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Research Article

Characterization of Wheat Genotypes for Terminal Heat Stress Tolerance in Bangladesh

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ABSTRACT

This study was aimed to determine the types and levels of variability, heritability, genetic progress, relationships between yield and the features that contribute to it, and some key indicators of terminal heat stress tolerance. Twenty different wheat genotypes were planted in the fields over the course of six different treatments spaced 10 days interval following a Randomized Complete Block Design with three replications. A high degree of significant variation was observed for all the characters studied. Estimates of the genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) revealed that the phenotypic coefficient of variation was higher than the genotypic coefficient of variation, which indicates a large effect of environment on the expression of the characters studied. The highest estimates of PCV and GCV were observed for grain yield/plant followed by the number of tillers/plant. Heritability estimates revealed that characters like pollen fertility and sterility exhibited the highest heritability followed by days to maturity. The genetic advance was higher for grains/plants followed by plant height. Grain yield showed significant and positive phenotypic and genotypic correlations with grains/plant and 100-grain weight. Phenotypic path analysis revealed a significant direct positive effect of 100-grain weight on grain yield. Principal component analysis (PCA) revealed that the first five components having greater than one Eigenvalue contributed to 83.41% variability. The heat stress tolerance indices revealed that Bijoy and BARI Gom-25 had the lowest tolerance index (TOL), stress susceptibility index (SSI) values and highest yield susceptibility index (YSI) values which show more tolerance and less susceptibility to terminal heat stress and produced moderate grain yield under terminal heat stress. Balaka and Shughat had the highest mean productivity (MP), geometric mean productivity (GMP), and stress tolerance index (STI) values and produced high yields under terminal heat stress conditions.

Introduction

Wheat is a winter-season crop that belongs to the Gramineae family and is hexaploid (2n = 6x = 42), grown all over the world as the third most important cereal crop to fulfill the demands of expanding population and is essential for ensuring a country's food security (Shiferaw et al., 2013; Rao et al., 2010; Farooq et al., 2011; Timsina et al., 2018). It is a crucial crop for both nutrition and agriculture, providing one-third of the world's population with around half of their protein and calories (Kumar et al., 2015). However, there are a number of environmental restrictions, including terminal heat stress, which is thought to pose a significant threat to the production of wheat. 40% of wheat crops worldwide experience yield loss as a result of terminal heat stress (Ruwali and Bhawsar, 2000). Terminal heat stress affects wheat crops during the reproductive growth stages mainly heading to the maturity stages (Reynolds et al., 2001).

In Bangladesh, wheat crops are subjected to terminal heat stress because over 60% of the total wheat is planted after the T-aman rice harvest has been delayed (Badruddin et al., 1994), and because 80-85% of the total wheat is put in the same field as the T-aman rice (Saunders, 1991). Delayed planting of wheat shortens the vegetative life span and accelerates the transition to the reproductive phase earlier due to terminal heat stress (Aslam et al., 2017). With each degree over the ideal temperature, the yield of wheat decreases by 3 to 15% (Mondal et al., 2013). Wheat suffers from the physiological effects of terminal heat stress during the anthesis and grain-filling stages, which results in diminished growth and poor seed and grain quality (Farooq et al., 2011). In wheat, terminal heat stress inhibits flowering, pollen fertility, and translocation of photosynthates to the developing kernel. It also promotes sterility and inhibits starch synthesis and deposition within the kernel, all of which reduce grain yield because of decreased grain number, grain weight,

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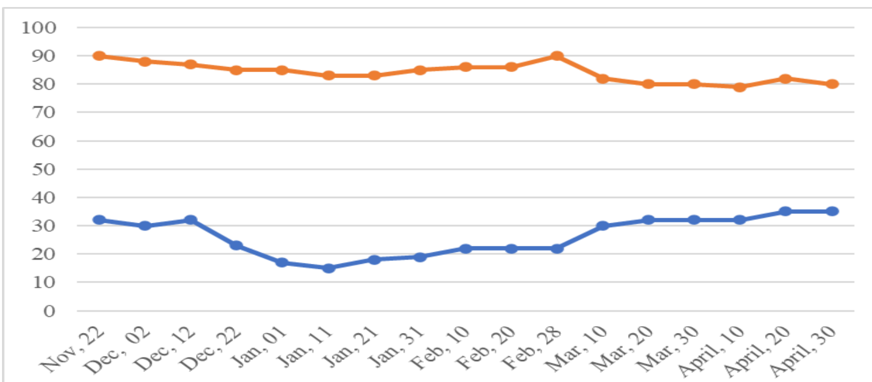
and grain quality (Reynolds et al., 2012; Gonzalez-Navarro et al., 2015). Moreover, higher canopy temperatures during the reproductive phases of wheat lead to lower grain yields and shorter crop growth cycles (Joshi et al., 2007).

For the purpose of developing selection criteria for terminal heat stress tolerance, the link between morpho-physiological traits related to heat tolerance is crucial. Wheat genotypes having genetic variation for terminal heat stress tolerance provide great opportunity for breeders to create more adaptable and resistant varieties using suitable breeding schemes through the recombination of desirable genes (Birendra et al., 2012; Kumar et al., 2015a). Based on the above background information, the present work was designed to characterize a number of wheat genotypes and also their stability under different terminal heat stress condition created using different sowing dates based on morpho-physiological traits and stress tolerance indices.

Materials and methods

Experimental site, duration and design

The experiment was conducted at the Farm Laboratory, Genetics and Plant Breeding Department, Bangladesh Agricultural University (BAU), Mymensingh, during the period November 2020 to April 2021.The experiment was carried out using a randomized complete block design (RCBD) in six plots with six sowing dates. The first sowing was done on November 22, 2020, and is regarded as the optimum treatment. Terminal heat stress was imposed by sowing the wheat genotypes at intervals of 10 days for a further five times after the optimum sowing date on December 2, 2020, December 12, 2020, December 22, 2020, January 1, 2021, and January 11, 2021, respectively, considered as late planting. Date wise temperature (^{0}C) and humidity (%) fluctuation data throughout the growth period are shown in below graph.



Data collection

Data were collected on different morpho-physiological characters related to heat tolerance including days to 50% germination, days to 50% booting, days to 50% heading, days to 50% flowering, days to 50% grain filling, days to 50% maturity, plant height, flag leaf length, flag leaf width, spike length, number of spikelets per spike, number of tillers per plant, grain per spike, grain per plant, 100-grain weight, grain yield per plant. Chlorophyll content was measured by SPAD meter after two weeks of anthesis. After two weeks of flowering, a handheld infrared thermometer was used to gauge the temperature of the canopy in bright sunlight. Pollen fertility was measured by observing under an electric microscope and scoring a percentage of the viable pollen grain. Each data was recorded in three replications and then the average was used.

Statistical analysis

Data were analyzed with the help of the MSTATC program, MS Office Excel program.

The stress tolerance indices were calculated by the following formulas:

1. Tolerance Index (TOL) = $Y_P - Y_S$ (Rosielle and Hamblin, 1981)

2. Stress Susceptibility Index (SSI) = $\dfrac{1-\frac{Y_P}{Y_S}}{1-\frac{Y_S}{Y_P}}$ (Fischer and Maurer, 1978)

3. Yield Stability Index (YSI) = $\dfrac{Y_S}{Y_P}$ (Bouslama and Schapaugh, 1984)

4. Mean Productivity (MP) = $\dfrac{Y_P + Y_S}{2}$ (Rosielle and Hamblin, 1981)

5. Geometric Mean Productivity (GMP) = $\sqrt{Y_P \times Y_S}$ (Ramirez and Kelly, 1998)

6. Stress Tolerance Index (STI) = $\dfrac{Y_P \times Y_S}{Y_P^2}$ (Fernandez, 1992)

Where,

Yp = Grain yield of genotypes under normal condition

Ys = Grain yield of genotypes under stress condition

$\overline{Y_p}$= Mean grain yields of all genotypes under normal condition

$\overline{Y_s}$= Mean grain yields of all genotypes under stress condition

Results and Discussion

Analysis of variance for morpho-physiological traits

Analysis of variance was carried out to investigate the significance of variations in the genotypes, treatments, and genotype-treatment interaction. The significantly substantial mean sum of the square for these characters demonstrated the genetic diversity of the lines under investigation. According to the analysis of variance, all the analysed characters genotype mean squares were significant at both 5% and 1% level of probability (Table 1), showing that there is enough genetic variation among the various genotypes to be used in breeding programs. For all of the features representing the various climatic situations, the treatment impact was significant. For all of the examined characters, the genotype treatment was significant, demonstrating that different wheat genotypes perform differently under various environmental conditions. Estimation of different genetic parameters showed that almost all the characters under study showed a high estimate of broad sense heritability and indicated higher to moderate genetic advance except for canopy temperature depression (Table 2).

According to Kandic et al., (2009), early vigor in wheat was highly important and correlated with high heritability and genetic advancement. Low and close GCV and PCV values suggested a restricted genotypic variability range brought on by fixed alleles and less environmental effect on the expression of the characteristics. The findings of this study supported those of Rahman (2009), who found little variance in these parameters across wheat genotypes. Moderate to high GCV and PCV readings indicated that the environment had a moderate to minimal impact on this trait. Similar findings were obtained by Sapi et al., (2017), Desheva and Kyosev, (2015), and Mohanty et al., (2016).

High heritability and high genetic advance as a percentage of the mean were found for grain per spike, grain per plant, 100-grain weight, and grain yield per plant (Table 2) indicating that these traits were less affected by environmental changes and that improvement in the trait would be more effective through selection due to their additive gene action. Shughat displayed the most grains per spike, indicating that choosing this character would improve yield while under stress from the heat. The genotype Pradip demonstrated the most grains per plant, indicating that using this genotype will be advantageous to increase yield potential. Shatabdi displayed a weight of over 100 grains, indicating that choosing this character can boost production potential. The maximum grain yield was produced by Bijoy, indicating that using this genotype may ultimately result in higher yields. These findings were in agreement with Khashif and Khaliq, (2004); Majumdar et al., (2008); Ahmad et al., (2010); Akram et al., (2008); Desheva and Kyosev, (2015); Kumar et al., (2014).

Table 1. Mean square (MS) values for 20 morpho-physiological characters in 20 wheat genotypes

Characters	Genotypes	Treatment	Genotype ×Treatment	Error
DTG	48.99**	287.71**	4.40**	1.81
DTB	214.00**	743.95**	24.97**	11.59
DTH	186.76**	443.41**	17.13**	1.35
DTF	144.46**	1018.78**	16.08**	1.79
DTGF	191.12**	1051.71**	25.59**	3.85
PF	567.61**	13369.52**	183.41**	1.25
PS	567.61**	13369.52**	183.41**	1.25
CC	94.10**	925.63**	17.91**	3.54
CTD	14.18**	2372.40**	5.02**	0.94
FLL	52.42**	104.47**	7.37*	5.56
FLW	0.122**	3.115**	0.019**	0.009
DTM	436.57**	3737.69**	23.24**	1.92
PH	1356.30**	16285.96**	99.05**	45.10
NTP^{-1}	23.27**	304.12**	9.61**	1.03
SL	17.48**	216.03**	3.57**	2.01
NSS^{-1}	47.70**	1130.00**	21.95**	4.75
GS^{-1}	422.65**	11029.10**	184.02**	15.88
GP^{-1}	13239.21**	753892.14**	11336.39**	604.27
100-GW	0.908**	35.746**	0.222**	0.053
YP^{-1}	8.185**	630.960**	5.874**	0.216

Note: * and ** indicate significance at 0.5 and 0.1 probability, respectively.

Legend,

DTG= Days to germination, DTB= Days to booting, DTH= Days to heading, DTF= Days to flowering, DTGF= Days to grain filling, PF= Pollen fertility, PS= Pollen sterility, LCC= Leaf chlorophyll content, CTD= Canopy temperature depression, FLL= Flag leaf length, FLW= Flag leaf width, DTM=

Days to maturity, PH= Plant height, NTP^{-1}= Number of tillers per plant, SL= Spike length, NSS^{-1}= Number of spikelets per spike, GS^{-1}= Grain per spike, GP^{-1}= Grain per plant, 100-GW= 100-Grain weight, GYP^{-1}= Grain yield per plant.

Table 2. Estimation of genetic parameters for 20 characters associated with heat tolerance in wheat

Characters	Mean	Range		Genotypic variation	Phenotypic variation	GCV (%)	PCV (%)	Heritability	GA	GA%
		Maximum	Minimum							
Days to germination	10.97	16.06	9.61	15.73	17.54	36.16	38.19	89.68	7.74	70.55
Days to booting	65.29	70.83	58.17	67.47	79.07	12.58	13.62	85.33	15.63	23.94
Days to heading	69.57	75.28	62.11	61.80	63.16	11.30	11.42	97.85	16.02	23.03
Days to flowering	73.12	77.17	66.72	47.56	49.35	9.43	9.61	96.37	13.95	19.07
Days to grain filling	19.81	27.39	15.22	62.42	66.28	39.89	41.11	94.19	15.80	79.75
Pollen fertility (%)	80.55	89.01	67.78	188.79	190.04	17.06	17.11	99.34	28.21	35.02
Pollen sterility (%)	19.45	32.22	10.99	188.79	190.04	70.64	70.88	99.34	28.21	145.05
Leaf chlorophyll content	37.86	43.16	33.14	30.19	33.73	14.51	15.34	89.49	10.71	28.28
Canopy temperature depression	86.50	88.23	85.07	4.41	5.36	2.43	2.68	82.43	3.93	4.54
Flag leaf length	20.84	26.23	19.02	15.62	21.18	18.97	22.09	73.74	6.99	33.55
Flag leaf width	1.39	1.57	1.26	0.04	0.05	13.93	15.50	80.71	0.36	25.77
Days to maturity	92.92	104.56	85.33	144.88	146.81	12.95	13.04	98.69	24.63	26.51
Plant height	86.53	107.78	78.00	437.07	482.17	24.16	25.38	90.65	41.00	47.38
Number of tillers per plant	5.71	8.56	4.06	7.41	8.45	47.70	50.91	87.79	5.26	92.07
Spike length	15.49	17.61	14.06	5.16	7.17	14.66	17.28	71.92	3.97	25.60
Number of spikelet per spike	35.26	37.94	31.44	14.32	19.07	10.73	12.38	75.07	6.75	19.15
Grain per spike	37.66	45.22	25.67	135.59	151.47	30.92	32.68	89.51	22.70	60.27
Grain per plant	157.24	198.22	97.61	4211.65	4815.92	41.27	44.14	87.45	125.02	79.51
100-grain weight	1.55	2.00	1.23	0.29	0.34	34.37	37.43	84.32	1.01	65.01
Grain yield per plant	2.97	4.08	1.63	2.66	2.87	54.92	57.11	92.48	3.23	108.79

Correlation coefficient of the characters studied

Breeders can benefit greatly from the knowledge of correlations between various plant qualities since it identifies the traits for which selection should be made in order to maximize yield under specific environmental conditions. Days to booting and days to heading had a positive and significant correlation with days to flowering pollen fertility, days to maturity, and the number of spikelets per spike and a significant negative correlation with pollen sterility (Table 3). Days to grain-filling showed a significant positive association with flag leaf length, days to maturity, plant height, and the number of tillers per plant, and a negative association with grain per spike. Pollen fertility and canopy temperature depression had significant and negative correlations with pollen sterility and the number of spikelets per spike, respectively (Table 3). Flag leaf length, days to maturity, and spike length had a significant and negative correlation with grain per spike. Flag leaf length showed a significant and positive association with days to maturity, plant height, number of tillers per plant, and spike length while days to maturity showed a positive significant correlation with plant height, number of tillers per plant, spike length, and number of spikelets per spike. Plant height had a positive significant correlation with the number of tillers per plant and spike length and grain per spike were positive with grain per plant. Grain per plant and 100-grain weight showed a positive and significant correlation with grain yield per plant (Table 3). The correlation between grain yield with grain per plant and 100-grain weight was positive and significant. Selecting the parameters that showed a significant and positive correlation with grain yield can be claimed to directly increase it under heat-stressed conditions. These results partially concurred with those of Lopes and Reynolds, (2012); Ahmad et al., (2010), and Akram et al., (2008).

Path coefficient analysis between studied traits to yield

Path analyses of morpho-physiological features on grain yield are presented in Table 4. Days to flowering, days to the grain filling, flag leaf width, number of tillers per plant, spike length, number of spikelets per spike, and 100-grain weight all had a direct positive effect on grain yield (Table 4). These characters are favourable direct effects imply that direct selection for these characters for high grain yield would be successful. Grain yield is directly affected negatively by the number of days to germination, days to booting, days to heading, pollen fertility, pollen sterility, chlorophyll content, flag leaf length, days to maturity, plant height, grain per spike, and grain per plant (Table 4). However, their beneficial indirect benefits neutralized any harmful direct effects or indirect consequences. Flag leaf area was found to have a favourable direct impact on grain yield per plant by Alam et al., (1993). Under conditions of terminal heat stress, Kashif and Khaliq (2004) showed that plant height had both positive and negative effects on grain yield. According to Ahmad et al., (1994), there is a strong direct correlation between the number of tillers per plant and grain yield. Under extreme heat stress circumstances, spike length had a strong positive direct effect as well as a highly significant positive connection with grain yield (Anwar et al., 2009). According to Choudhary et al. (2014), pollen sterility, number of tillers per plant, number of grains per spike, and pollen fertility all had more favourable indirect impacts.

Table 3. Phenotypic (P) correlation coefficients of various characters associated with heat tolerance in wheat

	DTB	DTH	DTF	DTGF	PF	PS	LCC	CTD	FLL	FLW	DTM	PH	NTP^{-1}	SL	NSS^{-1}	GS^{-1}	GP^{-1}	100GW	GYP^{-1}
DTG	0.072	0.105	0.066	0.101	0.164	-0.164	-0.085	-0.309	0.039	0.430	0.105	0.066	-0.163	0.012	0.043	0.089	-0.129	0.341	0.205
DTB		0.947**	0.948**	0.310	0.673**	-0.673**	0.177	-0.403	0.275	0.147	0.753**	0.363	0.242	0.218	0.672**	-0.275	-0.050	-0.348	-0.251
DTH			0.965**	0.304	0.705**	-0.705**	0.186	-0.404	0.293	0.133	0.759**	0.379	0.204	0.294	0.605**	-0.270	-0.091	-0.343	-0.256
DTF				0.301	0.668**	-0.668**	0.137	-0.440	0.371	0.134	0.772**	0.410	0.258	0.306	0.639**	-0.338	-0.114	-0.374	-0.288
DTGF					-0.004	0.004	0.223	-0.273	0.715**	0.049	0.830**	0.635**	0.576**	0.441	0.247	-0.629**	-0.434	0.119	-0.289
PF						-0.999**	-0.214	-0.188	0.044	-0.062	0.382	0.297	-0.048	-0.028	0.366	-0.202	-0.244	-0.346	-0.336
PS							0.214	0.188	-0.044	0.062	-0.382	-0.297	0.048	0.028	-0.366	0.202	0.244	0.346	0.336
LCC								-0.068	0.094	0.158	0.227	-0.163	0.034	0.090	0.207	0.305	0.375	-0.024	0.218
CTD									-0.149	-0.281	-0.436	-0.038	0.106	-0.085	-0.535*	0.025	0.222	0.326	0.195
FLL										-0.155	0.690**	0.755**	0.654**	0.644**	0.221	-0.668**	-0.404	-0.012	-0.316
FLW											0.110	-0.271	-0.098	0.106	0.047	0.114	0.138	0.430	0.332
DTM												0.659**	0.532*	0.470*	0.533*	-0.613**	-0.354	-0.137	-0.359
PH													0.547*	0.655**	0.126	-0.779**	-0.599**	-0.050	-0.439
NTP^{-1}														0.545*	0.161	-0.648**	0.041	0.097	-0.072
SL															0.007	-0.501*	-0.300	0.063	-0.222
NSS^{-1}																-0.091	-0.002	-0.437	-0.176
GS^{-1}																	0.499*	-0.021	0.350
GP^{-1}																		0.038	0.676**
100GW																			0.576**

**** and * indicate 1% and 5% levels of significance**

Legend: DTG = Days to germination, DTB = Days to booting, DTH = Days to heading, DTF = Days to flowering, DTGF = Days to grain filling, PF = Pollen fertility (%), PS = Pollen sterility (%), LCC = Leaf Chlorophyll content, CTD = Canopy temperature depresseion, FLL = Flag leaf length, FLW = Flag leaf width, DTM = Days to maturity, PH = Plant height, NTP^{-1} = Number of tillers per plant, SL = Spike length, NSS^{-1} = Number of spikelets per spike, GS^{-1} = Grain per spike, GP^{-1} = Grain per plant, 100GW = 100-grain weight., GYP^{-1} = Grain yield per plant

Table 4. Direct and indirect effects of yield contributing and heat tolerant related characters on yield per plant of wheat at the phenotypic level

	DTG	DTB	DTH	DTF	DTGF	PF	PS	LCC	CTD	FLL	FLW	DTM	PH	NTP^{-1}	SL	NSS^{-1}	GS^{-1}	GP^{-1}	100GW	GYP^{-1}
DTG	**-0.569**	-0.001	-0.097	0.079	0.014	-0.129	0.092	0.031	0.295	-0.021	0.145	-0.091	-0.057	-0.030	0.015	0.018	-0.059	0.139	0.430	0.205
DTB	-0.041	**-0.014**	-0.875	1.140	0.044	-0.529	0.377	-0.064	0.385	-0.148	0.050	-0.651	-0.312	0.045	0.271	0.276	0.183	0.054	-0.439	-0.251
DTH	-0.060	-0.013	**-0.924**	1.160	0.043	0.000	-0.395	0.256	-0.178	0.218	0.099	-0.115	-0.653	0.070	0.254	0.121	-0.402	0.292	-0.115	-0.256
DTF	-0.038	-0.013	-0.892	**1.202**	-0.036	-0.236	-0.374	0.242	-0.131	0.237	0.125	-0.116	-0.664	0.076	0.321	0.126	-0.425	0.365	-0.144	-0.288
DTGF	-0.057	-0.004	-0.281	-0.308	**0.140**	0.226	0.002	-0.001	-0.213	0.147	0.242	-0.042	-0.714	0.118	0.716	0.181	-0.164	0.679	-0.548	-0.289
PF	-0.093	-0.009	0.000	0.362	-0.040	**-0.786**	0.162	0.363	0.204	0.101	0.015	0.054	-0.329	0.055	-0.060	-0.012	-0.243	0.218	-0.308	-0.336
PS	0.093	0.009	-0.652	0.803	-0.001	0.227	**-0.560**	0.122	-0.204	-0.101	-0.015	-0.054	0.329	-0.055	0.060	0.012	0.243	-0.218	0.308	0.336
LCC	0.048	-0.002	0.652	-0.803	0.001	0.785	0.188	**-0.363**	-0.321	0.037	0.032	-0.137	-0.195	-0.030	0.042	0.037	-0.138	-0.329	0.473	0.218
CTD	0.176	0.006	-0.172	0.165	0.031	0.168	-0.120	-0.122	**-0.955**	-0.118	-0.050	0.243	0.375	-0.007	0.132	-0.035	0.356	-0.027	0.280	0.195
FLL	-0.022	-0.004	0.373	-0.529	-0.038	0.148	-0.105	0.025	-0.208	**-0.540**	0.066	0.134	-0.593	0.140	0.813	0.265	-0.147	0.721	-0.510	-0.316
FLW	-0.245	-0.002	-0.271	0.446	0.100	-0.035	0.025	-0.034	0.142	-0.105	**0.338**	0.273	-0.095	-0.050	-0.122	0.044	-0.031	-0.123	0.174	0.332
DTM	-0.060	-0.011	-0.123	0.161	0.007	0.049	-0.035	-0.057	0.268	0.084	-0.107	**-0.865**	-0.286	0.122	0.661	0.193	-0.354	0.662	-0.447	-0.359
PH	-0.038	-0.005	-0.701	0.928	0.116	-0.300	0.214	-0.082	0.416	-0.372	0.037	-0.287	**-0.860**	-0.066	0.680	0.269	-0.084	0.841	-0.756	-0.439
NTP^{-1}	0.093	-0.003	-0.350	0.493	0.089	-0.233	0.166	0.059	0.036	-0.407	-0.092	-0.570	0.309	**0.185**	-0.546	0.224	-0.107	0.700	0.052	-0.072
SL	-0.007	-0.003	-0.189	0.310	0.081	0.038	-0.027	-0.012	-0.101	-0.353	-0.033	-0.460	-0.470	-0.081	**1.243**	-0.030	-0.005	0.541	-0.379	-0.222
NSS^{-1}	-0.024	-0.009	-0.272	0.368	0.062	0.022	-0.016	-0.033	0.081	-0.348	0.036	-0.407	-0.563	0.101	-0.089	**0.411**	0.148	0.098	-0.003	-0.176
GS^{-1}	-0.051	0.004	-0.559	0.768	0.035	-0.287	0.205	-0.075	0.511	-0.119	0.016	-0.461	-0.108	0.030	0.009	-0.091	**-0.665**	0.190	0.630	0.350
GP^{-1}	0.073	0.001	0.250	-0.406	-0.088	0.159	-0.113	-0.111	-0.024	0.361	0.039	0.530	0.670	-0.120	-0.623	-0.037	0.117	**-1.080**	0.442	0.676**
100GW	-0.194	0.005	0.084	-0.137	-0.061	0.192	-0.137	-0.136	-0.212	0.218	0.047	0.306	0.515	0.008	-0.373	-0.001	-0.332	-0.378	**1.262**	0.576**

Residual effect: 0.03975; Bold numeric value indicates direct effect; * and ** indicate significant at 5% and 1% levels of probability, respectively

Legend: DTG = Days to germination, DTB = Days to booting, DTH = Days to heading, DTF = Days to flowering, DTGF = Days to grain filling, PF = Pollen fertility (%), PS = Pollen sterility (%), LCC = Leaf chlorophyll content, CTD = Canopy temperature depression, FLL = Flag leaf length, FLW = Flag leaf width, DTM = Days to maturity, PH = Plant height, NTP^{-1} = Number of tillers per plant, SL = Spike length, NSS^{-1} = Number of spikelets per spike, GS^{-1} = Grain per spike, GP^{-1} = Grain per plant, 100GW = 100-grain weight, GYP^{-1} = Grain yield per plant.

Heat stress tolerance indices

The grain yield of genotypes under both normal and heat-stress conditions was used to calculate heat-stress tolerance indices. To find the genotypes that are tolerant to heat, many researchers had previously used heat stress tolerance indices of grain yield (Singh et al., 2011; Sharma *et al*., 2013). The heat stress tolerance indices—tolerance index (TOL), stress susceptibility index (SSI), yield stability index (YSI), mean productivity (MP), geometric mean productivity (GMP), and stress tolerance index (STI)—for five different sowing dates considering a magnitude of terminal heat stress condition are shown in Figure 1, 2, 3, 4, 5, and 6, respectively. The computed indices showed a large range of variation in the genotypes. Bijoy and BARI Gom-25 exhibited the lowest TOL values in this trial, indicating that they had a high tolerance for heat stress. They consequently saw little yield decrease from heat stress. According to Nouri et al. (2011), the selection of high-yielding genotypes under stressful conditions is facilitated by a lower value of TOL. The genotype Bijoy and BARI Gom-25 had the lowest SSI value, indicating that they were very heat-tolerant and had a low susceptibility to heat stress. They consequently produced a lot of grain under both normal and heat-stressed circumstances. According to Kamrani et al. (2018), selection based on SSI enables the identification of genotypes with high yields in both stressed and non-stressed environments. Bijoy and BARI Gom-25 samples showed the highest YSI values, indicating that they had superior yield stability and reduced yield decline during heat stress. Balaka and Shughat outperformed all other genotypes in terms of grain yield under both ideal and heat-stress conditions because they had the greatest MP, GMP, and STI indices. Under heat stress, these genotypes were more productive. Similar findings were provided by Kamrani et al. (2018), who suggested genotypes with higher yields and tolerance to heat might be found by selection based on MP, GMP, and STI.

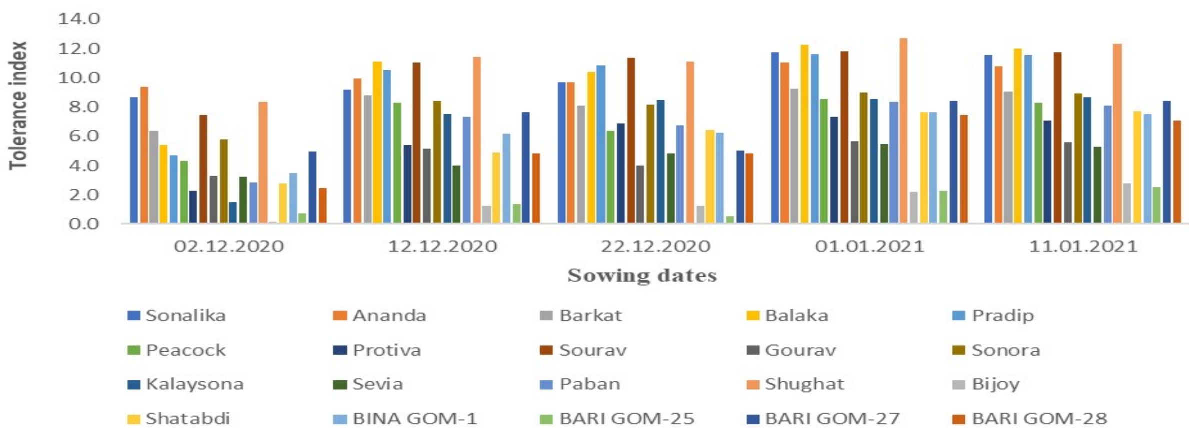


Figure 1. Tolerance index (TOL) of 20 wheat genotypes. The indices were estimated based on the optimum date of sowing. Different sowing date showing different level of tolerance based on terminal temperature fluctuation.

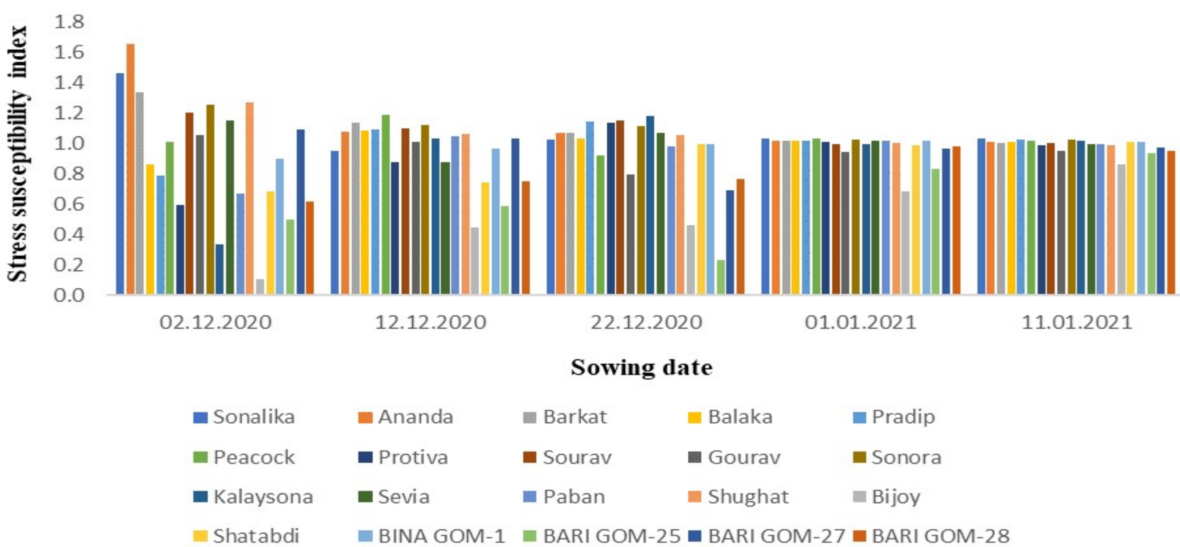


Figure 2. Stress susceptibility index (SSI) of 20 wheat genotypes. The indices were estimated based on the optimum date of sowing. Different sowing date showing different level of tolerance based on terminal temperature fluctuation.

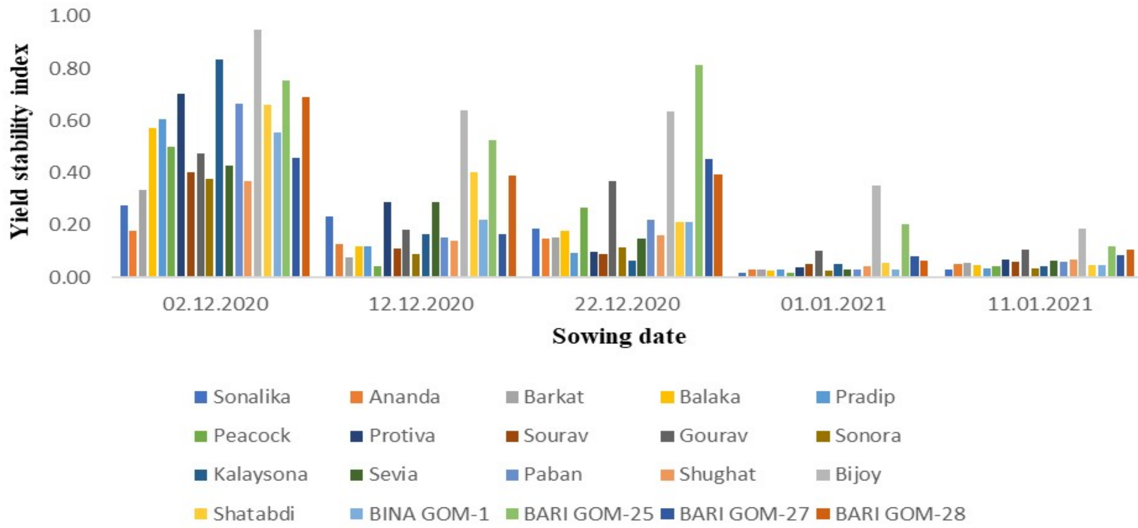


Figure 3. Yield stability index (YSI) of 20 wheat genotypes. The indices were estimated based on the optimum date of sowing. Different sowing date showing different level of tolerance based on terminal temperature fluctuation.

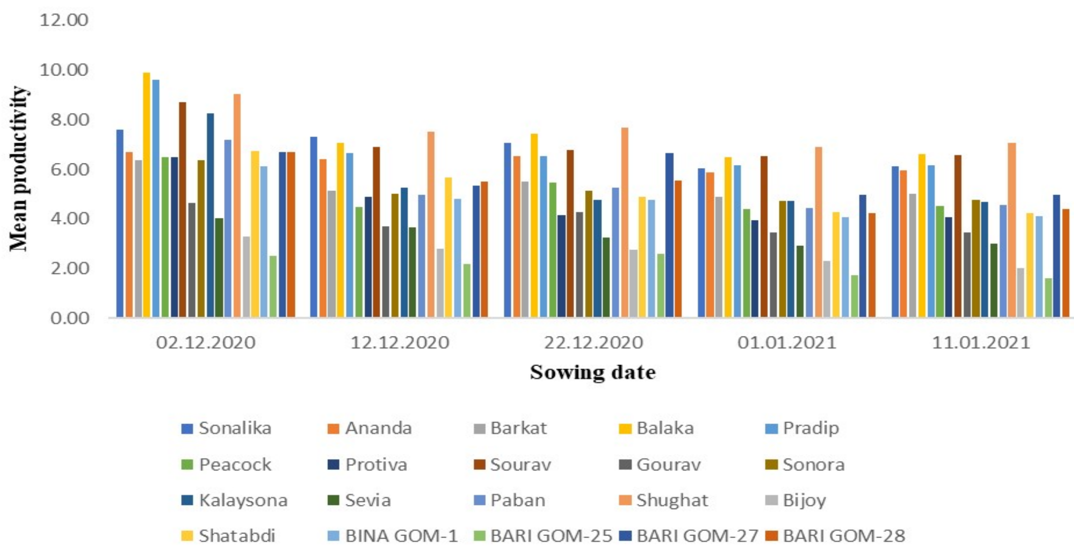


Figure 4. Mean productivity (MP) of 20 wheat genotypes. The indices were estimated based on the optimum date of sowing. Different sowing date showing different level of tolerance based on terminal temperature fluctuation.

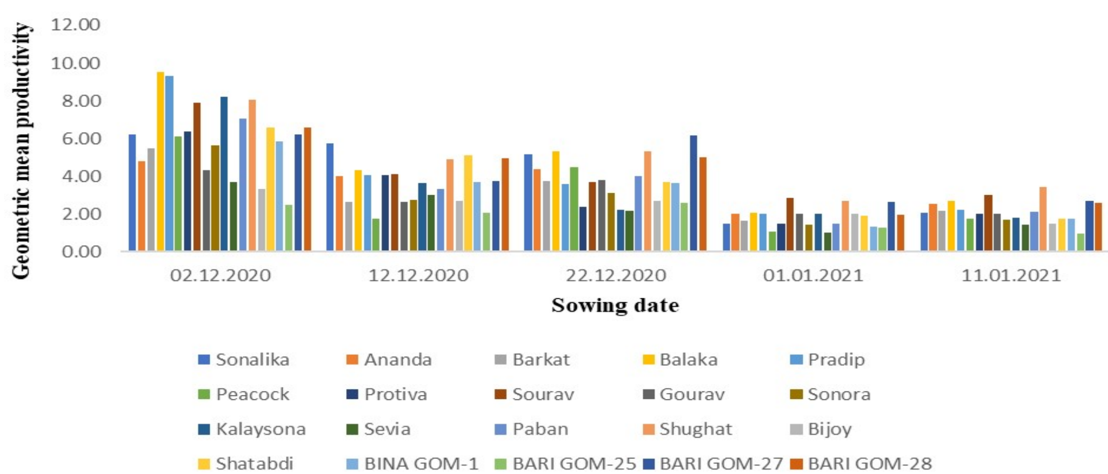


Figure 5. Geometric mean productivity (GMP) of 20 wheat genotypes. The indices were estimated based on the optimum date of sowing. Different sowing date showing different level of tolerance based on terminal temperature fluctuation.

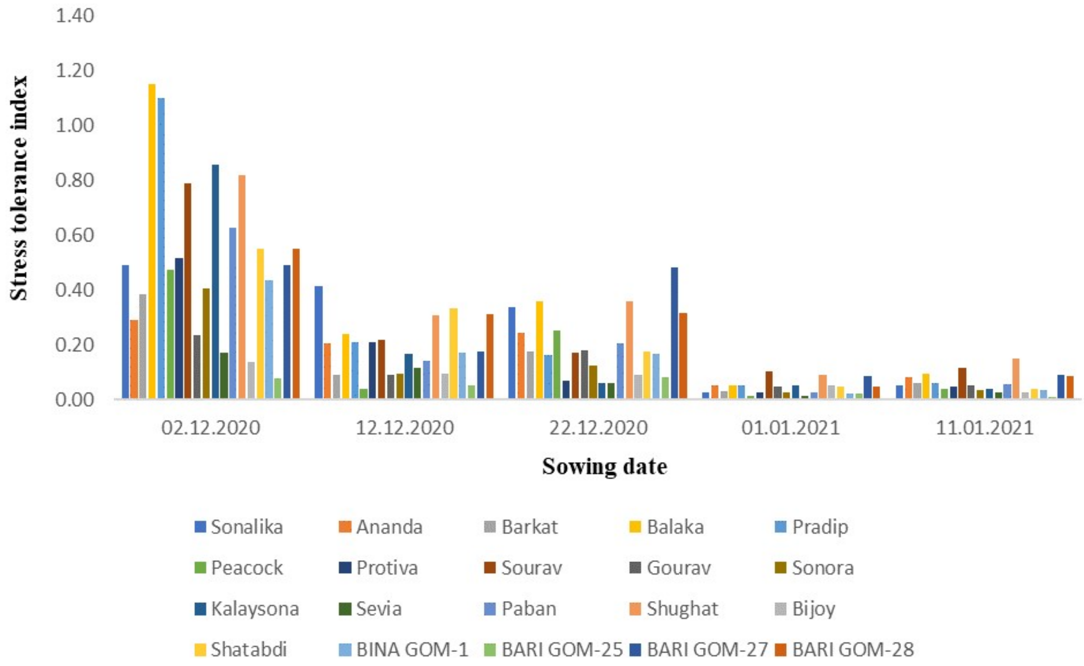


Figure 6. Stress tolerance index (STI) of 20 wheat genotypes. The indices were estimated based on the optimum date of sowing. Different sowing date showing different level of tolerance based on terminal temperature fluctuation.

Conclusion

Heat stress, yield, and yield-contributing traits were investigated in the performance of 20 wheat genotypes, and substantial variances were found among genotypes for all the traits, showing significant variability among genotypes that can be taken advantage of in upcoming breeding programs. For each of the traits, the treatment impact was also substantial. For all of the characteristics, the genotype treatment interaction effect was likewise significant. The genetic potential of wheat genotypes for grain yield will be improved through the direct selection of different yield-enhancing traits. Days to heading, pollen sterility, leaf chlorophyll content, flag leaf length, plant height, number of spikelets per spike, grain per plant, and 100-grain weight are genotypic characteristics that have a direct positive effect on grain yield. The heat stress tolerance indices TOL, SSI, and YSI may be helpful indicators for identifying genotypes with decreased heat stress susceptibility. Bijoy and BARI Gom-25 were very stable genotypes in the current study and had the highest YSI and lowest SSI, whereas TOL provided a moderate grain yield and might be suggested for arid and heat-stressed areas. The genotypes Balaka and Shughat were discovered to be the best genotypes using MP, GMP, and STI. They had a relatively high yield and were suited for both optimum and heat-stressed environments. Therefore, breeding efforts for areas with extreme heat can make use of these genotypes.

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