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EVALUATION OF SPRING WHEAT GENOTYPES (*TRITICUM AESTIVUM* L.) FOR HEAT STRESS TOLERANCE USING DIFFERENT STRESS TOLERANCE INDICES

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ABSTRACT. Twenty five spring wheat genotypes were evaluated for terminal heat stress tolerance in field environments in the Agro Ecological Zone-11 of Bangladesh, during 2009-2010 cropping season. The experiments were conducted at Wheat Research Centre, Bangladesh Agricultural Research Institute, using randomized block design with three replicates under non-stress (optimum sowing) and stress (late sowing) conditions. Seven selection indices for stress tolerance including mean productivity (MP), geometric mean productivity (GMP), tolerance (TOL), yield index (YI), yield stability index (YSI), stress tolerance index (STI) and stress susceptibility index (SSI) were calculated based on grain yield of wheat under optimum and late sowing conditions. The results revealed significant variations due to genotypes for all characters in two sowing conditions. Principal component analysis revealed that the first PCA explained 0.64 of the variation with MP, GMP, YI and STI. Using MP, GMP, YI and STI, the genotypes G-05 and G-22 were found to be the best genotypes with relatively high yield and suitable for both optimum and late heat stressed conditions. The indices SSI, YSI and TOL could be useful parameters in discriminating the tolerant genotypes (G-12, G-13, and G-14) that might be recommended for heat stressed conditions. It is also concluded from the present studies that biomass, grain filling rate and spikes number m^{-2} are suitable for selecting the best genotypes under optimum and late sowing conditions because these parameters are highly correlated with MP, GMP, YI and STI. However, high ground cover with long pre heading stage and having high grain filling rate would made a genotype tolerant to late heat to attain a high grain yield in wheat.

Key words: Heat stress; Stress tolerance indices; Principal component analysis; Biplot.

INTRODUCTION

Heat stress due to high ambient temperatures is a serious threat to crop production worldwide (Hall, 2001). It is a common constraint during anthesis and grain filling stages in

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many cereal crops of temperate regions. In wheat, high temperature effects on yield and grain weight had been reported by many authors (Wardlaw *et al*., 2002; Guilioni *et al*., 2003; Mian *et al*., 2007). Increasing heat tolerance in wheat is consequently a challenge for wheat breeders. A common method of selecting plants for heat stress tolerance has been to grow breeding materials in a hot target production environment and identify individuals/lines with greater yield potential (Ehlers and Hall, 1998). Hence, it is necessary for promising advanced lines of wheat to be tested under both normal and heat stress conditions.

Selection of different genotypes under environmental stress conditions is one of the main tasks of plant breeders for exploiting genetic variations to improve stress tolerant cultivars (Clarke *et al*., 1984). Therefore, a major challenge in traditional breeding for heat tolerance is the identification of reliable screening methods and effective selection criteria to facilitate detection of heat tolerant plants. Several screening methods and selection criteria have been proposed by different researchers, but very few were reported for screening heat tolerant genotypes in wheat. Rosielle and Hamblin (1981) defined stress tolerance (TOL) as the differences in yield between the non-stress and stress environments and mean productivity (MP) as the average yield of these two environments. They reported a positive correlation between mean productivity (MP) and yield under stress environment (Ys), therefore selection based on MP could improve average yield under both stress and non-stress environments. Several studies also showed a high and positive correlation between MP and Ys (Sanjeri, 1998; Ghagar Sepanlo *et al*., 2000; Nouri *et al.,* 2011).

Fischer and Maurer (1978) proposed genotype stress susceptibility index (SSI) as a ratio of genotypic performance under stress and non-stress conditions. They suggested the SSI for measurement of yield stability that apprehended the changes in both potential and actual yields in variable environments. Bansal and Sinha (1991) proposed to use SSI and grain yield as stability parameters to identify drought resistant genotypes of wheat. Several authors (Clarke *et al*., 1992; Guttieri *et al*., 2001) also used SSI to evaluate drought tolerance in wheat genotypes and suggested that an SSI > 1 indicated above average susceptibility to drought stress.

Fernandez (1992) proposed that stress tolerance index (STI) can be used to identify mungbean genotypes that produce high yield under both stressed and non-stressed conditions. Geometric mean productivity (GMP) is another index which is often used by breeders interested in relative performance (Ramirez and Kelly, 1998). GMP under both stressed and non-stressed conditions could be used to determine the extent or degree of susceptibility to avoid the effects of stress variation in different years (Fernandez, 1992; Kristin *et al.,* 1997; Mitra, 2001). Other yield based resistances estimates are yield index (YI) and yield stability index (YSI) were used by different authors (Bouslama and Schapaugh, 1984; Lin *et al*., 1986; Gavuzzi *et al*., 1997).

Many authors (Golabadi *et al*., 2006; Sio-Se Mardeh *et al*., 2006; Talebi *et al*., 2009; Nouri *et al*., 2011) suggested that breeders can choose better stress resistant durum wheat genotypes based on MP, GMP and STI under drought stressed and non-stressed environments. Combination of different stress indices was examined in different crops. For instance, SSI, STI and GMP were proved to be the most effective criteria for selecting heat tolerant and high yielding genotypes of maize (Khodarahmpour *et al*., 2011). They found positive and significant correlation of GMP and grain yield under both stressed and non stressed conditions and suggested that this index is more applicable and efficient for selection of parent material in producing maize hybrids tolerant to high temperatures and high yielding under both conditions. GMP in combination with SSI was found a desirable criterion for selecting improved drought resistant common bean genotype (Ramirez and Kelly, 1998) In another study, Moghaddam and Hadizadeh (2000) found STI more applicable than SSI for selection of maize genotypes tolerant to stress. Therefore, the present study was undertaken to examine the accuracy of different stress tolerance indices for identifying heat tolerance in spring wheat genotypes, thereby selecting suitable genotypes to recommend for cultivation in the heat prone areas of Bangladesh.

MATERIALS AND METHODS

Twenty four advanced spring wheat genotypes along with a popular variety 'Shatabdi' were evaluated during the cropping season 2009-2010. The experiments were conducted at the experimental field of the Wheat Research Centre, Bangladesh Agricultural Research Institute, Gazipur. There were two experiments, the first was covered the period from last week of November, 2009 to mid March, 2010 to avoid a high temperature during anthesis and grain filling period and considered as optimum sowing condition. The second experiment covered last week of December, 2009 to first week of April, 2010 to coincide with heat stress (high temperature during later growth stages) and considered as late sowing condition. Both the experiments were laid out in randomized complete block design with three replicates. The experimental site was situated between 23°46′N latitude and 90°23′E longitude with elevation of 8 m. above sea level. The Agro Ecological Zone (AEZ) of the area is High Ganges River Flood Plain (AEZ-11). The soil type is Gangetic calcareous alluvium soil and reaction is pH= 6.1-7.5. The organic matter content of the soil is very low (1.21%). The climate of this place is characterized by wet summer and dry winter. Temperature data recorded during the concerned period at weather yard, Wheat Research Centre, is presented in *Fig. 1*. Seeds of each genotype were sown in unit plot size of 2.5 m long with six rows in lines 20 cm apart. Standard agronomic practices were performed from time to time during the wheat crop growth.

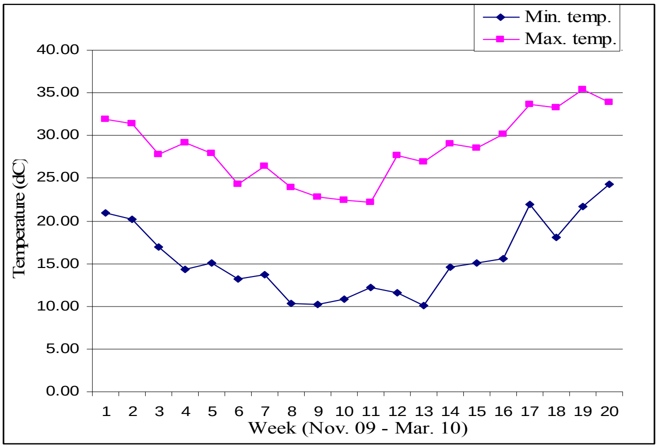

Figure 1 - Weekly average maximum and minimum temperatures at Wheat Research Centre, Gazipur, during the cropping season 2009-2010

Data were collected on the different phenological and physiological characters related to heat tolerance including flag leaf senescence (day), grain filling duration (day), ground coverage at 35 days (scale), canopy temperature at vegetative stage (^{o}C), canopy temperature at grain filling stage (^{o}C), chlorophyll content at 21 days after anthesis (SPAD unit), biomass m^{-2} (g) and grain filling rate (gm^{-2}d^{-1}). The central 1 metre of four rows of each plot were harvested for recording yield m^{-2} and primary yield contributing characters i.e., spikes number m^{-2}, grains number spike^{-1} and 1000 grain weight (g). Ground coverage was recorded visually at 35 days after sowing using 0-10 scale. Chlorophyll content of leaves was measured in five fully expended sunlit flag leaves in vivo by a Minolta SPAD metre at anthesis and 21 days after anthesis and expressed in SPAD unit. The canopy temperature was measured by a hand held infrared thermometer twice at 3 days interval at vegetative and grain filling stage and mean of two data was used for statistical analysis. Resistance indices were calculated using the following relationships:

1. Stress susceptibility index,

$$SSI = \frac{1-(y_s / y_p)}{1-(\bar{y}_s / \bar{y}_p)},$$ (Fischer and Maurer, 1978),

where y_s is the yield of genotypes under heat stress condition, y_p is the yield of genotypes under timely sowing condition, $\bar{y}_s$ and $\bar{y}_p$ are the mean yields of all genotypes under heat stress and timely sowing conditions, respectively, and $1-(\bar{y}_s / \bar{y}_p)$ is the stress intensity. The timely sown experiment was considered to be a non stress condition in order to have a better estimation of optimum environment.

2. Mean productivity,

$MP = \frac{y_p + y_s}{2}$ (Hossain *et al*., 1990)

3. Tolerance,

$TOL = y_p - y_s$ (Hossain *et al*., 1990)

4. Stress tolerance index,

$STI = \frac{y_p \times y_s}{y_p^2}$ (Fernandez, 1992)

5. Geometric mean productivity,

$GMP = \sqrt{y_p \times y_s}$ (Fernandez, 1992)

6. Yield index,

$YI = \frac{y_s}{\bar{y}_s}$ (Gavuzzi *et al*., 1997; Lin *et al*., 1986)

7. Yield stability index,

$YSI = \frac{y_s}{y_p}$ (Bouslama and Schapaugh, 1984)

Data were analyzed using MSTAT-C for analysis of variance and Duncan's multiple range test (DMRT) was employed for the mean comparisons (Gomez and Gomez, 1984). Simple correlations were estimated using the conventional formula used by Singh and Choudhary (1985). Principal component analysis (PCA) was used to classify the screening methods as well as the genotypes. Statistical analysis was performed by Excel, and Genstat soft wares.

RESULTS AND DISCUSSION

The analyses of variance for grain yield and other yield components in both timely and late sowing environments are given in *Table 1*. The results revealed significant variation due to genotypes for all characters in two sowing conditions. This suggested that the magnitude of differences in genotypes was sufficient to provide some scope for selecting genotypes with improved heat stress tolerance. Resistance indices were calculated on the basis of grain yield of the genotypes (*Table 2*). The genotypes showed wide ranges of variations for the estimated indices. Among the genotypes, G-5 and G-22 produced high grain yield under both optimum and heat stressed condition but showed low yield stability with respect to late sowing condition. On the other hand G-12, G-13, and G-14 produced moderate grain yield with high yield stability. This result supports the findings of several authors (Fischer and Maurer, 1978; Bruckner and Frohberg, 1987; Ehdaie *et al*., 1988; Bansal and Sinha, 1991; Khanna-Chopra and Viswanathan, 1999) all of whom confirmed that high stability in grain yield under stress was associated with poor or moderate grain yield potential.

When studied with stress indices we found the lowest TOL in G-14, followed by G-12, G-25 and G-13. Therefore, these genotypes had a lower yield reduction under late sowing condition. A greater TOL value was related to G-20, indicating that this genotype had a larger yield reduction under heat stressed condition and higher heat susceptibility. Nouri *et al*. (2011) stated that Larger TOL and SSI values represent relatively more sensitivity to stress, thus smaller TOL and SSI values are favored. Hence, low stress susceptibility indices (SSI<1) is synonymous with high stress tolerance (Fisher and Maurer, 1978). Several authors (Khanna-Chopra and Viswanathan, 1999; Singh *et al.*, 2011; Sharma *et al.*, 2013) evaluated stress susceptibility indices of yield and its different components of wheat genotypes for heat stress tolerance and grouped them into highly tolerant, tolerant and susceptible genotypes based on their SSI values. In our study, the estimates of SSI indices revealed that, the genotypes G-14, G-12 and G-13 had the lowest SSI value and therefore these genotypes had low heat susceptibility and high yield stability under late sowing condition. In contrast, genotype G-20, followed by G-7 and G-4 with the highest SSI values could be identified as highly susceptible to heat. It has been evident in literature that SSI could be a more useful index in discriminating better genotypes under drought stress condition (Golabadi *et al.*, 2006; Talebi *et al.*, 2009; Nouri *et al.*, 2011).

Table 1 - Analysis of variance showing mean squares for phenological, physiological and primary yield contributing characters related to heat tolerance in wheat under optimum and late sowing environments

Character	Optimum sowing condition			Late sowing condition		
	Replicate (2)	Genotype (24)	Error (48)	Replicate (2)	Genotype (24)	Error (48)
Anthesis days	3.38	21.68**	2.75	0.18	4.28**	0.55
FLS	0.50	7.01**	1.42	0.02	4.74**	0.48
GFD	1.62	14.41**	1.33	0.02	5.58**	0.60
GC_{35}	0.27	0.46**	0.14	0.19	0.45**	0.13
CT_{vg}	0.11	2.90**	0.87	0.19	1.49**	0.37
CT_{gf}	0.49	1.14**	0.35	0.08	1.60**	0.20
CHL_{21}	0.01	12.00**	2.78	0.08	24.50**	6.90
Bio m^{-2}	1058	29064.67**	6618.41	288	14154.71**	3941.12
GFR	0.26	4.44**	1.33	2.62	5.32**	1.68
Spikes number m^{-2}	144.50	4759.37**	1474.71	722	2948.21*	1218.87
Grains number $spike^{-1}$	31.05	103.25**	26.53	15.79	91.31**	33.82
1000 grain wt.	25.95	43.59**	6.33	0.30	31.73**	3.45
Yield m^{-2}	18	6479.46**	2183.62	1922	3411.33**	1234.50

Numerical values in parenthesis are degrees of freedom.
*and ** indicate significant at 5% and 1% levels of probability, respectively.
FLS=flag leaf senescence (day); GFD=grain filling duration (day); GC_{35}=ground coverage at 35 days; CT_{vg}=canopy temperature at vegetative stage (^oC); CTgf=canopy temperature at grain filling stage (^oC); CHL_{21}=chlorophyll content at 21 days after anthesis (Spad unit); Bio m^{-2} =biomass m^{-2}; GFR= grain filling rate (g m^{-2} d^{-1}).

Table 2 - Resistance indices of 25 wheat genotypes under timely sowing and late sowing conditions

Genotype no.	Y_P	Y_S	MP	TOL	GMP	YI	YSI	STI	SSI
G-1	555.0a-e	440.0ab	497.5	115	494.17	1.10	0.793	0.923	0.919
G-2	520.0a-g	445.0ab	482.5	75	481.04	1.12	0.856	0.875	0.640
G-3	522.5a-g	400.0b-e	461.25	122.5	457.17	1.00	0.766	0.790	1.040
G-4	582.5a-c	385.0b-e	483.75	197.5	473.56	0.97	0.661	0.848	1.504
G-5	592.5ab	450.0ab	521.25	142.5	516.36	1.13	0.759	1.008	1.067
G-6	520.0a-g	420.0a-d	470	100	467.33	1.05	0.808	0.825	0.853
G-7	522.5a-g	322.5e	422.5	200	410.50	0.81	0.617	0.637	1.697
G-8	575.0a-d	395.0b-e	485	180	476.58	0.99	0.687	0.858	1.388
G-9	465.0d-g	365.0b-e	415	100	411.98	0.92	0.785	0.641	0.954
G-10	502.5b-g	377.5b-e	440	125	435.54	0.95	0.751	0.717	1.103
G-11	462.5d-g	340.0c-e	401.25	122.5	396.55	0.85	0.735	0.594	1.175
G-12	460.0e-g	435.0ab	447.5	25	447.33	1.09	0.946	0.756	0.241
G-13	447.5e-g	397.5b-e	422.5	50	421.76	1.00	0.888	0.672	0.495
G-14	432.5fg	410.0a-d	421.25	22.5	421.10	1.03	0.948	0.670	0.231
G-15	502.5b-g	337.5de	420	165	411.82	0.85	0.672	0.641	1.456
G-16	532.5a-f	392.5b-e	462.5	140	457.17	0.99	0.737	0.790	1.166
G-17	540.0a-f	450.0ab	495	90	492.95	1.13	0.833	0.918	0.739
G-18	467.5d-g	390.0b-e	428.75	77.5	427.00	0.98	0.834	0.689	0.735
G-19	497.5b-g	400.0b-e	448.75	97.5	446.09	1.00	0.804	0.752	0.869
G-20	625.0a	365.0b-e	495	260	477.62	0.92	0.584	0.862	1.845
G-21	470.0c-g	342.5c-e	406.25	127.5	401.22	0.86	0.729	0.608	1.203
G-22	632.5a	492.5a	562.5	140	558.13	1.24	0.779	1.177	0.982
G-23	495.0b-g	415.0a-d	455	80	453.24	1.04	0.838	0.776	0.717
G-24	522.5a-g	425.0a-c	473.75	97.5	471.24	1.07	0.813	0.839	0.827
G-25	415.0g	367.5b-e	391.25	47.5	390.53	0.92	0.886	0.576	0.508
Mean	514.4	398.4	456.4	116	452.70	1.00	0.774	0.774	0.974

Means of the same column, followed by the same letter do not differ significantly at 5% level of probability.
Y_P=yield of genotypes under timely sowing condition; Y_S=yield of genotypes under heat stress condition; MP=mean productivity; GMP=geometric mean productivity; TOL=tolerance; YI=yield index; YSI= yield stability index; STI=stress tolerance index and SSI=stress susceptibility index.

The highest MP, GMP and STI indices were observed in G-22, followed by G-5 and G-1 and the lowest values in G-25, followed by G-11 and G-21. The genotype G-22 also showed the highest YI value. The highest YSI indices were observed for G-14, followed by G-12 and G-13.

To determine the most desirable heat stress tolerant criteria, the correlation coefficients between Yp and Ys and other quantitative indices of heat tolerance were calculated (*Table 3*). The association between Yp and Ys was found low and insignificant indicated that genotypes under timely sowing condition do not have a good response under late sowing condition. These two conditions discriminate genotypes independently. Similar results were reported by Talebi *et al*. (2009) and Nouri *et al*. (2011) in durum wheat under drought stress condition. A strong positive correlation was found between TOL and SSI. The indices YSI and YI showed negative correlation with TOL and SSI. These suggested that the genotypes would show tolerance to heat stress if yield increased under heat stress condition. A perfect positive correlation between YI and grain yield under late sowing condition (Y_S) indicated its suitability for selecting tolerant genotypes under heat stress condition. This result is in good agreement with the findings reported by Nouri *et al*. (2011).

Table 3 - Correlation coefficients between Y_P, Y_S and resistance indices of 25 wheat genotypes

	Y_S	MP	TOL	GMP	YI	YSI	STI	SSI
Y_P	0.383	0.886**	0.733**	0.837**	0.391	-0.601**	0.835**	0.598**
Y_S		0.768**	-0.348	0.825**	1.00**	0.499*	0.824**	-0.503**
MP			0.333	0.995**	0.773**	-0.166	0.993**	0.162
TOL				0.242	-0.340	-0.978**	0.240	0.977**
GMP					0.830**	-0.075	0.998**	0.071
YI						0.491*	0.829**	-0.496*
YSI							-0.074	-0.999**
STI								0.070

*and ** indicate significant at 5% and 1% levels of probability, respectively.
Y_P=yield of genotypes under timely sowing condition; Y_S=yield of genotypes under heat stress condition; MP=mean productivity; GMP=geometric mean productivity; TOL=tolerance; YI=yield index; YSI=yield stability index; STI= stress tolerance index and SSI=stress susceptibility index.

In the present study a significant positive correlation was found for SSI and TOL with Yp, but this correlation was negative with Ys, suggested that these indices had good response to heat stress condition. Ghobadi *et al.* (2012) screened wheat genotypes tolerant to drought based on SSI and TOL. According to Fernandez (1992) selection based on these two criteria favors genotypes with high yield potential under non-stressed conditions and low yield under stressed conditions. In our study also we observed that the genotypes with high grain yield under timely sowing condition have a high reduction in yield under heat stress condition. Consequently, the genotypes G-22 and G-20 in timely sowing condition had the highest grain yield value with high TOL. Therefore selection based on TOL will result in low yield reduction under heat stress condition. Similar results were reported by Mohammadi *et al*. (2010) and Nouri *et al*. (2011) in wheat under drought condition.

Moreover, the results exhibited that there were significant strong positive correlation among Yp and MP, GMP and STI indicated that with the increasing of these indices yield under timely sowing condition would be increased. Ys also showed significant positive correlation with MP, GMP, YI, YSI and STI. The indices MP, GMP and STI were strongly positively correlated with each other but they showed almost no correlation with TOL, SSI and YSI. So the indices MP, GMP and STI were the better predictor of potential yield, Yp and Ys than TOL and SSI which were considered as appropriate indices to identify genotypes with high grain yield and low sensitivity to heat stress environment. These results are in conformity with those of Shefazadeh *et al*. (2012) in bread wheat, Nikkhah-Kouchaksaraei *et al*. (2012) in durum wheat and Sareen *et al*. (2012) in synthetic wheat for heat stress. Several authors (Golabadi *et al*., 2006; Sio Se-Mardeh, 2006; Mohamamdi *et al*., 2010; Anwar *et al*., 2011; Nouri *et al*., 2011; Ghobadi *et al*., 2012) concurred with the findings, where these parameters were found suitable for discriminating the best wheat genotypes under drought stress and irrigated conditions. Najafian (2009) concluded that MP, GMP and STI indices are preferred for practical use.

Correlation coefficient of different resistance indices with phenological, physiological and yield contributing characters were shown in *Table 4*. The association of days to anthesis with different resistance indices indicated that this character had a good response to yield under both sowing conditions and it could be used to discriminate genotypes tolerant to heat. It showed significant negative correlation with MP, GMP and STI indicated longer reproductive phase facilitated to increase grain yield under timely sowing condition. But under late sowing condition anthesis days and GFR showed similar association with TOL, YSI and SSI suggesting that delayed anthesis with high GFR would reduces susceptibility to heat. Al-Karaki (2012) confirmed that durum wheat cultivars adapted to semiarid environments would have long preheading periods, followed by high grain filling rate and early maturity to avoid late-season drought and high temperature stress to attain high yields. In wheat, high ground cover might be reduced evaporative water loss from soil by developing leaves that better shade the soil. The association of ground cover with YSI, SSI and also with TOL under late sowing condition suggested that high ground cover at mid vegetative stage would reduce the susceptibility of the genotypes to late heat. Reynolds *et al*. (2001) stated that trait like ground cover affecting radiation use efficiency could be expected to be important under heat stress. A significant positive correlation was found for TOL and SSI with biomass and grain filling rate under timely sowing condition, but these correlations were negative under late sowing condition. In contrast, YSI showed negative association with biomass and grain filling rate under timely sowing condition whereas positive in late sowing condition. This indicates, the genotypes with high biomass and grain filling rate under timely sowing condition have a high reduction under stress condition. The significant positive correlation of MP, GMP, YI and STI with biomass, GFR and spikes m^{-2} under both timely and late sowing conditions indicated that these parameters could potentially be used in selecting better wheat genotypes.

Table 4 - Simple correlation coefficients between resistance indices and phenological, physiological and primary yield contributing characters of 25 wheat genotypes in timely sowing and late sowing conditions

Character	Sowing condition	Resistance indices						
		MP	TOL	GMP	YI	YSI	STI	SSI
Anthesis days	T	-0.437*	-0.399*	-0.411*	-0.165	0.347	-0.414*	-0.349
	L	-0.325	-0.442*	-0.296	-0.027	0.424*	-0.304	-0.430*
FLS	T	-0.362	-0.271	-0.344	-0.167	0.200	-0.356	-0.214
	L	-0.113	-0.302	-0.080	0.070	0.256	-0.102	-0.269
GFD	T	0.280	0.257	0.265	0.111	-0.248	0.262	0.240
	L	0.304	0.285	0.293	0.110	-0.298	0.281	0.289
Ground cover	T	0.030	0.018	0.028	0.014	-0.004	0.003	-0.000
	L	0.047	-0.372	0.082	0.295	0.422*	0.077	-0.435*
Biomass	T	0.838**	0.656**	0.797**	0.393*	-0.537**	0.798**	0.534**
	L	0.633**	-0.300	0.680**	0.835**	0.413*	0.691**	-0.417*
CTDvg	T	-0.400*	-0.420*	-0.371	-0.120	0.361	-0.380	-0.357
	L	0.025	-0.138	0.042	0.111	0.146	0.024	-0.135
CTDgf	T	-0.147	-0.423*	-0.111	0.136	0.418*	-0.123	-0.416*
	L	-0.100	-0.315	-0.074	0.097	0.327	-0.087	-0.325
CHA_{21}	T	0.170	0.343	0.144	-0.053	-0.363	0.135	0.356
	L	-0.038	0.185	-0.056	-0.156	-0.223	-0.048	0.221
GFR	T	0.685**	0.579**	0.645**	0.291	-0.460*	0.644**	0.462*
	L	0.527**	-0.480*	0.586**	0.849**	0.624**	0.591**	-0.623**
Grains $spike^{-1}$	T	0.120	-0.138	0.137	0.220	0.192	0.146	-0.180
	L	-0.122	-0.123	-0.115	-0.035	0.132	-0.116	-0.115
Spikes m^{-2}	T	0.507**	-0.031	0.525**	0.530**	0.110	0.511**	-0.121
	L	0.402*	-0.242	0.442*	0.567**	0.287	0.442*	-0.299
TGW	T	0.047	-0.032	0.057	0.071	0.005	0.056	0.002
	L	0.029	-0.153	0.048	0.134	0.135	0.041	-0.135

*and ** indicate significant at 5% and 1% levels of probability, respectively.
T= timely sown; L= late sown; FLS= flag leaf senescence (day); GFD=grain filling duration (day); CT_{vg}=canopy temperature at vegetative stage (^oC); CTgf=canopy temperature at grain filling stage (^oC); CHL_{21}=chlorophyll content at 21 days after anthesis (Spad unit); GFR= grain filling rate (g m^{-2} d^{-1}); TGW= 1000 grain weight (g).

In this study, a general linear regression model of grain yield under heat stress on STI revealed a positive correlation between this criteria with a similar coefficient of determination (R^2 = 0.67) (*Fig. 2*). Many authors (Golabadi *et al*., 2006; Talebi *et al*., 2009; Nouri *et al*., 2011) suggested selection based on a combination of indices may provide a more useful criterion for improving stress resistance of wheat although correlation coefficients are useful to find the degree of overall association between any two attributes. Thus, a better approach than a correlation analysis such as a biplot is needed to identify superior genotypes for both stressed and non stressed environments. PCA was performed to assess the relationships between all attributes at once.

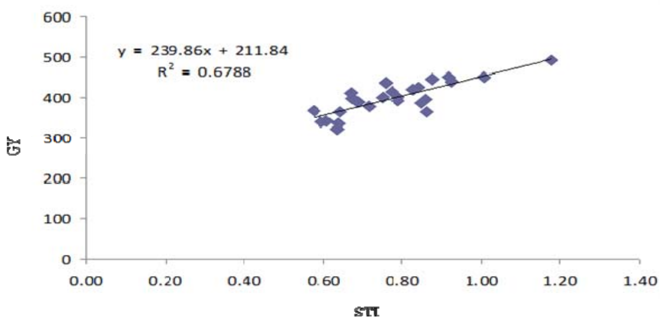

Figure 2 - Relationship between late sowing grain yield and stress tolerance index (STI)

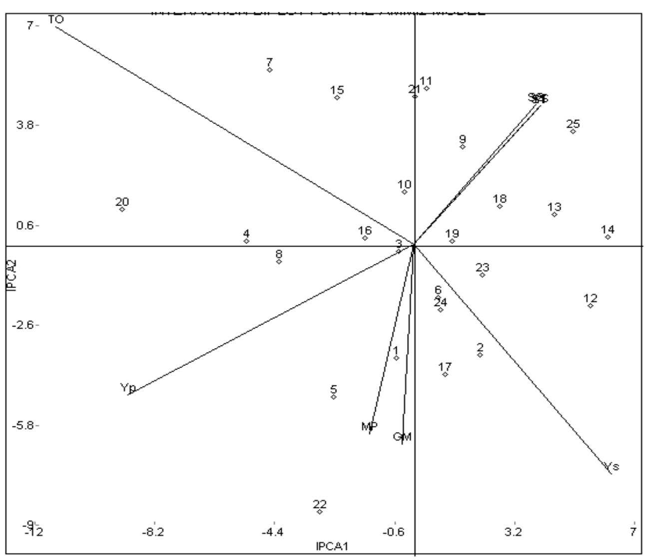

Figure 3 - Principal component analysis of stress tolerance indices

PCA indicated that the indices could discriminate the wheat genotypes. Principal component analysis revealed that the first PCA explained 0.64 of the variation with MP, GMP, YI and STI. Thus, the first dimension can be identified as yield potential and heat tolerance. Considering the high and positive value of this biplot, genotypes that have high values of these indices will be high yielding under stress and non-stress environments. The second PCA explained 0.35 of the total variability and correlated positively with TOL, SSI and YSI. Therefore, the second component can be termed as a stress susceptible component with low yield in a stressful environment. Kaya *et al*. (2002) revealed that genotypes with larger PCA1 and lower PCA2 scores gave high yields (stable genotypes), and genotypes with lower PCA1 and larger PCA2 scores had low yields (unstable genotypes). Thus, genotypes G-12, G-13, G-14, G-18 and G-25 were superior genotypes for both environments with high PC1 and low PC2. Genotypes G-7, G-11, G-15, G-20 and G-21 with high PC2 were more suitable for optimum condition than for heat stress condition. Khodarahmpour *et al*. (2011) obtained similar results in multivariate analysis of heat tolerance in maize. The use of biplot display in selecting drought tolerant genotypes has also been used by many authors (Fernandez, 1992; Farshadfar and Sutka, 2002; Souri *et al*., 2005; Golabadi *et al*., 2006; Karami *et al*., 2006; Sio-Se Mardeh *et al*., 2006; Talebi *et al*., 2009) in different crops. Yan and Rajcan (2002) stated that the correlation coefficient among any two indices is given approximately by the cosinus of the angle between their vectors. Hence, r = cos 180º = -1, cos 0º = 1, and cos 90º = 0. Thus, a strong positive association between MP, GMP and STI with Yp and Ys were revealed by the acute angles between the corresponding vectors. A negative association between YSI, SSI and TOL with Ys and YI were reflected by the larger obtuse angles between their vectors in a biplot display (*Fig. 3*). The results obtained from the biplot graph confirmed the correlation analysis. Results of this study are in accord with Khodarahmpour *et al*. (2011) for heat tolerance in maize and Golabadi *et al*. (2006) and Nouri *et al*. (2011) in durum wheat for drought tolerance.

CONCLUSIONS

The indices SSI, YSI and TOL could be useful parameters for discriminating genotypes that have lower susceptibility to heat stress. In the present study G-12, G-13, and G-14 were highly stable genotypes which had the highest YSI and the lowest SSI and TOL produced moderate grain yield and could be recommended for poor environments as well as heat stressed condition. Using MP, GMP, YI and STI, the genotypes G-05 and G-22 were found to be the best genotypes with relatively high yield and suitable for both optimum and heat stressed conditions. Therefore, these genotypes can be exploited in breeding programs for terminal heat stressed environments. During present study, using indices like biomass, grain filling rate and spikes m^{-2} were identified as powerful tools for selecting wheat genotypes under both timely and late sowing conditions. However, the association with different resistance indices revealed that high ground cover at mid vegetative stage with delayed anthesis having high grain filling rate would made a genotype tolerant to late heat.

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