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RESEARCH ARTICLE

Evaluation of rice genotypes for low phosphorus stress and identification of tolerant genotypes using stress tolerance indices

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Abstract

Soil phosphorus (P) deficiency has emerged as one of the major limiting factors in rice production. The development and deployment of tolerant cultivars are one of the plausible approaches to combat low P-tolerance in rice. Thus, the study was carried out to identify P-stress-tolerant rice genotypes using stress tolerance indices. In the present investigation, 31 rice genotypes were evaluated under P stress and normal conditions for grain yield in two growing seasons (*kharif* 2017 and *rabi* 2017). Results from the combined analysis of variance showed a significant effect of P stress and season on grain yield among genotypes for the stress indices. Association analysis identified stress tolerance index, yield stability index, and yield index as the most appropriate indices for the selection of P-stress tolerant rice genotypes. Based on these indices, Gangavati Sona, GNV-1109, IR-30864, and FL-478 were identified as the best-performing genotypes under both optimum and P-stress conditions. Genotypes Tanu, Tellahamsa, and MTU-1001 were identified as most sensitive to P-stress. The insights from this study along with tolerant lines can be used to develop low P tolerant cultivars in rice breeding programs, which in turn helps in getting higher yields under acidic and alkaline soils to increase the farmer's income.

Keywords: Landraces, soil nutrition, phosphorus stress, tolerance indices, association.

Introduction

Rice (*Oryza sativa* L.) is a principal calorific food crop for human kind, providing 21% of the energy and 15% of the protein requirements (Kennedy et al. 2002). Rice farming is the major livelihood for many people around the world. Hence, cost-effective rice farming strategies are critical for maintaining considerable profit margins for growers and inexpensive market pricing for consumers. Rice production is confronted by several biotic and abiotic stresses, thereby reducing productivity which in turn reduces the income levels of the farmers. Besides, the high cost of cultivation also reduces the profit margin for farmers since a farmer has to purchase all inputs in retail and sells the products wholesale. Insect pest, diseases and weeds mainly cause biotic stresses while abiotic factors involve stresses caused by drought, salinity, submergence, and nutrient deficiency.

Among the various plant nutrients, phosphorus (P) is a key macro-nutrients indispensable for the optimum growth and development of many crops, including rice. Although P exists in the soil in sufficient quantity, it may not be available to plants, as the phosphate form of fertilizer P may bind to chemicals and/or organic matter in soil, reducing the P use efficiency. The unavailable form of P will be made available to plants only when bound inorganic phosphate is released by hydrolysis (Alori et al. 2017). A deficiency of P in rice results in stunted growth with narrow leaves and spindly stems with a significant reduction in the number of tillers, leaves, panicles, and grains per panicle. Additionally,

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delays the flowering and maturity by one week to 20 days. In severe conditions, plants may not flower at all and even if they flower, a large number of empty grains are formed with poor quality (Dobermann and Fairhurst 2000). Eventually, severe P deficiency leads to greater yield losses in rice (Fageria and Baligar 1987). India mainly depends on the import of phosphatic fertilizers, which increases the burden on the country's revenue. Increased fertilizer costs and the gradual depletion of phosphate rock (a source of P fertilizer) have necessitated the development of plant varieties with improved tolerance to P deficiency.

There are several approaches to address the P deficiency problems in rice. However, identifying and developing rice genotypes that can perform well under low soil phosphorus could be a promising solution (Cordell et al. 2009; Rose and Wissuwa 2012). In the past, different selection criteria have been proposed for selecting the genotypes based on their performance in stress and normal environments. One such criterion was the selection of genotypes based on their relative performance under stress and normal environments through many selection indices (Clarke et al. 1992). In the present study, stress indices such as stress tolerance index (STI) (Fernandez 1992), tolerance index (TOL) (Rosielle and Hamblin 1981), yield reduction ratio (YR) (Golestani–Araghi and Assad 1998), stress susceptibility index (SSI) (Fisher and Maurer 1978), yield stability index (YSI) (Bouslama and Schapaugh 1984), yield index (YI) (Gavuzzi et al. 1997) and percent yield reduction (PYR) (Yaseen and Malhi 2009) were calculated. Several researchers used these indices for the assessment of drought tolerance in many crops (Mollasadeghi 2011; Ashraf et al. 2015). Recently reports were also found on using them to study salinity tolerance (Singh et al. 2015), and nitrogen deficiency tolerance (Rameeh 2015 in rapeseed; Khan and Mohammad 2016 in wheat). Reports on the use of these indices for assessing low P tolerance in rice were rather limited in literature (Mahadev swamy et al. 2019; Basavaraj et al. 2021). Thus, in the present study, an effort was made to assess the low P tolerance using the above-mentioned indices and to identify the most stable P stress tolerant genotypes which serve as valuable rice genetic resources for breeding for low phosphorus tolerance and identification of ideal selection indices for selection of relatively better-performing genotypes under stress and non-stress environment.

Materials and methods

The site of experimentation was ICAR-Indian Institute of Rice Research (IIRR), Rajendranagar, Hyderabad, India situated at an altitude of 542.3 m above sea level, 17°19' North latitude and 78°23' East longitude and lies in the Southern Zone (Zone-3) of Telangana state. The seed material (31 genotypes) were collected from rice-growing regions of Karnataka and were evaluated in specialized P experimental plots of IIRR using randomized complete block design (RCBD) in two replications under P_0 (stress, where available P is <3 ppm) and P_{60} (normal, where available P is 30 ppm) in *Kharif*-2017 and *Rabi*-2017 (hereafter K-2017 and R-2017 respectively) seasons. The 21-day-old nursery seedlings were transplanted to main plots; seedlings were planted following 20x15 cm spacing. P fertilizer has not been applied to the P stress plot(P_0) and whereas recommended dose (60 kg/ha) of P fertilizer has been provided for the normal plot (P_{60}). Other elements (nitrogen and potassium) have been applied as per recommended dose of fertilizer (RDF). Need-based plant protection measures have been taken upto ensure proper growth and establishment of plants.

The grain yield per plant was used to calculate P stress indices by averaging the five random plants' yield at the crop maturity stage. P stress indices were calculated using the following indices:

- Stress Tolerance Index (STI) = $(Y_P)(Y_S)/(\bar{Y}_P)^2$, Fernandez 1992
- Tolerance Index (TOL) = $(Y_P - Y_S)$, Rosielle and Hamblin 1981
- Stress Susceptibility Index (SSI) = $(1 - Y_S/Y_P)/(1 - \bar{Y}_S/\bar{Y}_P)$, Fisher and Maurer 1978
- Yield Stability Index (YSI) = Y_S/Y_P, Bouslama and Schapaugh 1984
- Yield Reduction Ratio (YR) = $1 - (Y_S/Y_P)$, Golestani–Araghi and Assad 1998
- Yield Index (YI)= $Y_S/\bar{Y}_S$, Gavuzzi et al. 1997
- Per cent Yield Reduction (PYR) = $(Y_P - Y_S)/Y_P$, Yaseen and Malhi 2009

Where,

Y_P is grain yield under normal soil P condition (P60), YS is grain yield under low soil P condition (P0),$\bar{Y}_P$and $\bar{Y}_S$ are the mean grain yield of respective genotypes under P60 and P0 conditions.

Statistical analysis

P stress indices were calculated season-wise using the above-mentioned formulas. To know the genotype x season interaction effects,combined analysis of variance (ANOVA) was computed between stress indices and grain yield using ADEL-R software of CIMMYT (Angela et al. 2017). The means of stress tolerance indices and grain yields were compared using Fisher'sLSD test. Correlograms were drawn using R-software version 4.2.2 (Maathuis et al. 2020) to know the association between stress tolerance indices and grain yield.

Results

Analysis of variance (ANOVA)

The results of the combined analysis of variance revealed the noteworthy consequences of P stress on rice grain yield (Table 1). The mean sum of squares due to genotype was found significant for all the stress indices studied. The interaction (genotype x season) effect was found to be significant for all the stress indices and grain yield. Due to the

Table 1. Combined analysis of variance (ANOVA) for grain yield under phosphorus stress (Ys), normal (Yp) conditions and stress tolerance indices of 31 rice genotypes

Source of variation	df	Mean square								
		Y_S	Y_P	STI	TOL	SSI	YSI	YR	YI	PYR
Genotypes	30	1.500**	76.842**	0.014**	71.830**	0.077**	0.005**	0.067**	1.497**	672.411**
Season	1	1.188**	99.628**	0.006**	79.056**	0.124**	0.003**	0.091**	0.0002^{ns}	908.458**
Genotype:Season	30	0.197**	12.809**	0.001**	10.183**	0.054**	0.001**	0.047**	0.216**	471.998**
Residuals	60	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Mean		1.012	14.408	0.075	13.395	0.965	0.069	0.897	1.000	89.796
CV		98.727	6.940	1318.027	7.465	103.542	1431.871	111.370	141.41	1.113
$LSD_{0.05\%}$		1.963	1.963	1.963	1.963	1.963	1.963	1.963	2.776	1.963

Significant at 0.01 levels of probability, ns = not significant. **Y_S = Yield under stress, **Y_P** =Yield under control, **STI =** Stress tolerance index, **TOL =** Tolerance index, **SSI =** Stress susceptibility index, **YSI =** Yield stability index, **YR =** Yield reduction ratio, **YI =** Yield index and, **PYR** = Per cent yield reduction index.

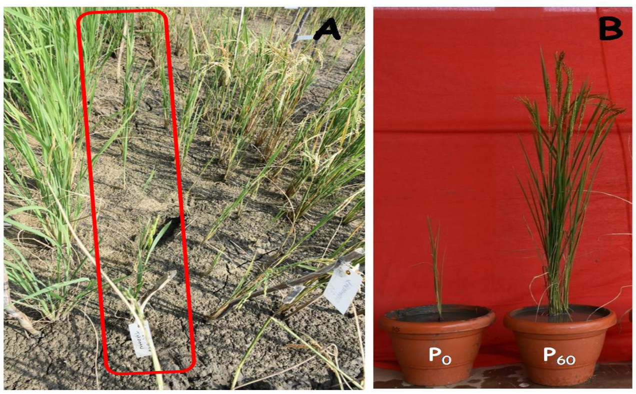

Fig. 1. Phenotypic growth representation of genotype, Tanu. A = Plant phenotypic growth of Tanu in P stress (P_0) condition and B = Comparison of Tanu genotype in stress (P_0) as well as normal (P_{60}) conditions

photosensitive nature of Ratnachudi and Ratnamudi, both genotypes have not flowered during the *rabi*-2017 season. Among 31 genotypes, Gangavati Sona, GNV-1109 and CTH-1 produced higher grain yield under both stress and normal conditions during *kharif*-2017 (Table 2A) whereas, in *rabi*-2017, CTH-1 and GNV-14-96-1 has produced higher grain yield under both stress and normal conditions (Table 2B). Genotypes Tanu (Fig. 1), MTU-1001, CTH-3 and, ARS-emergency have registered low grain yields under stress conditions and genotypes BPT-Sona, Pokkali, Gangakaveri, and CTH-3 have registered lower grain yields under normal conditions across both the seasons.

P stress tolerance indices

Various stress indices viz., STI, TOL, SSI, YSI, YR, YI, and PYR were calculated using the grain yields of genotypes that

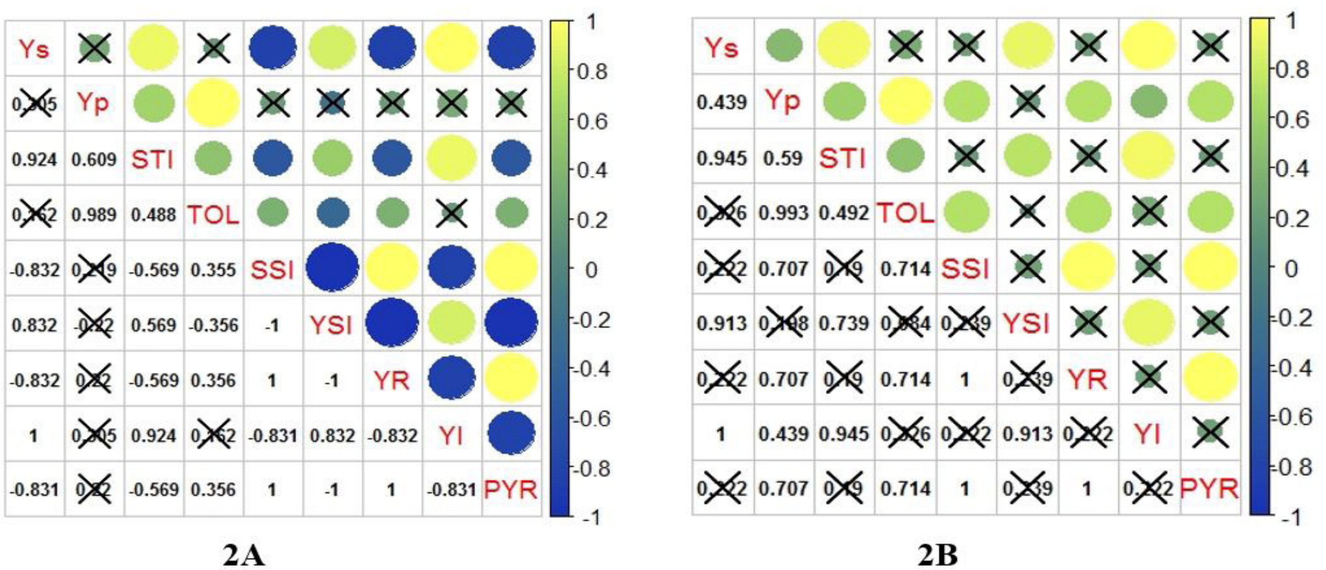

Fig. 2. (A and B) = Correlogram illustrating the association between grain yield under phosphorus stress (Ys), normal (Yp) conditions and stress tolerance indices during *kharif*-2017 and *rabi*-2017 respectively. Size of circle indicates the strength of association, bigger the circle stronger the association & vice versa, Circle and/or values without cross mark indicates a significant association, circle and/or values with cross marks is non-significant. **Note**: **Ys**, yield under low soil P condition; **Yp**, yield under normal soil P condition; **STI**, stress tolerance index; **TOL**, tolerance index; **SSI**, stress susceptibility index; **YSI**, yield stability index; **YR**, yield reduction ratio; **YI**, yield index; **PYR**, per cent yield reduction.

Table 2A. Stress indices values for rice genotypes based on grain yield under low soil P condition and normal condition for *kharif*-2017 season

S. No.	Genotypes	Y_S	Y_P	STI	TOL	SSI	YSI	YR	YI	PYR
1	ARS-Emergency	0.46	10.73	0.02	10.27	1.03	0.04	0.96	0.41	95.72
2	BPT Sona	1.16	8.88	0.04	7.72	0.94	0.13	0.87	1.04	86.97
3	BPT-5204	1.38	13.00	0.08	11.61	0.96	0.11	0.89	1.25	89.35
4	BR-2655	0.59	18.49	0.05	17.90	1.04	0.03	0.97	0.53	96.83
5	CSR-22	0.98	18.82	0.08	17.84	1.02	0.05	0.95	0.88	94.79
6	CTH-1	1.74	20.23	0.15	18.50	0.99	0.09	0.91	1.56	91.41
7	CTH-3	0.45	9.14	0.02	8.70	1.03	0.05	0.95	0.40	95.12
8	FL-478	2.20	14.91	0.14	12.71	0.92	0.15	0.85	1.98	85.22
9	Gangakaveri	1.32	9.66	0.05	8.34	0.93	0.14	0.86	1.19	86.36
10	Gangavati sona	2.72	19.53	0.23	16.82	0.93	0.14	0.86	2.45	86.09
11	GNV-0501	0.91	11.28	0.04	10.37	0.99	0.08	0.92	0.81	91.97
12	GNV-1089	0.94	15.01	0.06	14.07	1.01	0.06	0.94	0.84	93.76
13	GNV-1109	2.38	19.73	0.20	17.35	0.95	0.12	0.88	2.15	87.92
14	GNV-14-96-1	1.67	17.91	0.13	16.24	0.98	0.09	0.91	1.50	90.67
15	IR-30864	1.67	26.87	0.19	25.20	1.01	0.06	0.94	1.50	93.79
16	IRRI-154	0.50	10.51	0.02	10.02	1.03	0.05	0.95	0.45	95.26
17	Jaya	1.28	16.74	0.09	15.46	1.00	0.08	0.92	1.15	92.34
18	JGL-1798	0.94	15.01	0.06	14.07	1.01	0.06	0.94	0.85	93.73
19	MTU-1001	0.21	17.37	0.02	17.16	1.07	0.01	0.99	0.19	98.80
20	MTU-1010	0.88	14.79	0.06	13.91	1.01	0.06	0.94	0.79	94.04
21	Pokkali	0.85	10.41	0.04	9.55	0.99	0.08	0.92	0.77	91.80
22	Raksha	0.63	13.21	0.04	12.58	1.03	0.05	0.95	0.57	95.24
23	Rasi	1.24	17.17	0.09	15.93	1.00	0.07	0.93	1.11	92.81
24	Ratnachudi*	1.90	16.92	0.14	15.02	0.96	0.11	0.89	1.71	88.77
25	Ratnamudi*	1.74	11.24	0.08	9.50	0.91	0.15	0.85	1.56	84.54
26	RNR-15048	1.00	16.24	0.07	15.23	1.01	0.06	0.94	0.90	93.83
27	RP-Bio	0.79	9.22	0.03	8.43	0.99	0.09	0.91	0.71	91.46
28	Siri-1253	0.68	17.59	0.05	16.90	1.04	0.04	0.96	0.62	96.11
29	Swarna sub-1	0.53	14.49	0.03	13.96	1.04	0.04	0.96	0.48	96.34
30	Tanu	0.17	17.27	0.01	17.10	1.07	0.01	0.99	0.16	99.00
31	Tellahamsa	0.54	22.09	0.05	21.55	1.05	0.02	0.98	0.49	97.56
Mean		1.11	15.30	0.07	14.19	0.99	0.07	0.92	1.00	92.50
Min.		0.17	8.88	0.01	7.72	0.91	0.01	0.85	0.16	84.54
Max.		2.72	26.87	0.23	25.2	1.07	0.15	0.99	2.45	99.00
CD		0.33	4.28	0.05	4.37	0.005	0.005	0.005	0.33	0.005
SE (m)		0.11	1.47	0.01	1.50	0.002	0.002	0.002	0.11	0.022
SE (d)		0.16	2.08	0.02	2.13	0.003	0.002	0.002	0.16	0.002
CV		17.0	15.29	15.0	14.86	0.264	3.00	0.37	15.31	0.37

are grown under stress and normal conditions (Tables 2A and 2B). The STI values were highest for Gangavati Sona (0.227 and 0.245) and lowest for Tanu (0.013 & 0.010) during *kharif*-2017 and *rabi*-2017, respectively. Similarly, in both the growing seasons, the TOL values were highest and lowest for IR-30864 (25.196 and 24.366) and BPT-Sona (7.720 and 7.898), respectively. The lowest and highest SSI values were recorded for Ratnamudi (0.912) and Tanu (1.067), respectively during *kharif*-2017, whereas FL-478 (0.903) and MTU 1001 (1.066) recorded minimum and maximum values for SSI, respectively, in *rabi*-2017. During K-2017, the highest and lowest YSI values were recorded for Ratnamudi (0.155) and Tanu (0.010), respectively. Similarly, in *rabi*-2017, maximum and minimum YSI values were recorded for FL-478 (0.158)

Table 2B. Stress indices values for rice genotypes based on grain yield under low soil P condition and normal condition for *rabi*-2017 season

S. No.	Genotypes	Y_S	Y_P	STI	TOL	SSI	YSI	YR	YI	PYR
1	ARS-Emergency	0.33	10.37	0.02	10.04	1.04	0.03	0.97	0.36	96.81
2	BPT Sona	1.10	9.00	0.05	7.90	0.94	0.12	0.88	1.20	87.80
3	BPT-5204	1.18	11.60	0.07	10.42	0.96	0.10	0.90	1.29	89.83
4	BR-2655	0.67	15.72	0.06	15.05	1.03	0.04	0.96	0.73	95.76
5	CSR-22	0.85	16.17	0.08	15.32	1.02	0.05	0.95	0.93	94.73
6	CTH-1	1.68	19.28	0.18	17.60	0.98	0.09	0.91	1.83	91.30
7	CTH-3	0.24	10.09	0.01	9.84	1.05	0.02	0.98	0.26	97.61
8	FL-478	2.28	14.44	0.18	12.15	0.90	0.16	0.84	2.50	84.18
9	Gangakaveri	1.19	9.48	0.06	8.29	0.94	0.13	0.87	1.30	87.45
10	Gangavati sona	2.66	16.84	0.25	14.18	0.90	0.16	0.84	2.90	84.22
11	GNV-0501	0.70	9.87	0.04	9.17	1.00	0.07	0.93	0.77	92.91
12	GNV-1089	1.02	12.93	0.07	11.91	0.99	0.08	0.92	1.11	92.14
13	GNV-1109	2.26	16.30	0.20	14.04	0.92	0.14	0.86	2.47	86.16
14	GNV-14-96-1	1.61	17.96	0.16	16.35	0.98	0.09	0.91	1.76	91.03
15	IR-30864	1.46	25.83	0.21	24.37	1.01	0.06	0.94	1.60	94.33
16	IRRI-154	0.58	11.41	0.04	10.83	1.02	0.05	0.95	0.63	94.93
17	Jaya	1.15	15.44	0.10	14.28	0.99	0.07	0.93	1.26	92.52
18	JGL-1798	0.88	14.05	0.07	13.17	1.01	0.06	0.94	0.96	93.72
19	MTU-1001	0.10	17.64	0.01	17.54	1.07	0.01	0.99	0.11	99.42
20	MTU-1010	0.96	13.25	0.07	12.29	0.99	0.07	0.93	1.05	92.74
21	Pokkali	0.73	9.47	0.04	8.74	0.99	0.08	0.92	0.79	92.33
22	Raksha	0.57	12.08	0.04	11.51	1.02	0.05	0.95	0.62	95.29
23	Rasi	1.03	16.22	0.09	15.19	1.00	0.06	0.94	1.13	93.65
24	Ratnachudi*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25	Ratnamudi*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	RNR-15048	0.94	15.31	0.08	14.36	1.01	0.06	0.94	1.03	93.85
27	RP-Bio	0.58	11.59	0.04	11.01	1.02	0.05	0.95	0.64	94.98
28	Siri-1253	0.76	15.77	0.07	15.00	1.02	0.05	0.95	0.83	95.15
29	Swarna sub-1	0.40	15.17	0.03	14.77	1.04	0.03	0.97	0.44	97.34
30	Tanu	0.11	15.41	0.01	15.29	1.06	0.01	0.99	0.12	99.27
31	Tellahamsa	0.33	20.24	0.04	19.90	1.05	0.02	0.98	0.37	98.35
Mean		0.91	13.51	0.07	12.59	0.93	0.06	0.87	0.99	87.09
Min.		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.		2.66	25.83	0.25	24.37	1.07	0.16	0.99	2.9	99.42
CD		0.33	4.20	0.49	4.05	0.01	0.005	0.001	0.36	0.001
SE (m)		0.11	1.45	0.17	1.38	0.23	0.02	0.20	0.12	0.001
SE (d)		0.16	2.30	0.24	1.95	0.65	0.01	0.01	0.17	0.001
CV		17.00	15.10	14.00	15.33	0.73	4.00	0.57	17.20	0.54

*Genotypes did not flower, as they are photosensitive in nature.

and MTU-1001 (0.006), respectively.

The YR values were highest and lowest for Tanu (0.990) and Ratnamudi (0.845) respectively, during K-2017 and in R-2017, YR was minimum and maximum for FL-478 (0.842) and MTU-1001 (0.994) respectively. Lower values for YI during *kharif*-2017 and *rabi*-2017 were recorded for Tanu (0.156) and MTU 1001 (0.112) respectively, whereas, GangavatiSona (2.446 and 2.904) recorded Higher YI during both the growing seasons. The PYR value was highest and lowest for Tanu (99.000) and Ratnamudi (84.544), respectively, during K-2017, whereas FL-478 (84.178) and MTU 1001 (99.418) recorded minimum and maximum values for

PYR, respectively, during *rabi*-2017.

Association between grain yield and stress tolerance indices

Pearson's correlation coefficient between grain yields under stress, normal conditions and P stress indices were analyzed for two growing seasons (Fig. 2). Grain yield under P stress (Ys) was positively associated with Yp (r=0.305 and r=0.439*), STI (r=0.924** and r=0.945**), TOL (r=0.162 and r=0.326), YSI (r=0.832** and r=0.913**) and YI (r=1.000** and r=1.000**) in both *kharif*-2017 and *rabi*-2017. Meanwhile, Ys was negatively associated with SSI (r=-0.832**), YR (r=-0.832**) and PYR (r=-0.831**) in *kharif*-2017 and had a positive and non-significant association for the same indices during *rabi*-2017. Similarly, grain yield under normal conditions (Yp) had a positive association with STI (r=0.609** and r=0.590**), TOL (r=0.989** and r=0.993**), SSI (r=0.219 and r=0.707**), YR (r=0.220 and r=0.707**), YI (r=0.305 and r=0.439*) and PYR (r=0.220 and r=0.707**). Yp exhibited a negative non-significant association with YSI (r=-0.220) during *kharif* 2017.

Discussion

Phosphorus (P) is the crucial plant macro-nutrient and a major component of adenosine triphosphate (ATP). It is a key constituent of many of the fundamental life processes of plants such as nucleic acid, membrane lipid, protein synthesis, and energy metabolism (Maathuis 2009). It is reported that, globally, around 5.8 billion hectares of cultivable land are deficit in P (Deng et al. 2018). In India, 1.9, 48.8, and 49.3% of soils were found to have high, medium, and low levels of available P (Hasan 1996; Tiwari 2001). Thus, these constraints throw light on developing low P stress-tolerant varieties through different breeding approaches.

ANOVA revealed that all the stress indices and grain yield under stress and normal conditions showed highly significant variation among the genotypes indicating the diverse nature of genotypes which offers an opportunity to select superior genotypes for stress and optimum conditions. Further, significant variation was noticed across two growing seasons for grain yield and all the stress indices except yield index (YI), indicating the effect of the season (day length, relative humidity, temperature, and rainfall) on plant growth and development.

Identification and selection of genotypes based on their genetic potential performed in a suitable environment will be a good choice, while the performance of genotypes under stress and normal condition with the help of selection indices aids in a better selection process for a plant breeder (Kamrani et al. 2017). Although they are associated with each other as they are calculated from the same data, each index has significance in the identification of tolerant and sensitive genotypes. For example, STI is an advanced index for identifying high-yielding genotypes under stress and normal conditions (Fernandez 1992; Ashraf et al. 2015). Gangavati Sona and GNV-1109 recorded higher values of STI; therefore, they are designated as P stress-tolerant genotypes. Tanu and MTU-1001 had the lowest STI values as well as lower grain yield under stress conditions across the seasons, thereby identified as P stress susceptible genotypes.

Similarly, the TOL index is useful in identifying relatively same performing genotypes under stress and non-stress situations (Ghobadi et al. 2012) indices with lower values represent more stable genotypes for stress conditions. Therefore, genotypes with lower TOL values are designated as tolerant (BPT Sona and Gangakaveri) and vice versa. Oo et al. (2021) concluded the same for the TOL index while evaluating backcross inbred lines of Pusa 44 for drought stress tolerance. The stress Susceptibility Index (SSI) signifies the relative stress on the overall population. It is the ratio of yield under stress to normal yield. SSI values greater than one indicate above-average susceptibility, whereas SSI less than one indicates below-average susceptibility (Guttieri et al. 2001). Hence, SSI measures the advantage each tested line has over the population's average stress index; therefore, the lower SSI values indicate tolerance (Fischner and Maurer 1978).

According to YSI and YI, three genotypes, FL-478, Gangavati Sona, and GNV-1109 were identified as P stress tolerant genotypes and registered higher grain yield under stress as well as normal conditions across seasons. Based on YR and PYR indices, FL-478 and Gangavati Sona recorded lower values, thus designated as tolerant to low P stress conditions. These findings suggest that SSI and YSI were able to identify genotypes with higher yields under stress conditions rather than under normal conditions (Golestani-Araghi and Assad 1998; Ashraf et al. 2015).

The different stress indices have identified different genotypes as P stress tolerant, which might lead to contradictions in the selection of genotypes based on a single criterion. So, to discern the most desirable stress index, the correlation coefficient between grain yields under stress, normal condition and different stress indices were analyzed for both growing seasons. A significant positive correlation was observed between Ys and Yp (r=0.439), indicating that genotypes with high yield potential under optimum conditions might have performed better even under stress conditions for yield. A similar observation in wheat for drought stress was made by Aghaei-Sarbarze et al. (2009) and Karmani et al. (2015). However, contrary to our results Poudel et al. (2021) observed a very low and non-significant association between yield under normal and heat stress in wheat genotypes revealing that two growing environments (normal and stress) have an independent effect on the genotype potential. A positive and highly significant association was observed between STI and grain yields under stress conditions (r=0.924**, r=0.945**) and normal conditions (r=0.609**, r=0.590**) in both seasons, revealing the significance of STI as a vital index in the selection of genotypes with good yield under both stress and non-stress conditions. The association between TOL and grain yield under stress was positive but non-significant (0.162, 0.326), but it was positively and significantly associated (0.989, 0.993) with grain yield under normal conditions. SSI, YR and PYR indices had a highly negative correlation in the K-2017 season and a non-significant positive association in R-2017 season for grain yield under the P stress condition, explaining the decrease in grain yields under stress conditions upon selection of these indices. A change in correlation across the seasons is attributed to the difference in photoperiod, relative humidity, and other environmental factors in addition to stress. YSI and YI had a highly significant positive association with grain yield under stress condition across the seasons, therefore the selection of genotypes based on higher values of YI and YSI helps to identify low P stress-tolerant rice genotypes.

Selection based on STI, YSI, and YI can identify genotypes for higher grain yields and P stress tolerance. According to Fernandez (1992) a selection based on STI would identify genotypes with higher levels of yield potential and stress tolerance, our results are in line with Fernandez (1992). YSI was identified as a useful index in some drought tolerance experiments to identify drought tolerant and susceptible genotypes by Mohammadi et al. 2010. Nouri et al. (2011) reported that YSI is a useful parameter for discerning genotypes that have higher permanence and lower receptiveness to stress conditions.

Overall, phosphorus (P) is a vital nutrient indispensable for rice plants' normal growth and development. P deficiency reduces productivity levels to a significant extent in rice. Therefore, developing and deploying a low P-tolerant rice genotype is the ideal solution. Screening and identification of low P tolerant rice genotypes are crucial to improving rice productivity under low P stress conditions. Identification of tolerant and sensitive genotypes based on selection indices would be a potent tool for a breeder. Indices STI, YSI and YI could able to identify appropriate genotypes for stress and optimum conditions. Tolerant genotypes from this study such as Gangavati Sona, GNV-1109, FL-478, CTH-1, and GNV-14-96-1 could serve as potential donors for improving low P tolerance in rice breeding programs.

Authors' contribution

Conceptualization of research (MSA, PMS, CG, CAM, RMS); Designing of the experiments (MSA, CG, CAM); Contribution of experimental materials (RL, PMS, BH); Execution of field/lab experiments and data collection (CAM, PSB, BM, H); Analysis of data and interpretation (SR, KBK, LVS, RMK); Preparation of the manuscript (CAM, PSB, BM, H, RMS, PS, KS, MSA, CG).

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