N_4), CSRC(D)12-8-12, SR26B, and Swarna Sub-1 are the most stable genotypes. All four stability index (N_1, N_2, N_3, and N_4) of all the 25 genotypes in the present study along with their ranking based on these statistics are given in Table 6. Based on all the four statistics, CSRC(D)12-8-12, Nalini, and Gavir Sarur, and Geetanjali are the best genotypes. Sitaresmi *et al.* (2019) had also performed stability analysis of 12 rice genotypes grown under 16 different environments using non-parametric approach and compared them with regression-based statistics.

Genotype (G) and Genotype × Environment interaction (GE) analysis

Genotype and Genotype × Environment (GGE) biplot interaction established the stability of genotypes in the present study. The two major principal components determined 44.07% (PC1) and 18.91% (PC2) of variance. Zewdu *et al.* (2020) performed GGE biplot analysis to establish stability of 13 rice

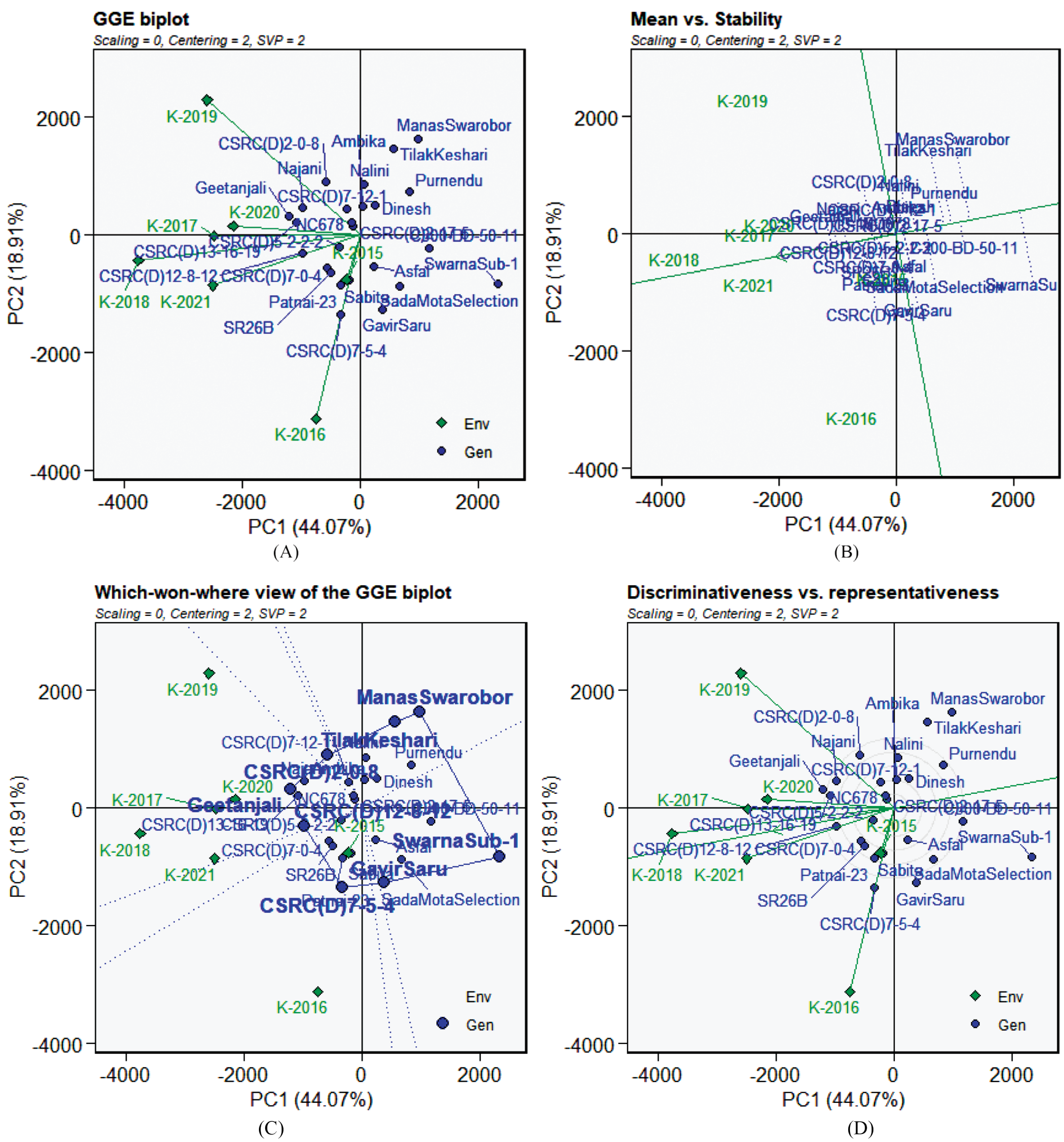

Fig. 4. *Genotype and Genotype-by-Environment (GGE) biplot for stability analysis of 25 genotypes evaluated under semi-deep conditions for seven Kharif seasons (2015-2021). (A) GGE Biplot; (B) Mean vs. Stability graph; (C) Which-Won-Where view of GGE Biplot; and (D) Discriminativeness vs. representativeness graph of GGE biplot*

genotypes evaluated under upland conditions. *Kharif* 2016 and *Kharif* 2019 were two distinct environments, while all others were clustering together; however, all the genotypes were on the same side of the Y-axis, representing a similar pattern of differentiating the genotypes based on environmentally specific response. All the genotypes were distributed among different quadrants of the plot, representing the trustworthiness of the analysis (Fig. 4A). Swarna Sub1, Manas Swarobor, and Tilak Keshari are the genotypes with very poor yield as well as poor stability as they are at most distant in the opposite direction on AEA axis as well as very distant from the axis line (Fig. 4B). CSRC(D)7-5-4 and Gavir Saru performed best in *Kharif* 2016, while Sawrna Sub1 and Manas Swarobor are the least suited varieties across environments. Tilak Keshari and CSRC(D)2-0-8 are stable and good performer during *Kharif* 2019. CSRC(D)12-8-12 and Geetanjali are the most stable and high yielding during *Kharif* 2015, *Kharif* 2017, *Kharif* 2018, *Kharif* 2020, and *Kharif* 2021 (Fig. 4C). CSRC(D)12-8-12 is altogether the most stable and high-yielding genotype based on being the one with the farthest from origin as well as in the direction of the average environmental axis (AEA). *Kharif* 2018 is the most discriminative and representative environment, as it is very distant from the centre as well as having the least angle from the average environment axis (Fig. 4D).

CONCLUSION

The present study highlighted the importance of diversity analysis and assessment of the stability of varietal performances across different environments evaluated under semi-deep water ecologies. Clustering of genotypes based on morphological observations were sufficient to establish relationship among genotypes as genotypes with similar parentages were clustering together. Based on parametric as well as non-parametric stability analysis, CSRC(D)12-8-12 was the most stable and high yielding genotype along with Geetanjali. Along with CSRC(D)12-8-12, other advanced breeding lines such as CSRC(D)13-16-19, CSRC(D)5-2-2-2, CSRC(D)7-5-4, and CSRC(D)2-17-5 were also suitable for the submission into varietal release pipeline.

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CONFLICTS OF INTEREST

Authors declare that there is no financial or competing interest.

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