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Tolerance indices based evaluation of wheat (*Triticum aestivum*) genotypes under terminal heat stress conditions

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ABSTRACT

Present study was carried out during winter (*rabi*) seasons of 2021–22 and 2022–23 at Crop Research Centre, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh to evaluate the terminal heat tolerance ability of 30 wheat (*Triticum aestivum* L.) genotypes using 8 heat stress tolerance indices. The results indicate that 12 genotypes showed low yield reduction as compared to average yield reduction. The stress susceptibility index (SSI) was observed as robust indicator for identifying heat-tolerant genotypes. Stress tolerance index (TOL) was observed crucial which reflects genotype's ability to maintain grain yield under terminal heat stress. Analysis of correlation revealed positive relationships between grain yield under normal and stress conditions, suggesting that best-performing genotypes under normal conditions also perform well under terminal heat stress conditions. Principal component analysis and biplot analysis further confirmed the importance of studied tolerance indices for identification of heat tolerance genotypes. PC1 was associated with yield potential and heat tolerance, while PC2 was associated with stress susceptibility. Based on analysis, genotypes, viz. DBW14, DBW90, HD2864, HD2932, HD2985, HS375, HUW234, RAJ4083, WH1021, WH1124, DBW71 and PBW757 exhibited higher terminal heat stress tolerance. Cluster analysis revealed two major clusters, cluster I contained 12 heat tolerant genotype while cluster II was consisting 18 heat susceptible genotypes. The SSI and TOL index were found promising indices for identification of heat tolerant genotypes of wheat.

Keywords: Cluster analysis, Susceptible, Tolerant, Terminal heat stress, Tolerance indices, Wheat

Wheat (*Triticum aestivum* L.) represents an important food crop on a global scale that controls more agricultural land than any other crop. About a third of the world's population relies heavily on wheat as a basic source of food supply (Lesk *et al.* 2016). The interaction of climate change and the growing population size poses significant challenges to the supply of food security. This dynamic is evidenced by the sharp rise in temperature caused by declining rainfall, changes in rainfall distribution patterns, and reduced winter periods. The most detrimental abiotic stress which affects grain yield and the final quality of crop is heat stress (Kumar *et al.* 2023). The potential increase in heat stress is expected to increase in light of subsequent changes in global climate parameters (Maulana *et al.* 2018). Climate-related forecasts suggest that by the end of this century, production of wheat may decline from 4.1–6.4% due to an average temperature rise of between 1°C and 4°C (Liu *et al.* 2016). For wheat, beyond the optimum temperature of 22–25°C during anthesis to grain maturity causes irreversible damage. Late sowing of wheat leads to a significant effect on the anthesis stage and grain-filling, which is significantly affected by the temperature rise from 25–32°C. Such condition promotes the early maturation of crop, which leads to a sharp drop in grain yields. Simultaneously, projections suggest that the global population is anticipated to reach 9.1 billion by the year 2050 (Farooq *et al.* 2011). Therefore, the productivity of wheat can be increased by developing heat tolerant varieties, to fulfill the demands of growing population (Poudel *et al.* 2021). Therefore, it is necessary for breeders to decipher the different genes that exhibit heat stress resistance (Kamrani *et al.* 2017). The use of genetic diversity across different wheat genotypes empowers breeders to develop heat-tolerant varieties. Thus, to find a better selection approach for the identification of stress-tolerant cultivars, breeders and researchers have suggested many stress tolerant indices. However, tolerance index, mean productivity index, stress tolerance index, stress susceptibility index, yield stability index, geometric mean productivity, yield index and percent yield reduction are more useful. Keeping in view, the above mentioned 8 stress tolerance indices were evaluated in 30

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wheat genotypes under timely and late sown conditions for identification and selection of heat tolerant genotypes.

MATERIALS AND METHODS

Experimental material: The experimental materials comprised 30 wheat genotypes, consisting of released varieties. These materials were sourced from the Indian Institute of Wheat and Barley Research (IIWBR), Karnal, Haryana (Supplementary Table 1).

Location, experimental site and environmental conditions: The current experiment was conducted during winter (*rabi*) seasons of 2021–22 and 2022–23 at the Crop Research Centre, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut (29°1 N and 77°45 E and at 237 m amsl), Uttar Pradesh, representing the North Western Plain Zone. The genotypes were sown on 18th November for timely sowing conditions and on 28th December for late sowing conditions for two consecutive years.

Experimental design: The experiment was laid out in a randomized block design (RBD), replicated thrice for both timely and late sowing condition. Each genotype was sown in two rows with spacing of 22.5 cm using a Norwegian seed drill.

Calculation of different indices to study the terminal heat tolerance:

Percent yield reduction (PYR) (Farshadfar and Javadinia 2011):

$$(PYR) = (Yp - Ys)/Yp \times 100$$

Stress susceptibility index (SSI) (Fischer and Maurer 1978):

$$SSI = \frac{1-(Y_s/Y_p)}{1-(Y_{sm}/Y_{pm})}$$

Stress tolerance (TOL) (Hossain *et al.* 1990):

$$TOL = Yp - Ys$$

Mean productivity (MP) (Rosielle and Hamblin 1981):

$$MP = (Yap + Ys)/2$$

Stress tolerance index (STI) (Fernandez 1992):

$$STI = (YP \times Ys) / Y^2p$$

Geometric mean productivity (GMP) (Fernandez 1992):

$$GMP = \sqrt{}Yap \times Ys$$

Yield index (YI) (Gavuzzi *et al.* 1997):

$$YI = YS/Ysm$$

Yield stability index (YSI) (Bouslama and Schapaugh 1984):

$$YSI = Ys/Yp$$

where Ys, Yield of genotypes under late sown condition; Yp, Yield of genotypes under timely sown condition; Ysm, Mean yield of all genotypes under late sown condition; Ypm, Mean yield of all genotypes under timely sown condition.

Variability package of R software was used for correlation coefficient analysis whereas, Past4.03 version 9 was used to exploit principal component analysis biplot analysis and cluster anlaysis for identification of tolerant and susceptible genotypes.

RESULTS AND DISCUSSION

Performance of different tolerance indices: In the present study, 8 selection indices proposed by researchers (Dubey *et al.* 2020, Devi *et al.* 2021, Lamba *et al.* 2023, Kumar *et al.* 2023) were used to find out terminal heat-tolerant genotypes from the pool of 30 genotypes. Pooled data of grain yield for timely and late sown conditions were used for analysis (Table 1). The percentage reduction in grain yield per plant ranged from 21.27% (WH1124) to 62.93% (HD3226) with a mean reduction of 42.93%. The evaluation of results for SSI values exhibited a range from 0.49 (WH1124) to 1.46 (HD3226) with an overall mean reduction of 1.00. The assessment of MP ranged from 41.35 (WH1142) to 63.00 (WH1124), with a mean value of 47.89. The TOL for grain yield per plant ranged from 13.87 (DBW14) to 45.96 (HD3226) with a mean value of 26.19. The STI values ranged from 0.37 (HD3226) to 0.79 (WH1124) with an average value of 0.57. The GMP values ranged from 38.67 (DBW303) to 62.55 (WH1124) with an average value of 45.76. The YI values displayed variation from 0.76 (WH1080) to 1.60 (WH1124) respectively, with a mean value of 1.00. The YSI values ranged from 0.37 (HD3226) to 0.79 (WH1124) with an average value of 0.57. The comparative performance of different selection indices revealed that SSI and TOL indices identified 18 heat susceptible genotypes, viz. HI8713, DBW93, HD2329, HD2868, HD2967, HD3086, HS 490, HS507, PBW 343, PBW644, WH1080, WH147, WH1142, PBW723, HD4728, WB02, HD3226 and DBW303 while, MP, STI, GMP, YI, YSI and PYR tolerance indices identified 12 heat tolerant genotypes, viz. DBW14, DBW90, HD2864, HD2932, HD2985, HS375, HUW234, RAJ4083, WH1021, WH1124, DBW71 and PBW757.

Correlation coefficients analysis between stress indices and grain yield: SSI showed positive and significant correlation with PYR (1.00**) and TOL (0.961**) while SSI showed negative and significant correlation with STI and YSI (-1.000**), YS (-0.943**), YI (-0.942**), GMP (-0.809**), and MP (-0.687**) (Table 2). MP showed positive and significant correlation with STI (0.684**), GMP (0.982**), YI (0.887**), YSI (0.684**), YS (0.889**) and YP(0.652**) while MP showed negative and significant correlation with SSI (-0.687**), TOL (-0.487**) and PYR (-0.677**). TOL showed positive and significant correlation with SSI and PYR (0.961**) while TOL showed negative and significant correlation with STI (-0.962**), GMP (-0.629**), YI(-0.827**), YSI (-0.962**), YS (-0.825**) and MP (-0.474**). STI showed positive and significant correlation with MP (0.684**), GMP

Table 1 Various tolerance indices of pooled data of wheat genotype for the crop year 2021–22 and 2022–23

Genotype	SSI	MP	TOL	STI	GMP	YI	YSI	PYR	YS	YP
HI8713	1.20	41.84	29.05	0.49	39.21	0.78	0.49	51.68	27.31	56.36
DBW14	0.53	54.24	13.87	0.77	53.79	1.37	0.77	22.70	47.30	61.17
DBW90	0.70	49.48	17.44	0.70	48.70	1.18	0.70	30.00	40.76	58.20
DBW93	1.21	48.65	33.89	0.48	45.60	0.91	0.48	51.72	31.71	65.60
HD2329	1.33	45.85	36.49	0.43	42.06	0.80	0.43	56.97	27.60	64.09
HD2864	0.61	47.48	14.31	0.74	46.94	1.17	0.74	26.21	40.33	54.64
HD2868	1.20	42.45	29.39	0.49	39.82	0.80	0.49	51.52	27.76	57.14
HD2932	0.71	55.70	20.01	0.70	54.79	1.32	0.70	30.52	45.70	65.70
HD2967	1.17	54.52	36.58	0.50	51.36	1.04	0.50	50.28	36.23	72.81
HD2985	0.74	47.73	17.94	0.69	46.88	1.12	0.69	31.66	38.76	56.70
HD3086	1.23	45.77	32.73	0.47	42.74	0.85	0.47	52.68	29.40	62.13
HS375	0.74	48.28	18.10	0.68	47.38	1.12	0.68	31.82	39.23	57.33
HS 490	1.19	45.05	30.74	0.49	42.31	0.85	0.49	51.00	29.68	60.41
HS507	1.14	47.67	30.68	0.52	45.10	0.93	0.52	48.79	32.33	63.00
HUW234	0.59	55.67	15.91	0.75	55.08	1.37	0.75	25.17	47.72	63.62
PBW 343	1.26	43.01	31.76	0.46	39.96	0.78	0.46	53.99	27.13	58.89
PBW644	1.22	46.02	32.60	0.48	43.03	0.86	0.48	52.36	29.72	62.31
RAJ4083	0.71	48.18	17.14	0.70	47.40	1.14	0.70	30.31	39.61	56.75
WH1021	0.58	54.43	15.45	0.75	53.87	1.35	0.75	24.91	46.70	62.15
WH1080	1.26	41.76	30.82	0.46	38.81	0.76	0.46	53.93	26.34	57.16
WH1124	0.49	63.00	14.95	0.79	62.55	1.60	0.79	21.27	55.52	70.47
WH147	1.21	41.47	29.04	0.48	38.83	0.78	0.48	51.94	26.94	55.98
DBW71	0.65	51.93	16.84	0.72	51.21	1.25	0.72	28.17	43.50	60.34
WH1142	1.13	41.35	26.49	0.52	39.16	0.81	0.52	48.59	28.11	54.59
PBW723	1.14	41.48	26.92	0.51	39.22	0.81	0.51	49.05	28.02	54.94
HD4728	1.31	47.02	36.64	0.44	43.27	0.82	0.44	56.24	28.70	65.34
WB02	1.31	44.63	34.74	0.44	41.11	0.79	0.44	56.04	27.26	62.00
PBW757	0.72	50.28	18.46	0.69	49.39	1.18	0.69	31.23	41.05	59.51
HD3226	1.46	50.12	45.96	0.37	44.52	0.78	0.37	62.93	27.14	73.10
DBW303	1.26	41.64	30.87	0.46	38.67	0.76	0.46	54.18	26.21	57.07
Mean	1.00	47.89	26.19	0.57	45.76	1.00	0.57	42.93	34.79	60.98
Max.	1.46	63.00	45.96	0.79	62.55	1.60	0.79	62.93	55.52	73.10
Min.	0.49	41.35	13.87	0.37	38.67	0.76	0.37	21.27	26.21	54.59

SSI, Stress susceptibility index; MP, Mean productivity; STI, Stress tolerance index; GMP, Geometric mean productivity; YI, Yield index; YSI, Yield stability index; PYR, Percent yield reduction; YS, Grain yield under late sowing condition; YP, Grain yield under timely sowing condition.

(0.806**), YI (0.942**), YSI (1.000**) and YS (0.940**) while STI showed negative and significant correlation with TOL (-0.962**), SSI and PYR (-1.000**). GMP showed positive and significant correlation with MP (0.982**), STI (0.806**), YI (0.957**), YSI (0.806**), YS (0.958**) and YP (0.500**) while GMP showed negative and significant correlation with TOL (-0.629**), and SSI (-0.809**). YI showed positive and significant correlation with MP (0.887**), STI (0.942**), GMP (0.957**), YSI (0.942**) and YS (1.000**) while YI showed negative and significant correlation with SSI (-0.943**) TOL (-0.827**) and PYR (-0.942**). YSI showed positive and significant correlation with MP (0.684**), STI (-1.000**), GMP (0.806**), YI (0.942**) and YS (0.940**) while showed negative and significant correlation with SSI (-1.000**), TOL (-0.962**) and PYR (-1.000**). PYR showed positive and significant correlation with SSI (1.000**) and TOL (0.961**) while PYR showed negative and significant correlation with SSI (1.000**), TOL (0.961**) and YS (-0.941**). YS showed positive and significant correlation with MP (0.889**), STI (0.940**), GMP (0.958**), YI (1.000**) and YSI (0.940**) while showed negative and significant correlation

Table 2 Correlation coefficient between grain yield (Yp and Ys) of wheat genotypes and stress tolerance indices

	SSI	MP	TOL	STI	GMP	YI	YSI	PYR	YS	YP
SSI	1									
MP	-0.687**	1								
TOL	0.961**	-0.474**	1							
STI	-1.000**	0.684**	-0.962**	1						
GMP	-0.809**	0.982**	-0.629**	0.806**	1					
YI	-0.943**	0.887**	-0.827**	0.942**	0.957**	1				
YSI	-1.000**	0.684**	-0.962**	1.000**	0.806**	0.942**	1			
PYR	1.000**	-0.686**	0.961**	-1.000**	-0.808**	-0.942**	-1.000**	1		
YS	-0.942**	0.889**	-0.825**	0.940**	0.958**	1.000**	0.940**	-0.941**	1	
YP	0.098NS	0.652**	0.358NS	-0.102NS	0.500**	0.228NS	-0.102NS	0.100NS	0.232NS	1

** Significant at 0.05 and *0.01 levels of probability; ns, not significant.

SSI, Stress susceptibility index; MP, Mean productivity; STI, Stress tolerance index; GMP, Geometric mean productivity; YI, Yield index; YSI, Yield stability index; PYR, Percent yield reduction; YS, Grain yield under late sowing condition and YP, Grain yield under timely sowing condition.

with SSI (-0.942**),TOL (-0.825**) and PYR (-0.941**). YP showed positive and significant correlation with GMP (0.500**) and MP (0.652**) while showed non-significant correlation with SSI, TOL, STI, YI, YSI, PYR and YS. The results of our study suggested that, heat tolerant genotypes can be identified on the basis of different tolerance indices. Poudel *et al.* (2021) reported congruent findings indicating that lower values of TOL and SSI, alongside higher values of YSI, facilitate the selection of stress-resistant genotypes. Moreover, they reported that STI, YI, MP, GMP and HM exhibited strong positive correlations with grain yields (Yp and Ys). Lamba *et al.* (2023) corroborated these correlations in heat-tolerant wheat genotypes, while Jha *et al.* (2016) advocated for the utilization of these indices for identifying high-yield genotypes across varied conditions. The results are in accordance with the findings of Farooq *et al.* (2011), Kamrani *et al.* (2017), Devi *et al.* (2021) and Kumar *et al.* (2023).

Biplot and principal component analysis: Principal component analysis (PCA) was used to evaluate grain yields (Yp and Ys) along with heat stress tolerance indicators aimed at stress-tolerant genotypes (Supplementary Table 2). Among the 10 principal components (PCs) analyzed, the initial two components with eigenvalues greater than 1.0 accounted for the most significant variation. In particular, the first primary component (PC1) and second (PC2) contributed 81.00% and 18.85% to the overall variability, respectively. The first principal component (PC1) showed a strong positive correlation with YS, YSI, YI and STI (0.35). It should be noted that of all the stress indexes,

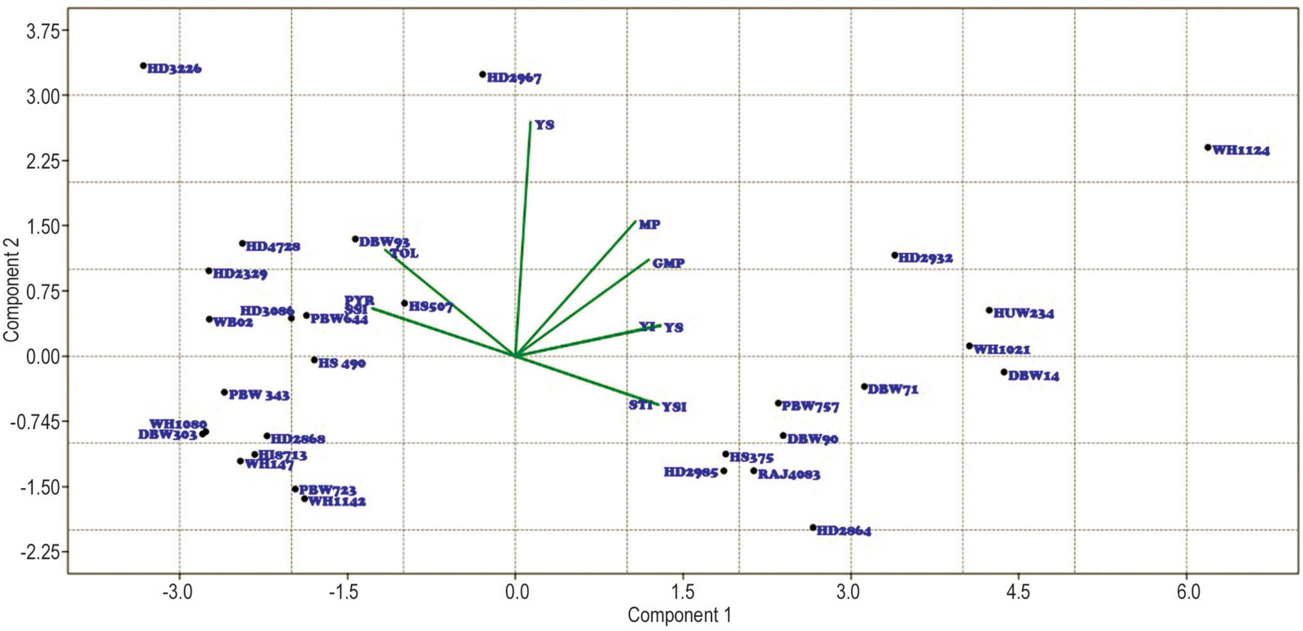

Fig. 1 Biplots illustrating trait correlations based on PCA results.

PC1 (Principal Component 1) represents the first dimension; PC2 (Principal Component 2) represents the second dimension.

YS, YSI, YI and STI showed the highest variability. This component could be properly labelled as the "yield potential and heat tolerance component." The second PC2 exhibited a high positive correlation with YP (0.72) followed by MP (0.42), TOL (0.33), GMP (0.30) SSI and PYR (0.15). This component can be called as stress susceptibility component. By a similar approach, Puri *et al.* (2015) and Kamrani *et al.* (2017) assigned the name to the first two principal components. In normal and stress conditions, genotypes that show good performance tend to have higher PC1 values and lower PC2 values. Consistent with the findings by Kaya *et al.* (2006) and Lamba *et al.* (2023) genotypes characterized by higher PC1 values but lower PC2 values were considered stable and *vice versa*. The biplot was generated utilizing PC1 and PC2 to evaluate the genotypes and the correlations between the heat resistance index (Fig. 1). Based on their greater PC1 values but low PC2 values, wheat genotypes DBW14, DBW90, HD2864, HD2932, HD2985, HS375, HUW234, RAJ4083, WH1021, WH1124, DBW71, and PBW757 (Fig. 1) were identified as the most heat-tolerant genotypes. Meanwhile, the remaining 18 genotypes exhibited heat susceptibility under stress conditions, as indicated by high PC2 values (positive) and low PC1 values (negative) aligns with the results reported by Lesk *et al.* (2016), Liu *et al.* (2016), Maulana *et al.* (2018) and Poudel *et al.* (2021).

Cluster analysis: Based on different tolerent indices 30 wheat genotypes were divided into 2 major clusters (I and II) (Fig. 2). Major cluster I have 18 heat susceptible genotype which divided into 3 subluclusters. Sublucluster (Ia) of major cluster I contain 2 genotype (HD2967 and HD3226), subcluster (Ib) contains 8 genotype (HD2868, WH147, HI8713, PBW343, DBW303, WH1080, WH1142 and PBW723) and subcluster (Ic) also contains 8 genotype (HD3086, PBW644, HS490, DBW93, HS507, HD4726, HD2329 and WB02). Major cluster II have 12 heat-tolerant genotypes which was also divided into 3 sublusters. Sublucluster (IIa) of major cluster II contain 4 genotype (HD2932, HUW234, WH 1021 and DBW14), subcluster (IIb) contains 7 genotype (HD2864, HD2985, HS375, RAJ4083, DBW90, PBW757 and DBW71) and subcluster (IIc) contain single genotype (WH1124). Genotypes within the same cluster displayed more similarities in their values of STI, indicating common heat tolerance traits among them. Conversely, genotypes belonging to different clusters exhibited greater variations in their heat tolerance indices, emphasizing differences in their responses to heat stress. Thanaa *et al.* (2019) categorized all examined genotypes into five clusters based on their performance and degree of stress tolerance. They observed that genotypes characterized by high values of MP, GMP, HM, STI, and YSI exhibit superior performance and stress tolerance. Lamba *et al.* (2023) conducted a classification of 48 wheat genotypes into six clusters based on their performance and stress tolerance level. They identified genotypes that exhibited high values of MP, GMP, HM, STI, and YSI could serve as potential parameters for parental selection in breeding programmes aimed at developing stress-tolerant genotypes, as suggested by Jha *et al.* (2018).

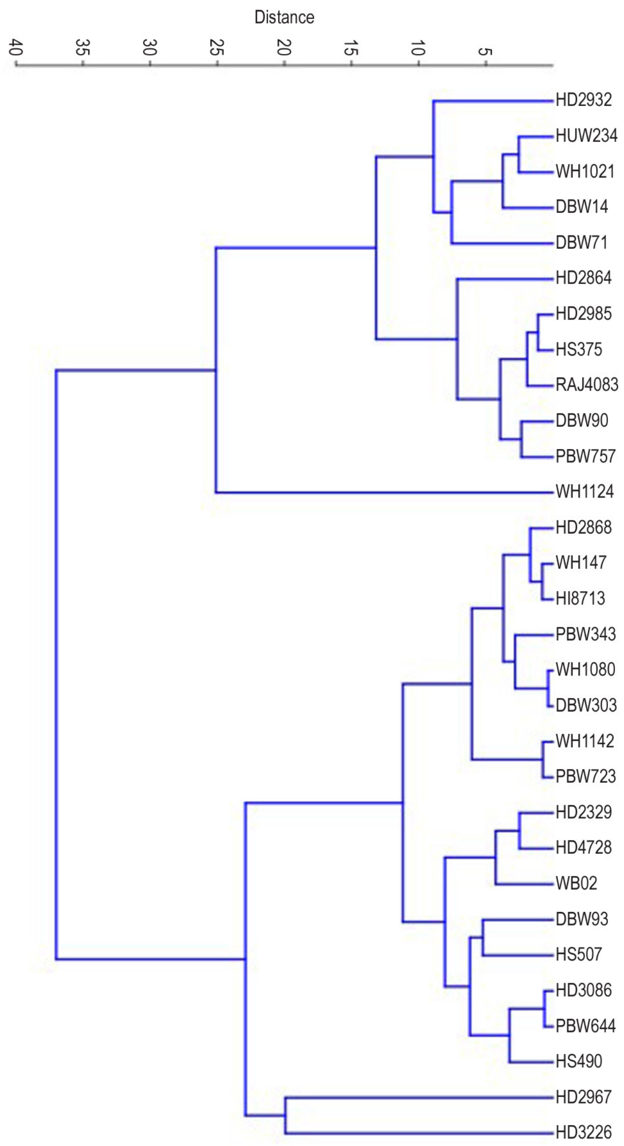

Fig. 2 Cluster analysis of wheat genotypes based on heat stress tolerance indices.

Based on the 2-year experiment it can be concluded that heat stress significantly decreased grain yield in all genotypes. The findings from correlation coefficient, PCA, and biplot analyses all pointed towards SSI emerging as a robust indicator for identifying heat-tolerant genotypes. SSI was correlated positively with PYR and TOL, and shows strong negative correlations with indices such as STI, YSI, YS, YI, GMP and MP. The TOL also found promising indicator for assessment of heat tolerance, as it reflected genotype's ability to maintain grain yield under heat stress. Cluster analysis, using the mentioned heat tolerance indices, successfully differentiated genotypes into categories of either heat-tolerant or heat-susceptible. The stress indices proved to be a promising approach for selecting heat-tolerant genotypes. Based on the tolerance indices mentioned above, genotypes including DBW14, DBW90, HD2864, HD2932,

HD2985, HS375, HUW234, RAJ4083, WH1021, WH1124, DBW71 and PBW757 were identified as tolerant under terminal heat stress conditions. Hence, these identified heat-tolerant genotypes serve as valuable genetic resources for ensuring the stability of grain yield under terminal heat stress conditions in wheat.

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