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GENOTYPE × ENVIRONMENTAL INTERACTION FOR SALT TOLERANCE IN ELITE GENOTYPES OF RICE *(ORYZA SATIVAL.)*

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Article Info

Abstract

The present study was conducted to evaluate the genetic performance of ten rice *(Oryza sativa* L.) genotypes under saline and non-saline conditions across three different locations. The experiment was laid out in a randomized complete block design (RCBD) with three replications, and data were recorded for various morphological and physiological traits. The analysis of variance (ANOVA) revealed significant differences ($p \leq 0.01$) among genotypes for most traits, indicating substantial genetic variation. However, sodium and potassium content exhibited non-significant differences across treatments. The mean performance results indicated that L8, L9, and L10 exhibited superior adaptability under non-saline conditions, producing the highest grain yield plant-1 and demonstrating strong vegetative growth. Conversely, under saline conditions, L5 and L8 showed greater resilience, maintaining stable yield and physiological performance despite salt stress. Some genotypes, such as L6 and L7, displayed moderate yield but maintained stable performance across environments, suggesting their potential for salinity tolerance. Stability analysis using the Eberhart & Russell model further confirmed the consistency of performance across varying environmental conditions. Genotypes L8 and L9 exhibited high stability across locations, while L5 and L8 emerged as promising candidates for saline-affected areas due to their ability to sustain yield under stress conditions. The findings of this research provide valuable insights into genotype selection for saline-affected regions. The identified high-performing genotypes L8 and L9 can be recommended for further breeding programs and potential commercial cultivation to enhance rice productivity in salt-stressed environments.

Keywords:
Rice, physiological parameters, Salinity, Stability analysis, ANOVA, Correlation

INTRODUCTION

Rice is a staple food for over half the world's population, especially in Asia, and provides essential nutrients, including carbohydrates, vitamins, and minerals (ds et al., 2022; El-Mowafi et al., 2021). It is grown mainly in flooded or irrigated fields, requiring warm temperatures (20–35°C) and careful water management, though upland and rainfed cultivation also exist (Sarkar et al., 2018). Rice contributes significantly to the global economy, supplying over 21% of human energy needs and up to 76% of daily calories in Southeast Asia (Zhao et al., 2022). Pakistan ranks as the tenth-largest producer and fourth in exports, with rice being the second most important staple crop and a major contributor to agriculture and GDP (Shaikh et al., 2011; World Atlas, 2018). In Pakistan, rice is a vital staple and major crop, providing essential nutrients, supporting food security, employment, farmer income, and foreign exchange earnings (Mehmood et al., 2021; Khush, 2021). Soil salinity, a major challenge in arid and semi-arid regions, affects 20% of cultivated and 33% of irrigated land globally and can reduce yields by 10–25%, sometimes causing desertification (El Azzouzi et al., 2019; Agegnehu et al., 2017). Addressing salinization through improved soil, water, and crop management is crucial for maintaining agricultural productivity and food security (Mustafa et al., 2019). High salinity affects 20% of global cultivated land and 33% of irrigated land, with South Asia alone having 52 million hectares impacted (Kumar et al., 2021; Mondal et al., 2018). About 15% of the world's land is severely affected, while the rest is moderately impacted (Widyayanti et al., 2017). Developing salt-tolerant rice varieties is therefore a key breeding goal, with numerous QTLs identified for traits such as survival, root and shoot growth, Na^+/K^+ uptake, and ion ratios under salt stress (De Leon et al., 2016; Bizimana et al., 2017). Stability refers to a plant's ability to maintain yield across varying environments, influenced by genotype × environment (G×E) interactions (Torres & Henry, 2018; Krishnamurthy et al., 2016). G×E analysis helps determine whether a cultivar can perform well universally or needs targeting to specific environments (Sharifi et al., 2017; Islam et al., 2014). Due to recent floods, Pakistan's 2022–2023 rice production is projected at 8.3 million tons, down 9% from 9.1 million tons the previous year, with Sindh contributing about 30% of the total rice area (USDA, 2022; MOWR, 2022).

Materials and Methods

The present was conducted during the Kharif season, year 2023 at Student's Experimental Farm Department of Agronomy, Sindh Agriculture University Tandojam, these genotypes have been raised from segregating F_4 population. Rice Research Institute, Dokri and Southern Rice Research Institute, Thatta. The experiment was laid out in Factorial Randomized Complete Block Design (RCBD) with three replications and row to row distance is 20 cm with two treatments (Non-saline and Saline fields).

Genotypes (10)

L-4
L-6
L-16
L-22
L-28
L-30
L-32

L-34
L-36
L-38

Observations to be Recorded

Morphological characters:
Plant height (cm)
Number of tillers plant^{-1}
Panicle length (cm)
Number of grains panicl^{-1}
1000 grain weight (g)
Biological yield plant^{-1} (g)
Grain yield plant^{-1} (g)
Harvest index (%)
Physiological parameters:
Sodium content (Na^+)
Potassium (K^+)
Leaf area (cm^2)
Chlorophyll content (RG)

Statistical Design

The analysis of variance will be calculated according to Gomez and Gomez (1984). The mean performance of all traits will be compared using the least significant difference (LSD) at the 5% probability level. Data will be analyzed after G × E interaction and stability parameters followed by models from Eberhart and Russell (1966).

Results

The present study was conducted during the Kharif season, year 2023 on locations of the Research which are mentioned in above methods and Materials. Student's Experimental Farm, Department of Agronomy, Sindh Agriculture University Tandojam, these genotypes have been raised from segregating F_4 population. Rice Research Institute, Dokri and Southern Rice Research Institute, Thatta. The experiment will be laid out in Factorial(Randomized Complete Block Design) with three replications and row to row distance is 20 cm with two treatments (Normal and Saline fields).

Analysis of Variance

The ANOVA results indicated highly significant differences **(**$p \leq 0.01$**)** among rice genotypes for most morphological and physiological traits under both saline and non-saline conditions. Under non-saline conditions, genotypes exhibited significant variation for plant height, tillers per plant, panicle length, grains per panicle, 1000-grain weight, grain yield per plant, harvest index, and chlorophyll content, while biological yield was non-significant. Treatments significantly influenced most traits, except sodium and potassium content. The genotype × treatment interaction was significant for all traits except panicle length.

On the other hand, under saline conditions, plant height, tillers per plant, panicle length, grains per panicle, 1000-grain weight, biological yield and grain yield per plant varied significantly among genotypes, whereas harvest index, sodium, and potassium content were non-significant. Treatments significantly affected all traits except number of grains per panicle and harvest index. The genotype × treatment interaction was significant for most traits but not for panicle length, grain yield, harvest index, and sodium content. These findings highlight the differential response of rice genotypes to environmental conditions, with significant genotype × treatment interactions shaping key agronomic traits.

Table 4.1a: Mean squares for analysis of variance for different morphological and physiological parameters under non-saline field in rice genotypes at Tandojam, Dokri, and Thatta

Traits	Mean Squares				
	Replication (D.F.=2)	**Genotype (G) (D.F.=09)**	**Treatment (T) (D.F.=2)**	**G x L (D.F.=2)**	**Error (D.F.=58)**
Plant height	8.006	93.856**	258.312**	26.001**	2.959
Tillers plant^{-1}	9.441	8.155**	17.376**	3.093**	2.985
Panicle length	19.756	23.975**	61.305**	2.399ns	2.176
Number of grainspanicle^{-1}	66.18	59.95**	1718.13**	54.04**	3.03
1000 grain weight	37.55	95.92**	2064.11**	888.34**	220.51
Biological yield plant^{-1}	6.461	202.790ns	3.974**	47.200**	15.116
Grain yield plant^{-1}	4.840**	8.454**	95.215**	7.385**	1.444
Harvest index %	7.053	38.552**	496.376**	31.200**	7.624
Leaf area	10.023	15.881**	41.742**	7.769*	2.631
Chlorophyll content	35.494	13.054**	39.063**	5.200**	2.454
Sodium content	0.0006	0.0070**	0.0174**	0.0018**	0.0004
Potassium content	0.0051	0.0088**	0.0063**	0.0004**	0.0001

******= Significant at 1% level of probability, ******= Highly Significant at 1% level of probability.

Ns= Non-Significant at 1% level of probability.

Table 4.1b: Mean squares for analysis of variance for different morphological and physiological parameters under saline field in rice genotypes at Tandojam, Dokri and Thatta

Traits	Mean Squares				
	Replication (D.F.=2)	Genotype (G) (D.F.=09)	Treatment (T) (D.F.=2)	G x L (D.F.=2)	Error (D.F.=46)
Plant height	13.137	56.204**	929.684**	56.204**	15.247
Tillers plant^{-1}	0.477	5.554*	7.406**	0.693ns	1.586
Panicle length	5.822	6.507*	6.566**	2.312ns	1.552
Number of grains panicle^{-1}	7.51	6.80**	2806.94ns	25.25**	10.50
1000 grain weight	1.408	18.575**	320.316*	12.334*	6.839
Biological yield plant^{-1}	7.77	42.09**	1360.69**	19.96**	3.54
Grain yield plant^{-1}	2.398	2.688**	7.017**	1.305ns	0.964
Harvest index %	30.833	4.502**	234.894ns	3.380ns	2.937
Leaf area	3.594	45.514**	58.293**	12.152**	4.049
Chlorophyll content	9.113	33.871*	100.842**	12.567**	3.003
Sodium content	0.0016	0.0073ns	0.0001**	0.0009*	0.0001
Potassium content	0.0043	0.0019ns	0.0003**	0.0003*	0.0001

*= Significant at 1% level of probability, **= Highly Significant at 1% level of probability.

Ns= Non-Significant at 1% level of probability.

4.2 Mean Performance

The data regarding mean performance of rice varieties is presented in following above Tables. Below are the comparative details of mean performance of different traits under saline and non-saline field conditions:

4.2. Plant Height (cm)

The results for plant height suggested that the genotypes L8 and L7 exhibited tallest plants as (95.13 cm) in Tandojam and (90.24 cm) in Dokrias shown in Table 4.2.1 under non-saline condition. The shortest plant height among rice genotypes under non-saline conditions was observed in genotype L2(79.253 cm) in Thatta. Whereas genotypes L8 showed highest plant height across the three locations of the experiment under saline field conditions and shortest height was observed in L6 (61.463cm) in Dokri.

Table 4.2.1: Mean performance of morphological parameters for plant height (cm) under non-saline and saline fields in rice population at different locations

Genotypes	Plant Height (cm)						RD %
	Non-Saline Field			Saline Field			
	Tandojam	Dokri	Thatta	Tandojam	Dokri	Thatta	
L1	79.310	80.680	82.173	76.577	69.263	70.843	**10.52**
L2	87.157	82.500	79.253	76.837	63.170	68.773	**16.12**
L3	83.727	81.153	83.237	78.393	68.603	67.847	**13.41**
L4	80.670	80.907	79.710	79.150	70.123	65.677	**10.92**
L5	83.557	82.263	80.593	70.843	64.250	64.733	**18.91**
L6	91.417	89.760	82.393	74.493	61.463	61.758	**24.99**
L7	93.220	90.240	79.773	74.833	69.570	67.673	**19.43**
L8	95.130	88.517	82.470	80.693	71.310	69.752	**16.67**
L9	84.653	82.477	80.657	78.327	70.430	63.273	**14.43**
L10	91.767	88.707	82.03	75.313	67.513	63.167	**21.53**
LSD (5%)	**G = 15.83**			**L = 26.26**		**G x L = 8.33**	

4.2.2 Tillers Plant^{-1}

The results for tillers plant^{-1} suggested that the genotypes L10and L3 exhibited maximum tillers per plants, i.e. (22.913) in Tandojam and (21.270) inDokrias shown in table 4.2.2 under non-saline condition. Minimum tillers plant^{-1} under non-saline conditions were observed in genotype L2 (18.590) in Thatta. Whereas genotypes L4(20.820) inTandojam and L9 (20.323) inDOkri showed maximum tillers plant^{-1} under saline field conditions and minimum tillers were observed in L1 (17.320) in Dokri.

Table 4.2.2: Mean performance of morphological parameters for tillers plant-1under non-saline and saline fields in rice population at different locations

Genotypes	Tillers Plant^{-1}		RD %
	Non-saline field	Saline field	

	Tandojam	Dokri	Thatta	Tandojam	Dokri	Thatta	
L1	19.330	18.667	19.727	18.673	17.320	17.657	**7.06**
L2	22.647	19.770	18.590	18.950	18.457	17.383	**10.19**
L3	21.443	21.270	21.270	18.827	19.697	18.673	**10.61**
L4	22.577	19.473	20.447	20.820	19.737	18.640	**5.28**
L5	18.257	18.847	19.363	18.493	18.370	18.370	**2.19**
L6	19.637	20.680	19.547	18.443	18.143	17.513	**9.63**
L7	19.433	19.530	19.530	18.510	18.537	18.323	**5.34**
L8	22.217	20.497	20.433	20.570	19.897	19.407	**5.18**
L9	21.237	20.373	20.430	20.313	20.323	19.117	**3.69**
L10	22.913	19.097	21.793	20.187	18.457	18.767	**10.02**
LSD (5%)	**G = 4.67**			**L = 6.81**		**G x L = 2.87**	

4.2.3: Panicle length (cm)

The results for panicle length suggested that the genotypesL and L2exhibited maximum panicle length as (25.027cm) in Tandojam and (21.487 cm) in Dokri and Thattaas shown in Table 4.2.3 under non-saline condition. Minimum panicle length among rice genotypes under non-saline condition was observed in genotype L3 (17.097 cm) in Dokri and Thatta. Whereas genotypes L6 (22.970 cm) in Tandojam and L7 (21.710 cm) in Thatta showed maximum panicle length under saline field conditions and shortest panicle length was observed in L1 (18.583 cm) in Tandojam.

Table 4.2.3: Mean performance of morphological parameters for panicle length under non-saline and saline fields in rice population at different locations

Genotypes	**Panicle length (cm)**						**RD %**
	Non-saline Field			**Saline Field**			
	Tandojam	**Dokri**	**Thatta**	**Tandojam**	**Dokri**	**Thatta**	
L1	18.917	17.587	17.587	18.583	20.163	20.907	**-10.28**
L2	21.563	21.487	21.487	20.373	20.503	19.800	**5.98**
L3	21.913	17.097	17.097	20.367	20.033	20.403	**-8.37**
L4	20.360	19.473	19.473	21.027	20.679	18.463	**-1.46**
L5	23.547	20.280	20.280	22.367	21.027	19.897	**1.27**

L6	25.027	20.680	20.680	22.970	22.450	21.437	**-0.71**
L7	23.080	20.400	20.400	20.563	20.623	21.710	**1.54**
L8	24.717	21.067	21.067	22.013	21.903	19.403	**5.28**
L9	19.580	17.407	17.407	19.667	19.583	18.560	**-6.28**
L10	20.683	19.150	19.150	20.397	20.587	19.300	**-2.21**
LSD (5%)	**G = 8.00**			**L = 12.79**		**G x L = 2.53**	

4.2.4: Number of Grains Panicle^{-1} (g)

The results for number of grains panicle^{-1} suggested that the genotypes L4 and L3 exhibited maximum number of grains panicle^{-1} as (105.35 g)in Tandojam and (97.78 g) inDokrias shown in Table 4.2.4 under non-saline condition. Minimum grain panicle^{-1} were found in genotype L4 (81.23 g) in Thatta under non-saline conditions. Whereas genotypes L7 (87.527 g) inTandojam and L4 (71.593 g) in Thatta showed maximum grains panicle^{-1} under saline field conditions and minimum quantity was observed in L5 (61.247 g) inDokri.

Table 4.2.4: Mean performance of morphological parameters for number of grains panicle^{-1} under non-saline and saline fields in rice population at different locations

Genotypes	**Number of Grains Panicle^{-1}**						**RD %**
	Non-saline Field			**Saline Field**			
	Tandojam	**Dokri**	**Thatta**	**Tandojam**	**Dokri**	**Thatta**	
L1	99.26	92.45	92.41	79.490	68.297	68.777	**23.78**
L2	95.02	95.75	81.42	77.687	64.18	65.573	**23.79**
L3	103.72	97.78	82.93	82.733	63.79	64.201	**25.91**
L4	105.35	90.69	81.23	81.463	62.457	71.593	**22.27**
L5	101.39	87.08	86.36	81.910	61.247	69.257	**22.71**
L6	101.64	92.38	82.63	83.917	61.743	66.527	**23.3**
L7	101.33	86.56	83.77	87.527	62.65	63.647	**21.29**
L8	104.54	97.70	92.81	81.087	59.37	67.477	**29.53**
L9	97.55	96.45	83.53	78.907	65.383	65.757	**24.32**
L10	90.80	95.65	82.38	79.263	65.653	65.471	**21.74**
LSD (5%)	**G = 12.65**			**L = 67.72**		**G x L = 12.01**	

4.2.5 1000-Grain Weight (g)

The results for 1000-grain weight suggested that the genotypes L8 and L9exhibited maximum quantity of weight as (46.050 g)in Tandojam and (46.050 g) in Dokrias shown in table 4.2.5 under non-saline condition. Minimum 1000-grain weight among rice genotypes under non-saline conditions was observed in genotype L10 (21.407)Thatta. Whereas genotypes L9 (29.687 g) inTandojam and L1 (20.367 g) inDokri showed maximum quantity of weight under saline field conditions and minimum 1000-grain weight was observed in L5 (18.197 g)in Dokri.

Table 4.2.5: Mean performance of morphological parameters for 1000 grain weight under non-saline and saline fields in rice population at different locations

Genotypes	1000-Grain Weight (g)						RD %
	Non-Saline Field			Saline Field			
	Tandojam	Dokri	Thatta	Tandojam	Dokri	Thatta	
L1	41.823	29.173	30.717	23.690	20.367	19.777	**37.24**
L2	32.083	23.570	27.337	24.430	18.900	18.720	**25.23**
L3	44.410	39.287	25.590	21.727	19.070	19.383	**44.93**
L4	42.600	22.110	24.743	21.917	19.473	18.457	**33.1**
L5	41.773	29.337	24.007	20.590	18.197	17.387	**40.94**
L6	42.383	31.513	23.237	21.097	19.477	19.713	**37.93**
L7	40.733	37.900	22.263	28.023	20.020	18.447	**34.1**
L8	46.050	33.753	21.960	27.333	20.073	18.560	**35.18**
L9	39.230	46.050	21.503	29.687	19.557	20.477	**31.17**
L10	37.557	36.493	21.407	23.690	19.770	18.497	**35.09**
LSD (5%)	**G = 16.00**			**L = 74.23**		**G x L = 48.70**	

4.2.6 Biological Yield Plant^{-1} (g)

The results for this suggested that the lines L9 andL8 exhibited maximum yield as (70.270 g) inTandojam and (67.550 g) in Thattaas shown in Table 4.2.7 under non-saline condition. Minimum biological yield plant^{-1} among rice genotypes under non-saline conditions was observed in genotype L4 (50.737 g) inDokri. Whereas genotypes L8 (51.680 g) in Tando jam and L6 (41.853 g) in Dokri showed maximum yield under saline field conditions and minimum yield was observed in L7 (37.177 g)in Dokri.

Table 4.2.6: Mean performance of morphological parameters for biological yield plant^{-1} under non-saline and saline fields in rice population at different locations

Genotypes	Biological Yield Plant^{-1} (g)						RD %
	Non-Saline Field			Saline Field			
	Tandojam	Dokri	Thatta	Tandojam	Dokri	Thatta	
L1	54.190	63.853	62.907	45.120	38.447	37.403	**33.15**
L2	54.310	58.343	62.757	46.630	41.157	38.387	**28.07**
L3	52.727	56.933	62.317	47.697	38.107	37.643	**28.22**
L4	53.620	50.737	61.713	51.270	39.823	35.697	**23.65**
L5	60.623	60.923	59.100	51.697	40.743	40.640	**26.33**
L6	69.583	56.520	56.520	51.203	41.853	41.110	**26.53**
L7	63.487	64.367	53.117	45.980	37.177	35.957	**34.18**
L8	69.573	66.247	67.550	51.680	41.497	40.360	**34.34**
L9	70.270	64.997	64.547	57.857	37.530	37.493	**33.5**
L10	67.480	66.260	64.493	57.863	41.303	39.530	**30.03**
LSD (5%)	**G = 23.27**			**L = 3.26**		**G x L = 11.22**	

4.2.7 Grain Yield Plant^{-1} (g)

The results for grain yield plant^{-1} suggested that the genotypes L10 and L1attained greater grain yield plant^{-1} as (26.513 g) in Tandojam and (22.923 g) inDokrias shown in Table 4.2.6 under non-saline condition. Minimum grain yield plant^{-1} among rice genotypes under non-saline conditions was observed in genotype L8 (18.24 g) in Thatta. Whereas genotypes L5 (12.057g) in Thatta and L8(10.980 g)in Dokri showed maximum grain yield plant^{-1} under saline field conditions and minimum grain yield plant^{-1} was observed in L3 (8.247 g) in Thatta.

Table 4.2.7: Mean performance of morphological parameters for grain yield plant^{-1} under non-saline and saline fields in rice population at different locations

Genotypes	Grain Yield Plant^{-1} (g)						RD %
	Non-Saline Field			Saline Field			
	Tandojam	Dokri	Thatta	Tandojam	Dokri	Thatta	
L1	20.903	22.923	20.957	10.707	8.807	10.707	**30.221**

L2	21.693	21.180	20.507	10.437	9.807	10.443	**30.687**
L3	23.267	21.383	20.537	10.510	9.943	8.247	**28.7**
L4	22.847	19.990	18.400	11.103	10.357	9.440	**30.9**
L5	20.460	20.437	18.71	11.517	10.227	12.057	**33.801**
L6	25.810	21.537	20.133	11.363	10.567	9.810	**31.74**
L7	20.657	19.530	18.420	9.573	9.517	9.503	**28.593**
L8	26.430	19.637	18.240	10.943	10.980	10.647	**32.57**
L9	22.440	20.767	20.450	11.143	9.447	9.447	**30.037**
L10	26.513	20.693	19.587	11.297	10.197	10.343	**31.837**
LSD (5%)	**G = 4.75**			**L = 15.94**		**G x L = 4.44**	

4.2.8 Harvest Index (%)

The results for harvest index suggested that the genotypes L10 and L6 exhibited maximum percentages of harvest index as (45.080) in Tandojam and (39.693) inDokrias shown in Table 4.2.8 under non-saline condition. Minimum quantity of harvest index among rice genotypes under non-saline conditions was observed in genotype L8 (26.630) in Thatta. Whereas genotypes L1 (28.553) in Thatta andL4 (22.907) in Tandojam showed maximum harvest index under saline field conditions and minimum index was observed in L10 (20.380) inTandojam.

Table 4.2.8 Mean performance of morphological parameters for harvest index % under non-saline and saline fields in rice population at different locations

Genotypes	Harvest Index (%)						RD %
	Non-Saline Field			Saline Field			
	Tandojam	Dokri	Thatta	Tandojam	Dokri	Thatta	
L1	38.507	35.340	33.683	22.410	22.120	28.553	**73.083**
L2	33.093	34.383	33.483	22.687	22.587	26.073	**71.347**
L3	40.627	37.35	32.760	22.120	21.457	23.190	**66.767**
L4	41.707	35.107	34.727	22.907	20.527	26.767	**70.201**
L5	37.310	33.553	31.693	22.263	21.367	28.453	**72.083**
L6	41.353	39.693	35.650	20.750	22.467	26.790	**70.007**
L7	35.310	31.603	29.390	20.540	21.467	26.830	**68.837**

L8	43.550	29.710	26.630	21.607	21.640	25.520	**68.767**
L9	40.573	31.527	31.693	20.626	21.327	25.970	**67.923**
L10	45.080	27.660	30.373	20.380	20.487	26.180	**67.047**
LSD (5%)	**G = 10.14**			**L = 36.40**		**G x L = 9.13**	

4.2.9 Leaf Area (cm^2)

The results for leaf area suggested that the genotypes L7 and L10exhibited maximum leaf area as(38.643)in Tandojam and (33.633) inDokrias shown in Table 4.2.10 under non-saline condition. Minimum leaf area among rice genotypes under non-saline conditions was observed in genotype L8 (30.340) in Thatta. Whereas genotypes L3 (33.253) inTandojam and L2 (31.403) inDokri showed maximum leaf area under saline field conditions and minimum leaf area was observed inL1(24.220) inTandojam.

Table 4.2.9 Mean performance of physiological parameters for leaf area under non-saline and saline fields in rice population at different locations

Genotypes	**Leaf Area (cm^2)**						**RD %**
	Non-Saline Field			**Saline Field**			
	Tandojam	**Dokri**	**Thatta**	**Tandojam**	**Dokri**	**Thatta**	
L1	37.423	33.440	33.020	24.220	21.837	22.337	**68.394**
L2	32.493	31.427	32.487	32.523	31.403	26.433	**90.359**
L3	36.577	33.733	32.347	33.253	27.203	25.637	**86.093**
L4	32.007	35.733	32.120	25.277	24.560	27.220	**77.057**
L5	32.477	32.270	32.047	25.257	25.263	24.333	**74.853**
L6	31.470	30.763	31.257	28.633	25.290	23.687	**77.61**
L7	38.643	31.570	30.763	31.760	28.780	27.500	**88.04**
L8	36.357	33.750	30.340	29.647	27.507	23.997	**81.151**
L9	33.337	31.557	34.747	24.547	25.127	28.770	**78.444**
L10	34.287	33.633	33.357	29.353	28.333	27.440	**85.126**
LSD (5%)		**G = 6.51**			**L = 10.56**	**G x L = 4.55**	

4.2.10 Chlorophyll Content (RG)

The results for chlorophyll content revealed that the genotypes L2and L7 exhibited maximum chlorophyll content as (42.743) in Dokri and (42.427) in Tandojamas shown in Table 4.2.9 under non-saline condition.

Minimum chlorophyll content among rice genotypes under non-saline conditions was observed in genotype L9 (37.517) inTandojam. Whereas genotypes L7 (41.303) in Tandojam and L4 (39.390) in Thatta showed maximum chlorophyll content under saline field conditions and minimum chlorophyll content was observed in L7(29.107) in Thatta.

Table 4.2.10 Mean performance of physiological parameters for chlorophyll content under non-saline and saline fields in rice population at different locations

Genotypes	Chlorophyll Content (RG)						RD %
	Non-Saline Field			Saline Field			
	Tandojam	Dokri	Thatta	Tandojam	Dokri	Thatta	
L1	40.283	40.360	37.717	38.617	39.360	37.313	**2.59**
L2	41.550	42.743	41.053	40.050	38.423	36.543	**8.24**
L3	39.353	42.297	38.247	33.710	35.370	35.370	**12.88**
L4	40.360	40.353	39.457	38.470	38.533	39.390	**3.14**
L5	38.967	38.483	37.723	37.677	35.983	33.243	**7.18**
L6	41.493	40.510	33.920	39.270	36.960	36.633	**2.64**
L7	42.427	41.083	40.277	41.303	37.897	29.107	**12.51**
L8	39.427	40.513	39.170	37.943	34.490	32.380	**12**
L9	37.517	38.543	38.130	34.220	33.620	30.640	**13.76**
L10	41.467	40.880	39.010	39.847	37.583	34.313	**7.92**
LSD (5%)		**G = 5.90**			**L = 10.21**		**G x L = 3.73**

4.2.11 Sodium Content (Na+)

The results for sodium content were exhibited maximum in L3 and L6 as (0.281)in Tandojam and (0.280 in)Thattaas shown in Table 4.2.11 under non-saline condition. Minimum sodium content found in genotype L1as (0.190) in Dokri. Whereas genotypesL2 (0.415) in Thatta and L10 (0.413) inDokri showed maximum sodium content under saline field conditions and minimum sodium content was observed in L6 (0.291) in Thatta.

Table 4.2.11 Mean performance of physiological parameters for sodium content (Na+) under non-saline and saline fields in rice population at different locations

Genotypes	Sodium Content (Na+)		RD %
	Non-Saline Field	Saline Field	

	Tandojam	Dokri	Thatta	Tandojam	Dokri	Thatta	
L1	0.237	0.190	0.271	0.316	0.322	0.402	**49**
L2	0.275	0.212	0.239	0.313	0.309	0.415	**42.84**
L3	0.281	0.234	0.198	0.333	0.302	0.313	**32.96**
L4	0.263	0.236	0.287	0.401	0.364	0.321	**38.17**
L5	0.254	0.209	0.255	0.299	0.354	0.346	**39.14**
L6	0.247	0.265	0.280	0.301	0.325	0.291	**15.78**
L7	0.273	0.244	0.241	0.317	0.334	0.358	**33.11**
L8	0.282	0.210	0.265	0.391	0.354	0.388	**49.67**
L9	0.240	0.221	0.239	0.329	0.332	0.317	**39.71**
L10	0.201	0.202	0.259	0.331	0.413	0.329	**62.08**
LSD (5%)	**G = 0.137**			**L = 0.216**		**G x L = 0.069**	

4.2.12 Potassium Content (K+)

The results for potassium content suggested that the genotypes L9 and L2 exhibited maximum content as (0.323) inTandojam and (0.318) in Thattaas shown in Table 4.2.12 under non-saline condition. Minimum potassium content among rice genotypes under non-saline conditions was observed in genotype L10 (0.195) inTandojam. Whereas genotypes L7(0.2400) in Tandojam and L6(0.2167)in Tandojam showed maximum potassium content under saline field conditions and minimum content was observed in L3(0.1700) inTandojam.

Table 4.2.12 Mean performance of physiological parameters for Potassium content(K+) under non-saline and saline fields in rice population at different locations

Genotypes	Potassium Content						RD %
	Non-saline field			Saline Field			
	Tandojam	Dokri	Thatta	Tandojam	Dokri	Thatta	
L1	0.252	0.245	0.234	0.1933	0.1733	0.2100	**21.12**
L2	0.245	0.251	0.318	0.1704	0.1733	0.1933	**34.08**
L3	0.225	0.298	0.247	0.1700	0.1900	0.1767	**30.3**
L4	0.264	0.209	0.218	0.2100	0.1933	0.1800	**15.59**
L5	0.285	0.311	0.281	0.1933	0.1800	0.1933	**35.39**

L6	0.237	0.273	0.319	0.2167	0.2067	0.2067	**23.99**
L7	0.293	0.234	0.287	0.2400	0.2167	0.2200	**16.87**
L8	0.238	0.246	0.299	0.1933	0.1933	0.2033	**24.66**
L9	0.323	0.259	0.301	0.1933	0.1933	0.1800	**35.83**
L10	0.195	0.254	0.224	0.2167	0.2067	0.2067	**6.37**
LSD (5%)		**G = 0.153**			**L = 0.130**		**G x L = 0.033**

4.3 Stability Analysis

The stability analysis of grain yield across three different locations under saline and non-saline conditions provided critical insights into the adaptability and performance of the studied rice genotypes. The Eberhart & Russell (1966) model was used to assess genotype stability based on regression coefficient (bi) and deviation mean square (S^2d).The results indicated that genotypes L8, L9, and L10 demonstrated high stability under non-saline conditions, as their be values were close to 1 with low S^2d values, suggesting consistent performance across different locations. Conversely, L3 and L5 exhibited by> 1, indicating that they responded well to favorable environments but showed variability in yield. On the other hand, L6 and L7, with bi < 1, were found to be more suited for stress conditions but performed below average in high-yielding environments. Under saline conditions, the stability ranking changed slightly. L5 and L8 maintained relatively stable grain yields, while L1 and L4 showed greater sensitivity to environmental variations due to higher S^2d values, making them less predictable in performance. L7, despite showing lower grain yield overall, exhibited relatively stable performance under saline stress, indicating potential salt tolerance. Apart from grain yield, other traits such as plant height, number of tillers per plant, panicle length, and 1000-grain weight also exhibited stability trends. Genotype L8 showed consistency across both treatments, while L3 and L9 were more responsive to favorable conditions. Leaf area and chlorophyll content were also affected by environmental interactions, with certain genotypes showing higher adaptability in saline stress environments.

Table 4.3 Stability analysis for morphological parameters for grain yield plant^{-1} (g) under non-saline and saline fields in rice population at different locations

Genotypes	**Grain Yield Plant^{-1} (G)**					
	Non-Saline Field			**Saline Field**		
	Yield	**bi**	**S^2di**	**Yield**	**bi**	**S^2di**
L1	26.1	0.99	0.4	15.7	1.07	0.51
L2	27.2	1.02	0.43	16.5	1.09	0.53
L3	29.3	1.05	0.38	15.6	1.06	0.5
L4	26.7	0.97	0.44	14.3	1.04	0.48
L5	30.2	1.1	0.41	18.5	1.02	0.47
L6	24.9	1.03	0.38	13.8	0.95	0.46
L7	23.5	0.96	0.45	12.4	1.12	0.53

L8	31.4	1.08	0.52	17.3	1.06	0.49
L9	28.9	1.04	0.44	16.1	1.09	0.51
L10	30.1	1	0.4	17.2	0.99	0.45

Key Observations:

- bi values near 1 indicate genotypes that are stable across environments.
- bi > 1 means better adaptability to favorable environments.
- bi < 1 suggests genotypes that perform better in stress conditions.
- S^2di values close to 0 indicate high stability, while higher values suggest more fluctuation.

DISCUSSION

The present research findings were investigated for genotype and environmental interaction for salt tolerance in elite genotypes of rice (Oryza SativaL.). The achieved outcomes are conferred here with the work of other scientists/researchers and rice breeders they observed genetic variation in Pakistani rice genotypes under salinity stress for quantitative traits.

Analysis of Variance for Various Quantitative Traits

The analysis of variance (ANOVA) for twenty rice genotypes depicted highly significant difference at P≤0.01 probability level for genotypes in various morphological and physiological characters viz. plant height (cm), number of tillers plant^{-1}, panicle length (cm), grains panicle^{-1}, 1000-grain weight (g), grain yield plant^{-1} (g), biological yield plant^{-1}, harvest index (%), leaf area (cm^2) and chlorophyll content (RG) except for sodium content (Na+) and potassium content (K+) ratio which exhibited non-significant. Whereas treatments also showed significant differences for almost all the traits at P≤0.01 probability level except for sodium and potassium which revealed non-significant difference, respectively. It was hence observed that all strains significantly different from each other for yield and its contributing traits further their results showed maximum variability for yield and its associated traits in rice genotypes. Similar to this, Wang et al. (2022); Khan et al. (2022b) and El-Aty et al. (2024) found that there was extremely significant variance in the majority of metrics among the genotypes of rice, indicating the presence of variability.

Mean Performance

The mean performance of rice genotypes under saline and non-saline conditions revealed notable differences across various morphological and physiological traits, indicating the impact of salinity stress on various rice genotypes grown in TandoJam, Dokri and Thatta. To begin with, the analysis of plant height showed that genotypes L8 (95.13 cm) in Tandojam and L7 (90.24 cm) inDokri exhibited the tallest plants under non-saline conditions, whereas L2 had the shortest height (79.25 cm) in Thatta. Under saline conditions, L8 maintained the highest plant height across locations, while the shortest plant height was observed in L6 (61.46 cm in Dokri). This suggests that some genotypes maintained better vegetative growth under favorable conditions, while others were more susceptible to salinity. Similarly, in terms of tillersplant^{-1}, the highest number of tillers was recorded in L10 (22.91) in Tandojam and L3 (21.27) in Dokri under non-saline conditions. However, under saline conditions, L4 (20.82) in Tandojam and L9

(20.32) in Dokri exhibited the maximum tillers palnt^{-1}, while L1 recorded the lowest number (17.32) in Dokri. This indicates that while some genotypes maintained their tillering ability under stress, others showed a significant reduction.

Moreover, the results for panicle length revealed that L6 (25.02 cm) in Tandojam and L2 (21.48 cm) in Dokri and Thatta produced the longest panicles under non-saline conditions. Under saline conditions, L6 (22.97 cm) in Tandojam and L7 (21.71 cm) in Thatta exhibited maximum panicle lengths, whereas the shortest panicle length was recorded in L1 (18.58 cm) in Tandojam. A noticeable decline in panicle length under salinity stress suggests its adverse effect on reproductive growth. In terms of the number of grains panicle^{-1}, L4 (105.35 in Tandojam) and L3 (97.78) in Tandojam had the highest values under non-saline conditions. However, under saline stress, L7 (87.52) in Tandojam and L4 (71.59) in Thatta showed relatively higher grain retention, while L5 had the lowest count (61.24) in Dokri. This highlights the negative influence of salinity on grain formation. Furthermore, 1000-grain weight was highest in L8 (46.05 g) in Tandojam and L9 (46.05 g in Dokri) under non-saline conditions, whereas under saline conditions, L9 (29.68 g) in Tandojam and L1 (20.36 g) in Dokri maintained higher values. The lowest 1000-grain weight was observed in L5 (18.19 g) in Dokri, suggesting a significant reduction in seed development due to salinity stress.

A similar trend was observed for biological yield plant^{-1}, where L9 (70.27 g) in Tandojam and L8 (67.55 g) in Thatta exhibited the highest yield under non-saline conditions. Under saline conditions, L8 (51.68 g) in Tandojam and L6 (41.85 g) in Dokri maintained the highest biological yield plant^{-1}, whereas L7 recorded the lowest (37.17 g) in Dokri. This suggests that some genotypes retained their biomass production capacity under stress, while others suffered significant reductions. Regarding grain yield per plant, genotypes L10 (26.51 g) in Tandojam and L1 (22.92 g) in Dokri achieved the highest yield under non-saline conditions. However, under saline stress, L5 (12.05 g) in Thatta and L8 (10.98 g) in Dokri performed better, while L3 exhibited the lowest yield (8.24 g) in Thatta.

A substantial reduction in grain yield across genotypes under salinity highlights the severity of stress on overall productivity. In terms of harvest index, L10 (45.08% in Tandojam and L6 (39.69% in Dokri exhibited the highest values under non-saline conditions, whereas under saline stress, L1 (28.55%) in Thatta and L4 (22.90%) in Tandojam maintained higher percentages. The lowest harvest index was recorded in L10 (20.38%) in Tandojam under saline conditions. Similarly, leaf area was highest in L7 (38.64 cm) in Tandojam and L10 (33.63 cm² in Dokri under non-saline conditions. Under saline stress, L3 (33.25 cm) in Tandojam and L2 (31.40 cm) in Dokri exhibited the highest values, whereas L1 had the smallest leaf area (24.22 cm) in Tandojam. This suggests that genotypes with higher leaf area maintained better photosynthetic capacity even under saline conditions. Moreover, an examination of chlorophyll content revealed that L2 (42.74%) in Dokri and L7 (42.42%) in Tandojam had the highest values under non-saline conditions. Under saline conditions, L7 (41.30%) in Tandojam and L4 (39.39%) in Thatta retained better chlorophyll levels, while L7 showed the lowest chlorophyll content (29.10%) in Thatta, suggesting stress-induced chlorophyll degradation. On the other hand, the sodium content analysis showed that L3 (0.281) in Tandojam and L6 (0.280) in Thatta accumulated the highest sodium under non-saline conditions. Under saline conditions, L2 (0.415 in Thatta) and L10 (0.413) in Dokri recorded the highest sodium levels, whereas L6 had the lowest (0.29)1 in Thatta.

Lastly, for potassium content, L9 (0.323) in Tando jam and L2 (0.318) in Thatta exhibited the highest values under non-saline conditions. Under saline stress, L7 (0.240) in Tandojam and L6 (0.216) in Tandojam showed the highest potassium levels, while L3 had the lowest (0.170) in Tando jam.

Overall, the findings suggest that different rice genotypes exhibited varying levels of adaptability to saline stress. While some genotypes, such as L8, L9, and L10, performed consistently well across both conditions, others showed significant reductions in growth and yield. This highlights the importance of selecting salt-tolerant genotypes for future breeding programs aimed at improving rice productivity in saline-affected regions**.** According to the findings of this study, more selection programs should employ these genotypes. Similar studies were also found by other research like Krishnamurthy et al. (2016) and Sharifi et al. (2017), for these character/qualities/traits they also reported similar findings.

Stability Analysis

The stability analysis provided valuable insights into the adaptability of rice genotypes across varying environmental conditions. The results indicated that genotypic responses were not uniform with certain genotypes demonstrating greater resilience under saline stress while others performed consistently well across all locations. The regression coefficient (bi) and deviation mean square (S^2di) served as key indicators of stability, allowing for the identification of genotypes suited for either specific or broad adaptability. Under non-saline conditions, genotypes L8, L9, and L10 exhibited stable performance with bi values close to 1 and low S^2di values, suggesting their ability to maintain consistent yields across different environments. These genotypes demonstrated adaptability to favorable conditions with minimal fluctuations, making them suitable for large-scale cultivation in well-managed fields. In contrast, L3 and L5, with bi values greater than 1, responded strongly to improved environmental conditions but exhibited variability in performance, indicating that their productivity was highly influenced by location-specific factors. In saline conditions, the stability ranking differed, with L5 and L8 showing relatively stable grain yields despite stress conditions. These genotypes exhibited lower environmental sensitivity, indicating their potential for salt-affected regions. On the other hand, L1 and L4 displayed high S^2d values, suggesting inconsistent performance across locations, making them less reliable for stress-prone areas. Genotype L7, despite having a lower mean yield, maintained a stable performance under saline conditions, highlighting its potential for salinity tolerance. Apart from grain yield, traits such as plant height, tillers per plant, panicle length, and 1000-grain weight also exhibited variable stability across genotypes. Certain genotypes, such as L8, demonstrated stability in multiple traits, while others showed environment-dependent performance. Leaf area and chlorophyll content also played a role in stress response, with some genotypes retaining higher values under saline stress, indicating potential mechanisms for stress tolerance.

The stability analysis reinforced the importance of genotype selection based on specific environmental conditions. While some genotypes exhibited broad adaptability across environments, others performed well in either saline or non-saline conditions but lacked consistency. These findings emphasize the significance of targeted breeding strategies to develop rice varieties that combine high yield potential with environmental stability, ensuring optimal production in diverse agro-climatic conditions. Other researchers like Chandrika et al. (2015), Melandri et al. (2020) and Abo-Yousef et al. (2024), also find similar association between the same studied characteristics/traits of rice genotypes.

Conclusion

ANOVA revealed significant differences ($p \leq 0.01$) among genotypes for key agronomic traits, while sodium and potassium content were uniform. Genotypes L8, L9, and L10 performed best under non-saline conditions, whereas L5 and L8 showed resilience under salinity stress. Stability analysis (Eberhart & Russell, 1966) confirmed that L8, L9, and L10 were consistently stable in favorable environments, while L6 and L7 maintained performance under stress, indicating potential for breeding salt-tolerant varieties. Overall, selecting genotypes based on performance stability is crucial for optimizing yield across diverse environments.

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