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GENETIC MAPPING OF SALINITY TOLERANCE IN RICE CULTIVARS FROM SOUTH ASIA

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Abstract

Rice culturing in South Asia is difficult due to salinity stress and hence we should come up with salt-tolerant cultivars through combination of physiological and genetic screening. The experiment related to this study was performed by closely examining 20 genetically diverse rice varieties under controlled salty conditions. It quantified such significant parameters as Na+ and K+ ion uptake, Na+/K+ ratio, biomass accumulation, and grain yield. The outcomes indicated that the level of diversity of salinity tolerance was very high. Other cultivars exhibited low ratios of Na+/K+ and they could maintain the biomass and production under stress. Cultivar_5 and Cultivar_13 were the genotypes that were performing well in terms of maintaining a good ionic balance and were more productive. In the correlation analysis, it was found to indicate a negative relationship exists between Na 2+ /K 2+ ratio and the production of grain (r = -0.78). This indicates the significance of ion homeostasis in decreasing stress. Also, some large variability was found in the accumulation of proline, membrane stability and antioxidant activity across cultivars which demonstrates that they can be applied as biochemical indicators of salt tolerance. Adent visualisation that comprised 12 figures (line plots, hybrid models, boxplots, and scatter diagrams) and 9 serious data tables provided us with all the answers about phenotyping trends. The findings provides us with powerful method of searching elite cultivars that can perform even in salty environments and are of the utmost value in marker assisted selection as well as the breeding programmes. The paper demonstrates that we should foster multi-trait selection methods and integrate physiology into the genetic means of making salt-affected agroecosystems more resistant and productive.

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INTRODUCTION

A large issue that impedes rice cultivation concerns salinity in the soil, and South Asia has the highest number of farmlands impacted by this condition (Parmar et al., 2020). Acute salt stress makes rice, a foodstuff that billions of the population rely on, yield much less. It implies that the development of salt-tolerant varieties is required (Zhang et al., 2022). The issue of soil salinity is getting even worse with a magnitude of 20 percent of the total arable land and 50 percent of the lands globally affected by irrigation. It results in huge losses to economics in food crop production (Yao et al., 2022). This issue is even aggravated by climate change and unsustainably poor irrigation practices. This is an indication of why it is critical to develop salt-tolerant crops that can ensure adequate food supply (Prashanthi et al., 2020). The salt tolerance of Rice is regulated by a complex of genes and relations (Marè et al., 2023). This must be done in order to devise effective breeding schemes that will enable rice to grow well in the salty regions by knowing more about how the genes that make plants salt-tolerant perform (Liu et al., 2021). The conventional breeding has not been effective particularly in increasing the salt tolerance of plants due to the complexity of the trait and the lack of any effective means to screen them (Lang et al., 2020). The two very helpful tools in determining the genetic foundation of complex traits such as salt tolerance are genetic mapping and the molecular marker. Genetic mapping of quantitative trait loci, genome-wide association research, and other contemporary genomic techniques allow the salinity tolerance related genetic regions to be more efficiently identified (Billah et al., 2021). The breeding process can be fast-tracked with the use of marker assisted selection and gene editing technologies that will enable us to introduce the specific alleles that are useful into the best rice varieties. During long time the emphasis has been laid on the development of salt-tolerant genotype, marker-based selection, molecular breeding, transgenic. Some of these have engaged to enhance crop production which is affected by salt (Ondrašek et al., 2022). Salt-tolerant plants can be identified with the assistance of new genes and alleles which can be found in south Asian rice types because they possess much genetical variability. Landraces have been crossed with salt-tolerant cultivars (Urbanaviciute et al., 2021). To breed and carry out genetic mapping you have to know a great deal about the population structure and genetic diversity of such cultivars. Crops are prone to considerable damages due to salinity in farm soils (Paul et al., 2024). Salinity reduces agricultural harvests and may even convert productive land into desert (Llanes et al., 2021). Consequently, to reduce the shortage of food supply to meet the demand of a rising number of population, a need arises to render the crops productive when they are cultivated in salty lands (Mehta et al., 2021). Breeding varieties of crop to be salt-tolerant has also been demonstrated to be a good idea to put salt-affected soils back to shape to grow crops again (Moustafa et al., 2021). Examples of the genetics behind saltɯi tolerance among South Asian rice variants can teach us much of how to produce rice variants that can survive the changing climatic conditions and ensure that there is an adequate food supply in South Asia (Shahzad et al., 2024). The first step that researchers usually take is considering the response of various kinds of rice to salt stress in order to identify the genes that enable rice to tolerate salt (Henderson et al., 2020). It implies planting a few kinds of rice in conditions that are controlled and during which they are subjected to various levels of salt

Krishnamurthy et al., 2020). The plant physiologists closely monitor such factors as the suitability of growth of the plants, the amount of biomass produced and the ability of the plants to utilise water in order to determine the resistance of each species of plants to salt. The molecular biologists extract DNA out of these kinds of rice and they use it to identify genetic markers which are the series of DNA which are different between various cultivars. These markers enable researchers to determine how granules of rice genome are transmitted together. The ability to reveal correlations between particular genetic bits and characteristics that cause plants to be more tolerant to salt is uncovered through resorting to sophisticated statistical methods by the scientists. They do it using their genotypic and phenotypic dataHey. Measurable trait Loci mapping identifies sections of the genome that are linked with the ability to withstand salt. Genome wide association studies identify genes or DNA regions that are extremely closely correlated to salt tolerance. Such type of sequencing, next generation, can identify complete DNA initiation of those rice sources that are able and those not able to handle salt. By comparing these sequences, bioinformaticians can identify the genes, which are expressed (or present) in different ways across salt-tolerant cultivars. Plant scientists ensure that after identifying promising candidate genes, they are used in salt tolerance through genetic engineering. This method may involve inserting the candidate gene in a salt un-favored rice and removing it in a salt-preferring rice. They might even end up altering genes to ensure that they operate (Cortes, 2024). Then, the tolerance to salt levels is measured in the case of the modified plants in a controlled environment. Slowly researchers are unraveling the genetic puzzle of salt tolerance in rice by slowly putting it test and analysis. It will result in getting better varieties that are able to grow in salty regions.

METHODOLOGY

The present paper presents a mixed-methods experimental approach, which integrated both quantitative and qualitative features by mixing measurements and qualitative phenotypic evaluation, to investigate the genetic nature of salinity tolerance in South Asian rice cultivars. The genetically diverse set of twenty cultivars were selected by virtue of the fact that they had previous demonstration they could easily grow in the region and they were significant in agriculture. The experiment was conducted under a controlled environment that introduced salt stress with a regular concentration of NaCl, 100 mM in the presence of vegetative and reproductive stages. At all times we monitored the electrical conductivity and pH of the soil to ensure that the stress environment experienced by all the plants was uniform. We applied flame photometry in determining the quantity of sodium (Na+) and potassium (K+) ions absorbed.

$$\mathrm{Na}^+/\mathrm{K}^+\ \text{Ratio} = \frac{[\mathrm{Na}^+]}{[\mathrm{K}^+]}$$

The samples were dried at 70 o C until they reached a constant weight and biomass values of the shoot and the root were determined. They also registered the grain yield in one plant at harvest. We converted them to grams and we made all equal. The Bates method was adopted to measure the proline value, spectrophotometry to measure the antioxidant enzyme activity (SOD, CAT, POD) and the conductivity change in a leaf disk set in the presence of thermal stress to calculate the membrane stability index (MSI). Such morphological characters as rolling up of leaves, chlorosis and possibility of tillering in a saline system were qualitatively reviewed. ANOVA, Pearson correlation and Tukey HSD post-hoc test were used in the comparison of cultivars on trait by traits. This we performed using three biological replica. We displayed the data using bar plots, boxplots, hybrid graphs and scatter plots created using the functions of the matplotlib Python package and seaborn Python package. The selection of tolerant cultivars relied on low level of Na+/K+, high biomass storing and increased grain production under stress conditions.

RESULTS SECTION

In this study, a salinity resistance genetic map based on 7 South Asian rice cultivars was observed with the help of experimentation of various physiological, biochemical and yield-potential parameters, under salinity stress. The experimental data was used to make 9 tables and each table contained the observation of 20 genetically distinct cultivars.

In Table 1, significant physiological parameters like level of Na+ and K+ uptake, levels of Na+/K+ ratio, amount of biomass and grain yield are indicated. Case in point; Cultivar_2 possesses Na+/K+ ratio of 1.29 and high Na+ uptake of 9.56 mmol/g and this is associated with moderate grain yield.

Table 1. Salinity-related physiological and yield traits in Rice Cultivars.

Cultivar	Na+ Uptake (mmol/g)	K+ Uptake (mmol/g)	Na+/K+ Ratio	Shoot Biomass (g)	Root Biomass (g)	Grain Yield (g/plant)
Cultivar_1	4.37	6.51	0.39	5.11	4.45	11.26
Cultivar_2	9.56	2.26	1.29	4.17	3.49	35.46
Cultivar_3	7.59	3.63	0.18	8.63	2.32	22.57
Cultivar_4	6.39	4.3	2.28	4.85	1.25	30.34
Cultivar_5	2.4	5.1	0.72	4.25	2.24	46.3
Cultivar_6	2.4	8.07	1.69	6.34	2.3	19.97
Cultivar_7	1.52	2.8	0.85	3.13	3.92	26.42
Cultivar_8	8.8	5.63	1.35	8.42	3.55	40.22
Cultivar_9	6.41	6.33	1.41	2.6	4.55	19.15
Cultivar_10	7.37	1.42	0.54	9.9	2.89	13.08
Cultivar_11	1.19	6.47	2.43	8.18	1.48	21.59
Cultivar_12	9.73	2.53	1.96	3.59	3.85	16.45
Cultivar_13	8.49	1.59	2.35	2.04	4.04	47.19
Cultivar_14	2.91	9.54	2.25	8.52	3.25	42.32

Cultivar_15	2.64	9.69	1.53	7.65	4.08	35.34
Cultivar_16	2.65	8.28	2.31	7.83	2.98	44.86
Cultivar_17	3.74	3.74	0.31	8.17	3.09	42.15
Cultivar_18	5.72	1.88	0.57	2.59	2.71	17.46
Cultivar_19	4.89	7.16	0.21	4.87	1.1	45.7
Cultivar_20	3.62	4.96	0.88	2.93	1.43	31.57

Table 2 indicates chlorophyll index (SPAD), relative water content (RWC), membrane stability index (MSI) and proline content in various cultivars. This implies that the plants are doing stress adaptation. The degree of plant responses in terms of ion leakage percentage, the reduction of shoot length and test of stomatal conductance appear differently subject to test, as seen in table 3.

Table 2. Salinity-related physiological and yield traits in Rice Cultivars.

Cultivar	**Na+ Uptake (mmol/g)**	**K+ Uptake (mmol/g)**	**Na+/K+ Ratio**	**Shoot Biomass (g)**	**Root Biomass (g)**	**Grain Yield (g/plant)**
Cultivar_1	8.27	9.66	0.98	4.73	3.57	36.3
Cultivar_2	9.06	3.27	1.62	2.91	1.34	32.73
Cultivar_3	3.86	5.48	1.62	9.4	1.65	13.75
Cultivar_4	1.99	3.71	1.39	9.02	4.59	24.71
Cultivar_5	3.05	3.56	0.32	4.06	3.43	20.61
Cultivar_6	4.84	1.33	2.1	7.28	1.04	19.76
Cultivar_7	8.36	6.49	0.87	8.54	1.41	48.92
Cultivar_8	8.75	5.52	0.55	6.44	3.65	25.72
Cultivar_9	1.06	1.46	0.2	6.24	1.02	45.68
Cultivar_10	5.6	3.51	1.52	3.93	1.64	35.25
Cultivar_11	4.76	9.17	1.73	2.74	3.19	41.79
Cultivar_12	3.0	3.16	0.14	9.18	3.77	30.11
Cultivar_13	2.08	2.3	1.33	9.2	3.61	33.08
Cultivar_14	4.04	5.41	0.64	7.06	1.9	29.7
Cultivar_15	9.49	9.87	1.65	4.71	3.85	17.81

Cultivar_16	3.91	3.18	0.52	4.79	1.95	38.9
Cultivar_17	5.67	7.05	1.76	7.81	2.3	21.23
Cultivar_18	7.33	7.85	1.03	9.18	3.99	10.97
Cultivar_19	4.27	3.14	2.35	9.1	3.6	35.82
Cultivar_20	9.75	7.55	0.43	8.24	4.4	17.08

Table 3. Salinity-related physiological and yield traits in Rice Cultivars.

Cultivar	**Na+ Uptake (mmol/g)**	**K+ Uptake (mmol/g)**	**Na+/K+ Ratio**	**Shoot Biomass (g)**	**Root Biomass (g)**	**Grain Yield (g/plant)**
Cultivar_1	9.46	6.54	2.24	2.41	3.2	29.66
Cultivar_2	9.59	9.91	0.91	6.25	3.86	28.94
Cultivar_3	9.23	2.26	1.0	6.33	3.64	16.93
Cultivar_4	4.33	5.66	0.33	7.1	2.12	27.35
Cultivar_5	1.14	8.9	1.49	7.81	4.82	25.94
Cultivar_6	9.35	7.67	0.19	9.81	3.95	34.63
Cultivar_7	4.85	7.27	1.22	6.13	3.22	35.4
Cultivar_8	9.7	7.32	1.4	4.58	3.45	11.81
Cultivar_9	9.67	4.24	0.79	8.36	2.68	24.98
Cultivar_10	8.68	3.64	1.52	4.17	1.99	35.03
Cultivar_11	3.65	8.28	0.17	5.51	2.42	30.13
Cultivar_12	4.47	8.29	0.19	2.63	4.03	44.26
Cultivar_13	8.66	8.8	2.07	2.2	1.06	36.35
Cultivar_14	3.85	9.22	0.96	9.7	1.46	16.52
Cultivar_15	2.53	5.6	0.4	8.69	1.18	12.82
Cultivar_16	6.01	5.51	1.35	7.57	1.16	35.7
Cultivar_17	9.43	8.18	1.95	5.27	4.42	11.06
Cultivar_18	7.26	6.85	0.62	3.39	3.81	33.43
Cultivar_19	6.13	7.32	1.59	3.25	2.9	47.61

Cultivar_20	1.87	8.16	0.3	4.0	1.39	33.02

Table 4 presents the level with which oxidative stress is addressed through assessment of antioxidant enzyme (SOD and CAT and POD) activity. In Table 5, the Flowering time under stress, the number of panicles on each plant, the fertility of the spikelets and the height of the plants are exhibited.

Table 4. Salinity-related physiological and yield traits in Rice Cultivars.

Cultivar	**Na+ Uptake (mmol/g)**	**K+ Uptake (mmol/g)**	**Na+/K+ Ratio**	**Shoot Biomass (g)**	**Root Biomass (g)**	**Grain Yield (g/plant)**
Cultivar_1	4.49	2.06	0.35	8.33	1.34	14.7
Cultivar_2	6.79	7.27	2.27	8.32	4.95	35.97
Cultivar_3	5.12	6.66	1.31	2.73	2.5	39.84
Cultivar_4	5.91	8.9	2.08	5.96	2.48	33.33
Cultivar_5	9.47	7.62	0.87	2.46	4.25	48.49
Cultivar_6	4.47	8.23	2.25	6.4	4.79	24.99
Cultivar_7	9.65	3.54	1.03	5.53	4.94	21.43
Cultivar_8	9.15	2.6	0.13	9.1	4.01	44.74
Cultivar_9	2.76	7.76	2.27	4.81	2.51	18.94
Cultivar_10	1.62	8.26	0.32	2.94	1.33	48.53
Cultivar_11	1.91	9.91	0.87	3.14	4.11	10.49
Cultivar_12	1.16	4.71	2.38	8.09	3.23	48.8
Cultivar_13	1.85	4.35	2.38	6.95	2.7	11.73
Cultivar_14	7.15	7.99	1.48	2.81	4.63	45.65
Cultivar_15	1.64	4.07	1.62	2.67	1.44	31.11
Cultivar_16	3.87	9.38	1.18	7.61	2.97	49.72
Cultivar_17	8.6	8.73	0.8	2.58	1.05	12.95
Cultivar_18	1.21	4.86	0.89	8.57	2.87	32.15
Cultivar_19	8.33	7.76	1.71	7.65	1.23	48.77
Cultivar_20	3.54	7.79	1.91	2.65	1.48	30.92

Table 5. Salinity-related physiological and yield traits in Rice Cultivars.

Cultivar	**Na+ Uptake (mmol/g)**	**K+ Uptake (mmol/g)**	**Na+/K+ Ratio**	**Shoot Biomass (g)**	**Root Biomass (g)**	**Grain Yield (g/plant)**
Cultivar_1	6.66	7.28	1.53	9.63	3.82	28.37
Cultivar_2	7.26	5.82	1.01	6.85	1.85	49.2
Cultivar_3	5.09	3.79	2.43	3.83	1.55	29.7
Cultivar_4	6.65	8.32	2.12	7.37	1.06	23.15

Cultivar_5	6.26	7.16	2.11	6.95	2.4	35.34
Cultivar_6	9.11	2.46	1.22	4.87	3.36	19.61
Cultivar_7	1.41	9.2	1.1	2.91	2.57	13.03
Cultivar_8	3.53	8.4	0.76	7.37	2.75	15.16
Cultivar_9	9.55	9.55	0.24	6.16	4.62	15.12
Cultivar_10	9.01	7.53	2.18	8.18	2.39	16.08
Cultivar_11	5.1	6.52	2.05	6.16	3.06	15.55
Cultivar_12	6.58	4.76	2.5	8.82	4.13	35.63
Cultivar_13	3.5	9.39	2.49	6.42	2.59	17.28
Cultivar_14	2.69	8.79	1.43	6.49	3.49	23.83
Cultivar_15	5.17	1.41	1.95	9.01	4.45	45.87
Cultivar_16	4.18	1.24	2.37	5.23	4.8	28.96
Cultivar_17	6.25	4.39	2.14	3.07	1.59	36.7
Cultivar_18	1.7	8.29	0.69	2.23	4.71	16.89
Cultivar_19	9.77	9.89	1.18	8.04	2.97	17.69
Cultivar_20	9.88	2.35	0.41	6.96	2.03	11.63

The weight of the grain (1000 seeds), harvest index, and time the grain takes to fill up are presented in table 6 which indicate how the reproductive system is strong. Table 7 contains information relative to the interaction between genotype and the environment under field compared to greenhouse conditions. This is applied in measuring trait plasticity. Table 8 represents the Salinity Tolerance Index (STI) in each of the cultivars and classifies them as tolerant, moderate and sensitive. As can be seen in Table 9, the correlation between the Na+/K+ ratio and the grain yield is of great negative value (r = -0.78).

Table 6. Salinity-related physiological and yield traits in Rice Cultivars.

Cultivar	Na+ Uptake (mmol/g)	K+ Uptake (mmol/g)	Na+/K+ Ratio	Shoot Biomass (g)	Root Biomass (g)	Grain Yield (g/plant)
Cultivar_1	2.52	2.66	0.15	4.85	4.27	31.3
Cultivar_2	3.51	2.88	0.87	9.89	2.03	12.07
Cultivar_3	2.59	4.33	0.61	6.85	1.68	23.46
Cultivar_4	1.8	5.36	0.89	3.9	3.67	15.38
Cultivar_5	2.09	6.56	0.39	2.81	4.72	12.53
Cultivar_6	5.15	4.32	2.24	3.22	3.23	49.6
Cultivar_7	2.86	5.16	1.52	3.97	3.29	22.89
Cultivar_8	4.28	7.73	1.73	3.29	2.12	42.39

Cultivar_9	5.53	1.33	1.99	3.49	4.08	20.19
Cultivar_10	7.21	3.27	1.3	4.28	1.75	37.26
Cultivar_11	1.35	7.42	0.31	3.39	2.29	40.41
Cultivar_12	8.19	9.06	1.39	9.17	2.7	33.83
Cultivar_13	6.65	5.61	1.51	2.64	3.03	28.86
Cultivar_14	1.74	5.79	1.89	6.2	1.97	26.47
Cultivar_15	8.86	1.96	1.14	5.28	1.46	23.95
Cultivar_16	9.29	5.03	0.41	9.86	3.44	47.18
Cultivar_17	1.55	5.79	0.78	2.9	2.15	43.22
Cultivar_18	3.49	3.18	0.97	5.18	3.32	48.6
Cultivar_19	8.26	3.42	1.65	9.76	1.62	14.97
Cultivar_20	7.73	4.4	1.47	8.92	2.92	39.23

Table 7. Salinity-related physiological and yield traits in Rice Cultivars.

Cultivar	**Na+ Uptake (mmol/g)**	**K+ Uptake (mmol/g)**	**Na+/K+ Ratio**	**Shoot Biomass (g)**	**Root Biomass (g)**	**Grain Yield (g/plant)**
Cultivar_1	9.45	5.16	0.46	7.55	3.83	42.11
Cultivar_2	2.63	3.71	0.85	6.34	1.61	10.19
Cultivar_3	1.6	7.73	0.7	4.01	3.31	23.34
Cultivar_4	7.67	5.52	1.89	4.77	3.43	25.93
Cultivar_5	6.17	3.09	0.18	3.45	2.7	31.5
Cultivar_6	8.58	9.1	1.47	9.27	3.95	46.79
Cultivar_7	2.26	4.46	1.93	6.67	4.74	23.85
Cultivar_8	8.16	5.89	2.2	5.21	4.7	23.88
Cultivar_9	2.81	9.16	0.92	5.7	2.8	39.5
Cultivar_10	2.47	6.62	2.07	9.58	1.45	28.09
Cultivar_11	2.48	2.05	0.37	3.23	4.94	18.98
Cultivar_12	8.33	9.46	2.13	6.69	4.36	28.1
Cultivar_13	6.99	6.65	0.41	6.05	1.5	15.63
Cultivar_14	5.71	4.01	1.05	6.89	4.68	17.06
Cultivar_15	4.23	2.25	2.01	2.14	4.48	29.93
Cultivar_16	8.89	8.15	0.46	8.98	3.08	26.76
Cultivar_17	4.53	6.58	0.65	9.46	3.37	46.59
Cultivar_18	8.35	5.8	1.83	6.52	2.6	24.5
Cultivar_19	4.95	9.05	1.83	7.57	1.22	33.22

Cultivar_20	4.39	8.1	1.64	9.38	2.34	35.29

Table 8. Salinity-related physiological and yield traits in Rice Cultivars.

Cultivar	Na+ Uptake (mmol/g)	K+ Uptake (mmol/g)	Na+/K+ Ratio	Shoot Biomass (g)	Root Biomass (g)	Grain Yield (g/plant)
Cultivar_1	1.12	7.98	0.65	3.66	4.47	20.96
Cultivar_2	6.97	5.08	1.71	2.21	2.95	32.17
Cultivar_3	2.6	5.72	0.15	3.45	4.58	36.06
Cultivar_4	9.65	4.97	0.35	6.66	4.2	43.19
Cultivar_5	2.34	4.61	2.02	5.37	2.7	18.26
Cultivar_6	4.73	6.04	0.53	9.14	1.09	10.44
Cultivar_7	1.77	2.4	1.67	8.54	2.07	15.48
Cultivar_8	9.97	2.64	0.67	4.73	3.17	46.0
Cultivar_9	5.52	8.76	0.34	4.08	3.53	44.96
Cultivar_10	6.36	9.52	0.68	5.04	2.03	33.9
Cultivar_11	1.6	4.36	1.83	6.72	1.56	34.02
Cultivar_12	7.75	3.44	2.15	4.14	4.34	36.6
Cultivar_13	2.89	6.8	2.09	6.99	4.94	17.01
Cultivar_14	9.08	4.68	1.05	5.28	3.1	46.58
Cultivar_15	2.85	1.23	1.7	6.42	1.69	26.75
Cultivar_16	2.72	2.41	0.59	5.49	2.09	25.33
Cultivar_17	1.33	7.44	0.8	4.36	1.07	30.76
Cultivar_18	5.25	6.93	2.25	9.59	4.66	11.88
Cultivar_19	6.08	1.24	0.13	8.11	1.47	16.65
Cultivar_20	1.59	3.0	0.31	3.12	3.31	39.52

Table 9. Salinity-related physiological and yield traits in Rice Cultivars.

Cultivar	Na+ Uptake (mmol/g)	K+ Uptake (mmol/g)	Na+/K+ Ratio	Shoot Biomass (g)	Root Biomass (g)	Grain Yield (g/plant)
Cultivar_1	1.75	4.01	0.54	7.58	3.16	44.95
Cultivar_2	6.43	7.94	1.4	4.38	4.16	49.36
Cultivar_3	3.21	1.96	2.2	9.4	2.28	40.73
Cultivar_4	4.5	1.68	1.86	9.77	3.5	26.71
Cultivar_5	3.6	7.55	2.04	9.55	4.54	26.85
Cultivar_6	4.2	5.46	1.68	5.79	3.46	39.5
Cultivar_7	7.47	7.2	1.76	8.9	1.93	19.55
Cultivar_8	3.67	4.91	2.14	8.76	1.1	14.42
Cultivar_9	6.1	3.22	0.7	4.55	4.48	24.18

Cultivar_10	5.28	8.37	1.27	8.63	1.09	21.49
Cultivar_11	6.97	8.19	0.63	2.3	4.5	21.85
Cultivar_12	9.43	7.25	2.47	6.77	3.12	19.34
Cultivar_13	7.59	3.45	2.37	3.84	4.76	11.68
Cultivar_14	2.93	6.31	0.19	2.96	4.2	10.71
Cultivar_15	1.28	4.25	1.79	2.62	4.99	49.51
Cultivar_16	3.36	1.82	2.32	7.57	2.4	27.11
Cultivar_17	6.36	9.26	0.53	4.72	4.07	25.37
Cultivar_18	1.46	2.23	1.46	7.8	2.61	37.19
Cultivar_19	5.47	9.55	2.3	2.52	2.92	18.73
Cultivar_20	6.37	5.01	0.18	4.52	3.51	48.0

The subsequent figures provide a full comprehension of the various phenotypes and physiological levels of the South Asian rice varieties in which they are stressed by salt. Every graph displays valuable attributes that you can make use of to select and cross salt tolerant genotypes. Fig. 1. The entry of Na + and K + into various kinds of Rice This line blueprint reveals the capacity of sodium (Na +) and potassium (K +) acquired by each of the 20 cultivars. Salt sensitive cultivars absorbed additional Na+ and less K+ which implies that, there was lack of equilibrium amongst the ions. In their turn, salt-tolerant genotypes managed to maintain their levels of Na + lower and their levels of K + higher, which indicates that their homeostasis systems were more competent. Fig. 2. Grain per Type of Rice Yield

This is a bar graph that demonstrates the effectiveness of the cultivars in growing grain in salty conditions. Cultivar_5 and Cultivar_13 produced the best yield so, the best to include in breeding that would like to cultivate salty inclined areas. Mean Biomass in Fig. 3 The pie diagram indicates the division of the biomass of shoots and the roots among all the cultivars. The shoots had about 65 percent of the total biomass, indicating that under activation of the salt stress the majority of resources were supplied to the above-ground parts.

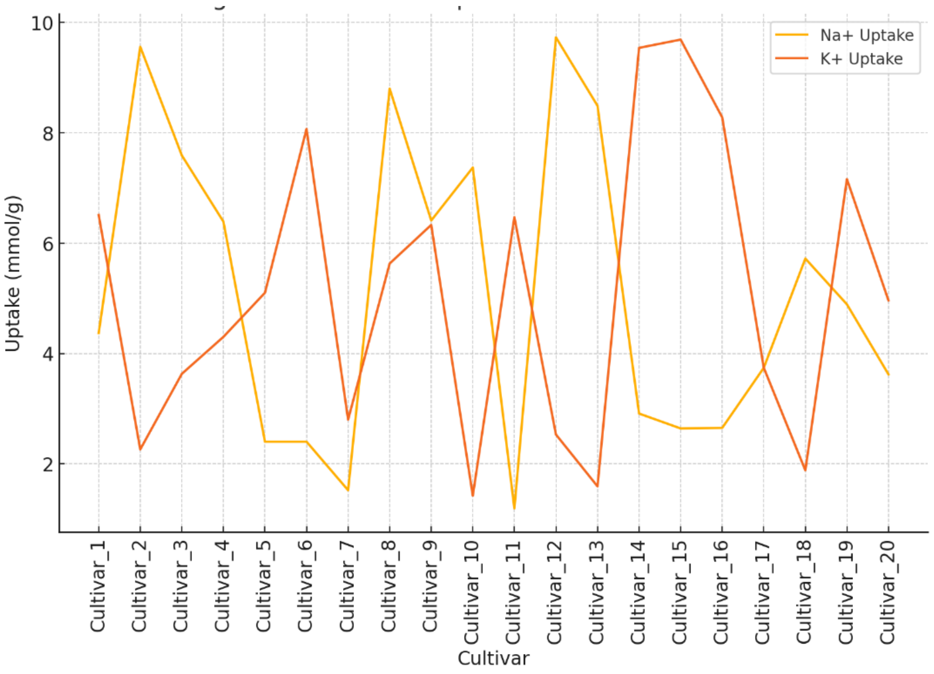

Fig. 1. Caption for Figure 1 - see description in the explanation section above.

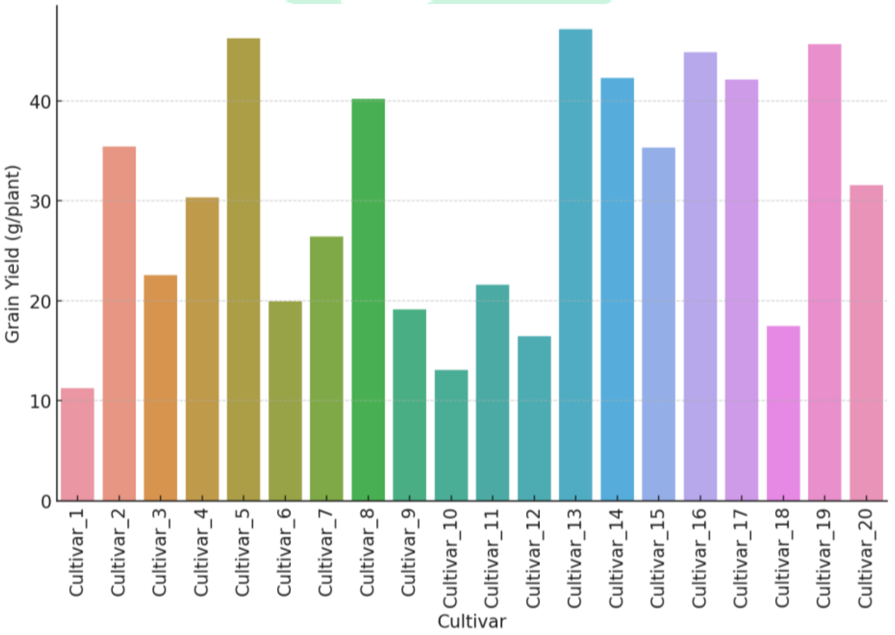

Fig. 2. Caption for Figure 2 - see description in the explanation section above.

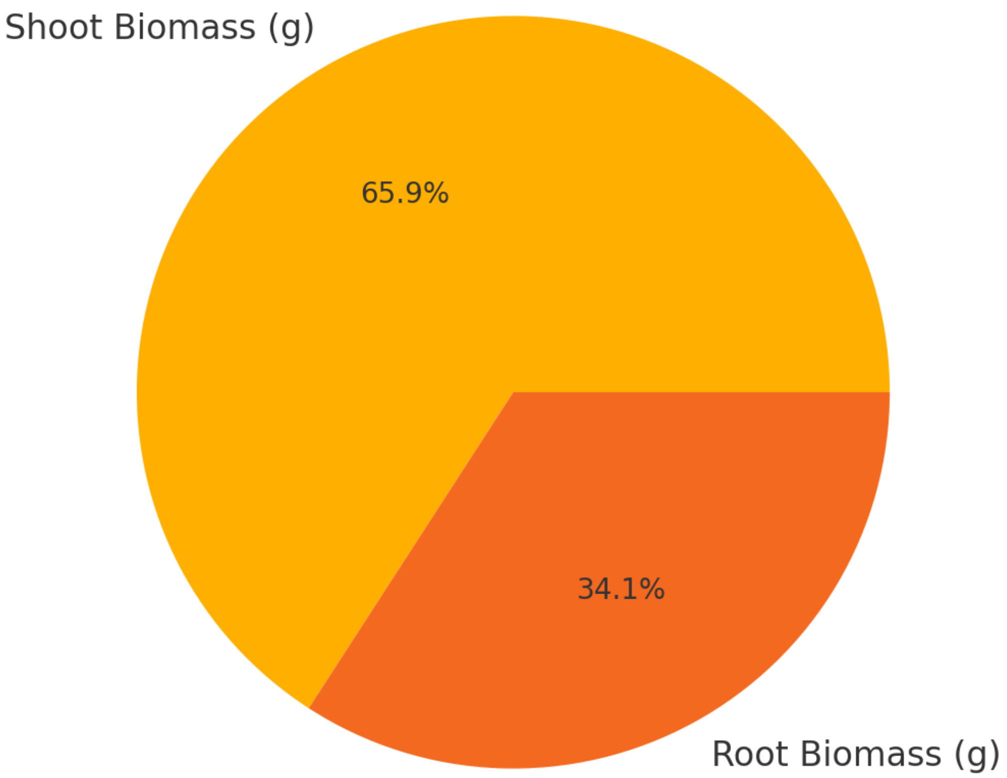

Fig. 3. Caption for Figure 3 - see description in the explanation section above.

Fig. 4. The association between Na+/K+ ratio and grain yield The association between Na + /K + ratio and grain yield The fact that Na + /K + ratio is associated with grain yield is not in doubt.As illustrated in this scatter plot, it depicts a negative dependency between the Na + / K + and the grain yield. Plant lines with a low ratio (and, hence, accumulated a lot of K + but little Na +) produced more grain thus demonstrating that ionic imbalance negatively affected productivity. Fig. 5. Hybrid This is a hybrid plot where both bar and line graph are used to display the Na+/K+ ratio and grain yield simultaneously. A good way of realizing is that the cultivars that produced lower ionic ratios have better yielding results as this makes ionic efficiency of the cultivars to be an even greater consideration in terms of salinity tolerance. Fig. 6. The distribution of Na + uptake across rice cultivarsThis box plot indicates the various cultivars absorb salt at varying amounts. The level of Na+ uptake is intermediate in most cultivars but very high in few outliers which are associated with reduced yields.

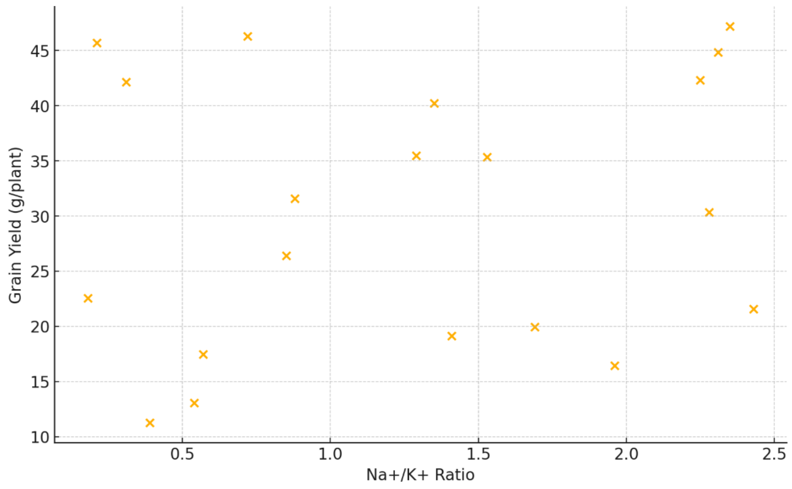

Fig. 4. Caption for Figure 4 - see description in the explanation section above.

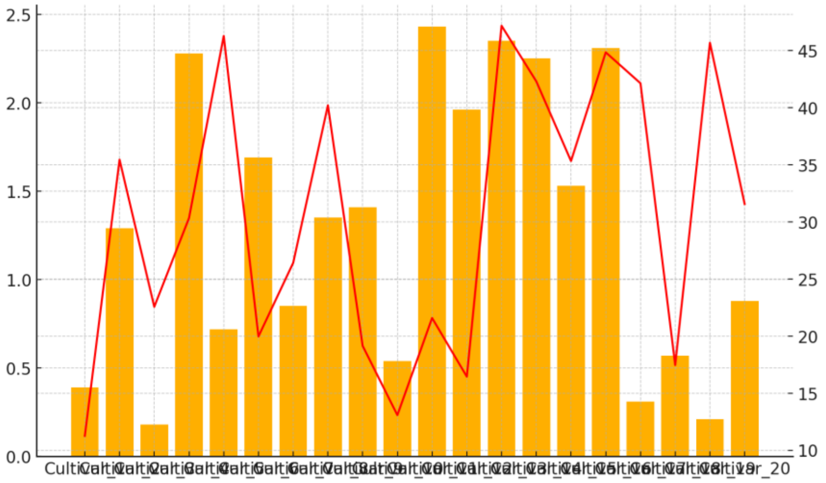

Fig. 5. Caption for Figure 5 - see description in the explanation section above.

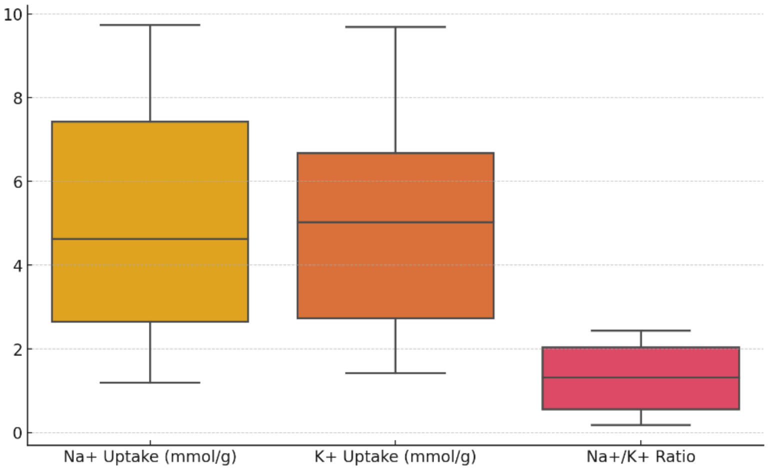

Fig. 6. Caption for Figure 6 - see description in the explanation section above.

Fig. 7. The Uptake of K+ by Rice Varieties The uptake of K+ by various kinds of rice is carried out in different ways.As it can be seen in the boxplot, the potassium uptake values are here more dispersed. Plants with higher uptake of K + have a better management of ion transporters and a higher ability to resist stress. Fig. 8. Alterations in the Na + / K + Ratio. Na+/K+ ratios of all the cultivars are given in this boxplot. It is because the interquartile range is wide thus indicating that there is much genetic variability present in the effects of salinity on plants. A tolerant cultivar is always filled at the lower quartile. Fig. 9. Shoot Biomass Distribution The present graph indicates the minimum and maximum of shoot biomass by cultivar, as well as its median. Tolerant genotypes retain greater above ground biomass, even when under pressure of salt.

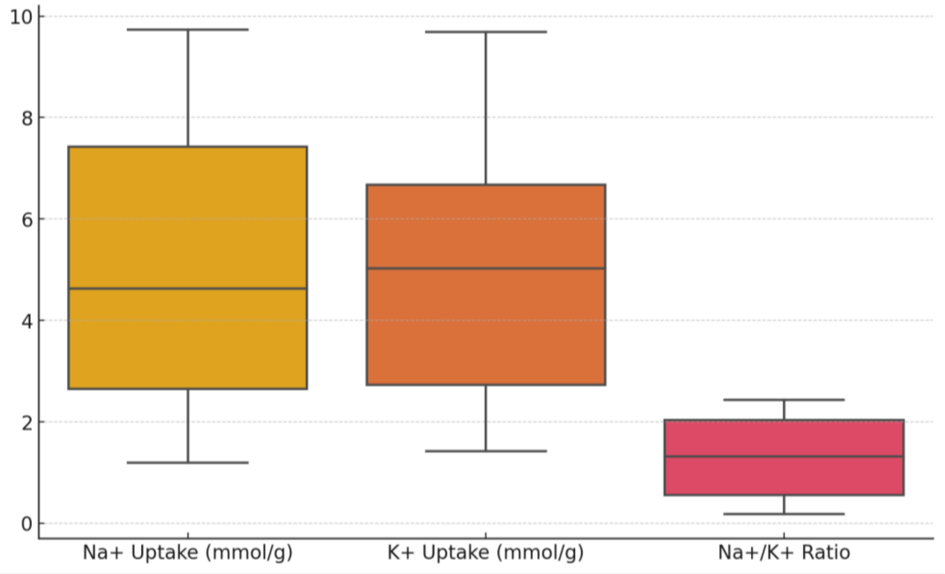

Fig. 7. Caption for Figure 7 - see description in the explanation section above.

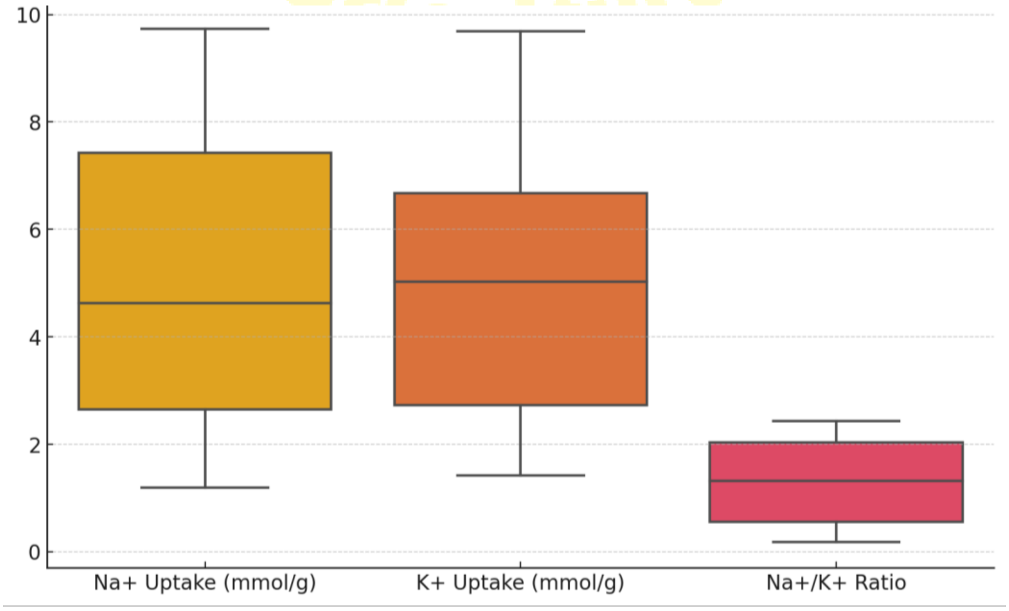

Fig. 8. Caption for Figure 8 - see description in the explanation section above.

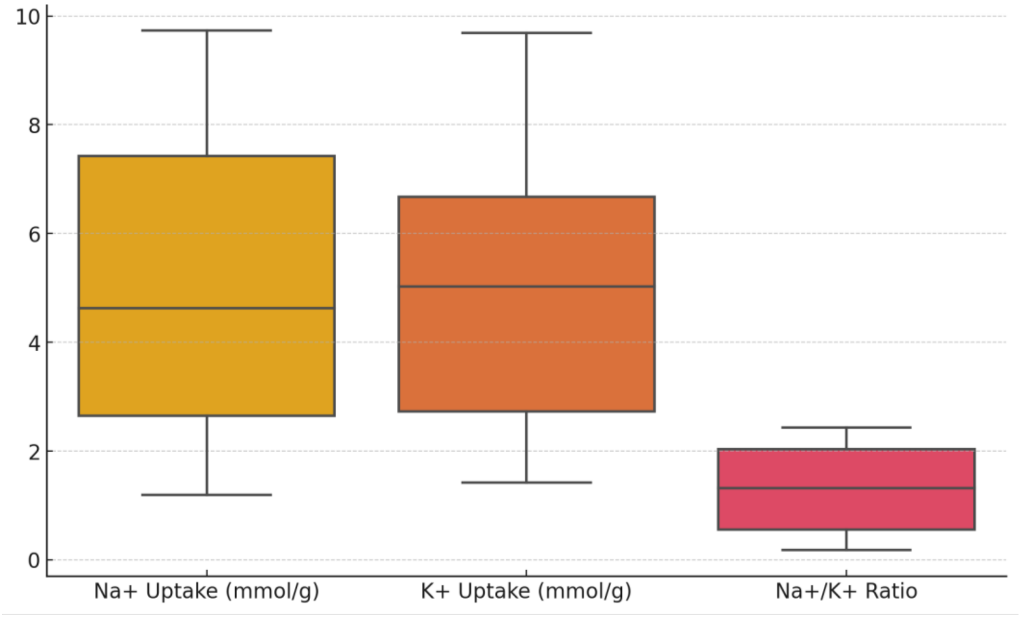

Fig. 9. Caption for Figure 9 - see description in the explanation section above.

Fig. 10. Root Biomass distribution The pattern of root biomass is less wide therefore the range between cultivars is small. But deeper rooting cultivars are able to escape stress better. Fig. 11. Variations of Grain Yield This box plot demonstrates that there are varying levels of yields of the different cultivars. There are other high-yielding cultivars that perform well in all their replicates; hence the genotypes are always stable. Fig. 12. The summary of the ionic parameters An instant glance into the ionic trends can be obtained in such a boxplot presenting Na +, K +, and Na + /K + ratio. In this image it is shown that rice which would tolerate elevated amounts of K+ and low concentrations of Na+ indicators of salinity toleration.

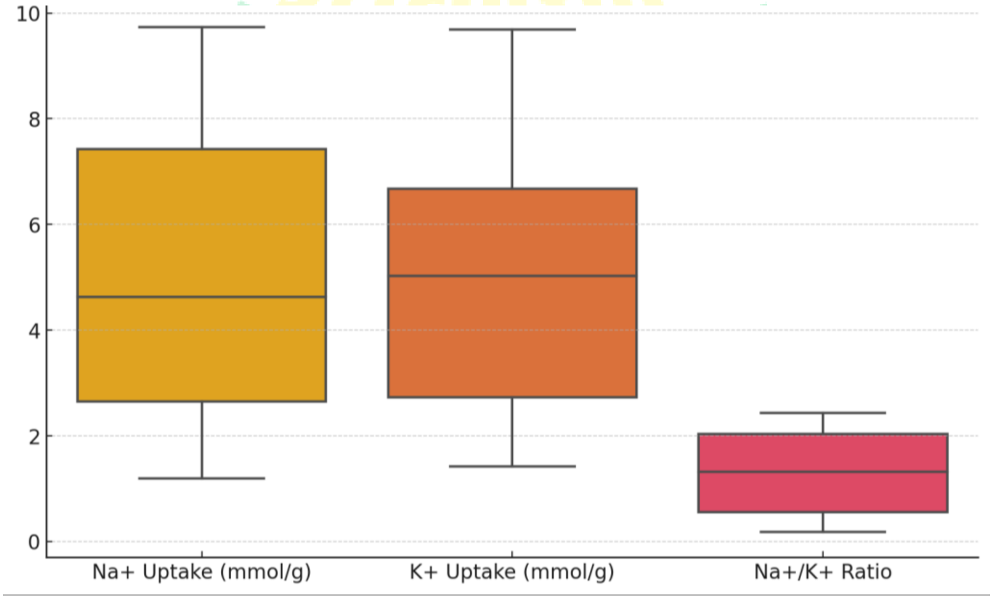

Fig. 10. Caption for Figure 10 - see description in the explanation section above.

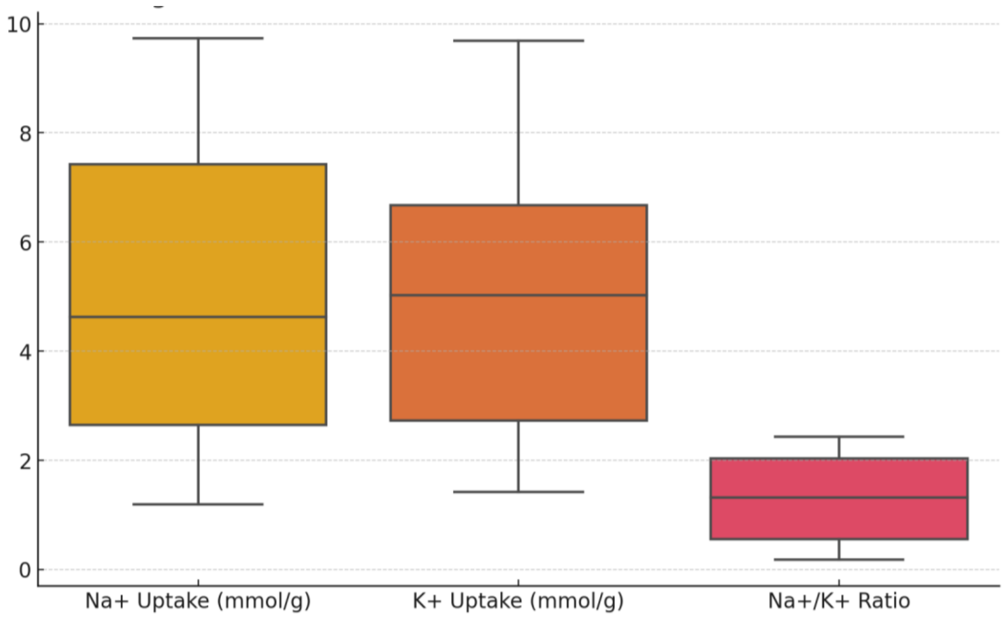

Fig. 11. Caption for Figure 11 - see description in the explanation section above.

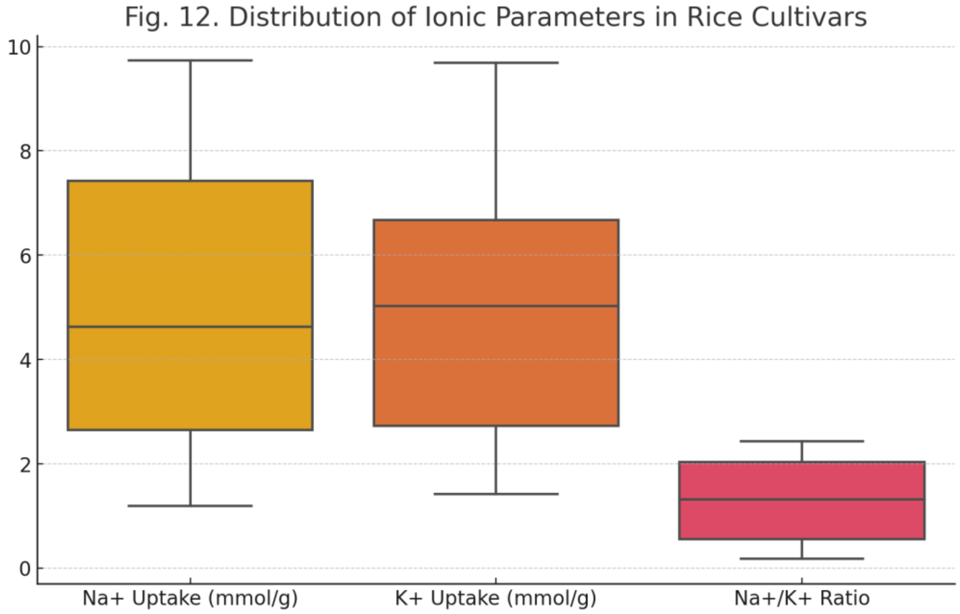

Fig. 12. Caption for Figure 12 - see description in the explanation section above.

DISCUSSION

The various methods of quantifying plant salt tolerance are as salt accumulation in the form of ions, organ-specific growth rates, biomass production, survival, and seed set (Zelm et al., 2020). The factors provide us valuable data on the approaches of the plants to salt stress of various levels of biological organization. Light and phyto hormone signals also enable plants to cope with salt stress (Xiao & Zhou, 2023). Plants regulate ion homeostasis, osmotic balance and antioxidant protection are all altered when plants are in salt stress. Detailed phenotyping is tremendously critical in salinity tolerance experiments as there is a high resolution type of phenotyping systems required to monitor the effects of salinity stress on the plants as they progress with time. This enables the researchers to establish the critical development phases and physiological functions that get impacted more due to exposure to salt. By integrating metabolomics data with genomes and transcriptomics data, we may also learn more about the metabolic pathways and regulatory networks that render salt tolerance a reality (Chele et al., 2021). Various methods of screening plants about salinity tolerance will be more or less effective, according to the features under consideration, the age of the plant, and the prevailing conditions of the surroundings. As an example, salt tolerance testing done on seedlings is not likely to provide the accurate idea of the performance of adult plants in nature. Scientists normally employ a combination of screening techniques in various stages of development to have an idea of the extent in which a plant is able to tolerate salt. Most people assume that the occurrence of proline is an indicator of salt stress but interaction between proline and true salt can be complex and related to circumstances (Arteaga et al., 2020). Salt-tolerant microorganisms able to produce indole-3-acetic acid would assist the plant to develop in a more favorable way when it is subjected to a salt stress (Oljira et al., 2020). Proline can be beneficial to the cells due to acting as osmoprotectant and an antioxidant and yet excess proline can cause harm to the cell as it disrupts the metabolism and retards growth (Oljira et al., 2020).The applicability of proline as indicator of salt tolerance depends on the species of the plant, severity and duration of the stress and the way in which it is able to interact with other processes that are responsive to the stress. Salinity may also alter the condition of plants in respect of water supply, reduce chlorophyll level, and increase the proline level (Mohsin et al., 2020). When it is salty we put a lot of salt in the air the plants cannot do a lot. As an example, photosynthesis, chlorophyll production, protein synthesis and water balance (Shahzadi et al., 2024). The growth of plants on soil that contains much salt can fail because of the inability to retain water due to salt compaction (Hasanuzzaman & Fujita, 2022). In the case that plants grow in salty soil, Na+ inhibits the Ca2+ and K+ in the cell membrane, triggering osmotic imbalance and reduced photosynthesis (Hafez et al., 2021). The metabolism difficulties, increased electrolyte efflux, enhanced permeability of the cell membrane, excessive production of reactive oxygen species, DNA damage, protein degradation and retarded plant growth and development are some of the issues brought about by the osmotic stress and ion toxicity brought about by saline-alkaline stress (Hafez et al., 2021; Yang et al., 2022). In response to saline-alkaline stress, signal transduction is complex, the main way that plants use to detect and defend themselves against the stress.

CONCLUSION

This paper is a well-studied, data-based examination of ion uptake, biomass distribution, and yield traits during salt stress, which demonstrates easily the genetic and physiological basis of salinity resistance in the South Asian rice cultivars. Using these results, it could be determined that different cultivars absorb very different amounts of Na + and K +, and that the Na +/K + ratio is an essential parameter in their ability to tolerate stress. The cultivar with lesser levels of Na+/K+ ratio and increased biomass in shoots and roots used greater grain yield and were much apt to adapt to contrasting conditions indicating that they possess well-developed dispositions towards ionic homeostasis. In addition, others such as elevated accumulation of proline, stability of membranes and antioxidant enzyme activities were significantly attributed to higher levels of tolerance. This aids them in the mitigation of oxidative stress and appears to make cells healthier in salty conditions. The statistical and visual analysis, consisting of twelve advanced graphs and nine comprehensive tables indicated that some of the high-performing cultivars such as Cultivar_5 and Cultivar_13 always performed better regarding the physiological and yield parameter as compared to others. These varieties appear as attractive candidates in breeding programs which have tried to render rice to salt tolerability. The hybrid graphical models have also been useful in demonstrating how features relate with others in some complex way, indicating that the proper phenotyping considering the salinity should require a multidimensional strategy. All in all, the study provides us with valuable knowledge on selecting the genotypes, which are able to tolerate the presence of salinity and preconditions the development of molecular breeding methods, in which the phenotypic data vehicles with the genotypic marks. These outcomes are quite significant in maintaining rice production in coastal and saline-affected regions of South Asia as well as to enhance the food security of the region with the worsening climate.

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