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Use of multiple stress indices as a measure of heat tolerance in wheat accessions

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Abstract

Wheat is a crop of global significance, grown in diversified environments. Heat stress affects a number of morpho-physiological traits in crops including wheat. A set of 40 wheat accessions along with four checks were screened for heat tolerance based on various stress indices. The present study was undertaken during *rabi* 2018-19 in randomized block design having three replications at CCS Haryana Agricultural University, Hisar under two dates of sowing *i.e.* 24th November and 24th December. Significant variance was observed among genotypes based on heat susceptibility index of all the traits except plant height and spike length. Based on heat susceptibility index and stress tolerance, the accessions DT 126, DT 46, DT 142, DT 102 and DT 124 were found to be most tolerant to heat stress, whereas on the basis of heat response index, heat tolerance index, mean productivity and geometric mean productivity, the promising accessions identified were DT 116, DT 101, DT 181, WH 1124, HD 3059 and DT190. The accessions identified as heat tolerant would form an important resource for the development of high yielding varieties under heat stress condition.Correlation coefficients based on HSI of different traits revealed significant positive association of grain yield per plant with biological yield per plant, harvest index, NDVI 1, tillers per plant and 1000 grain weight, denoting that these traits can be used effectively, for selection of heat tolerant genotypes. Grain yield was found to be positively correlated with the indices viz., HRI, HTI, MP and GMP while, negatively with HSI and TOL under stress condition. The stress indices used under study were recognized as paramount for identifying cultivars with high tolerance to heat stress.

Keywords: Wheat, heat stress, morpho-physiological, stress indices

1. Introduction

Wheat is one of the most important and widely cultivated crops in the world, belongs to the genus *Triticum* of the family *Poaceae* and tribe *Triticeae*. It is the second most important staple food next to rice,used mainly for human consumption and supports nearly 35% of the world population (Mohammadi-joo *et al.,* 2015) and provides about 20 per cent of the total food calories. It has been described as the 'King of cereals' because of the acreage it occupies, high productivity and the prominent position it holds in the international food grain trade. It is also known for its remarkable adoption to a wide range of environments and its role in the world economy.India has reported a record production of 107.18 million tonnes wheat from an area of 30.55 million hectare during the crop season 2019-20 with a productivity of 35.08 q/ha. In Haryana, 12.07 million tonnes wheat was produced on an area of 2.50 million hectare with average productivity of 48.29 q/ha (ICAR-IIWBR, 2020).

Abiotic stresses such as heat, cold, drought, salinity, and nutrient stress have a huge impact on world agriculture, and wheat is also no exception to this. Among abiotic stresses, heat stress is one of important abiotic stress which wheat faces today. The average global temperature is reported to be increasing at a rate of 0.18°C every decade (Hansen *et al*., 2012). Though, heat stress affects the metabolic pathways at every stage of life of wheat finally leading to yield reduction, the effect of high temperature is particularly severe during grain filling; these losses may be up to 40% under severe stress (Hays *et al*., 2007). Other effects of high temperatures includes decreased grain weight, early senescence, shriveled grains, reduced starch accumulation, altered starch-lipid composition in grains, lower seed germination and loss of vigour (Balla *et al*., 2012). To adapt new crop varieties to the future climate, we need to understand how crops respond to elevated temperatures and how tolerance to heat can be improved (Halford, 2009).

It is the need of the hour to counteract the detrimental effects of heat stress on global wheat production. Some of the adaptive measures which can mitigate terminal heat stress are surface cooling by irrigation (Lobell and Field, 2007), antioxidant defense (Caverzan *et al.,* 2016), osmoprotectants (Kaushal *et al.,* 2016), heat priming in early stages (Fan *et al.,* 2018) and use of plant growth regulators (Sharma *et al.,* 2019). Deryng et al. (2014) considered choice of cultivars and management of sowing dates as an adaptive measure under extreme heat stress conditions. The generation of improved pre-breeding material is indispensable for any breeding program (Ortiz *et al.,* 2008). It requires the evaluation of genetic diversity for adaptation to future climatic conditions, and thereby the selection and induction of stress inducible genes of genetic resources for developing new varieties in the production systems (Chapman *et al.,* 2012). Thus, there is an immediate need to explore genetic resources and develop such genotypes that can withstand terminal heat stress or can mature early without facing yield loss by escaping the stress conditions. Screening of genotypes under natural heat stress condition in various inconsistent environments is problematic. Susceptibility index proved to be a consistent parameter for selection of heat tolerant cultivars(Sharma *et al.,* 2013).

Hence, the present investigation was undertaken to screen wheat accessions for their heat tolerance based on various stress indices.

2. Materials and methods

TThe present study was conducted at Research Area of Wheat and Barley Section of Department of Genetics & Plant Breeding, CCS Haryana Agricultural University, Hisar which is located at latitude of 29° 10' N, longitude of 75° 46' E and at an altitude of 215.2 meters above mean sea. The experimental material consisted of 40 wheat accessions along with four check varieties namely WH 711, WH 542, WH 1124 and HD 3059 grown in randomized block design (RBD) with 3 replications during *rabi* 2018-19. These wheat accessions were received from NBPGR, New Delhi for screening against stress tolerance.The experiment was planted at two dates of sowing i.e. normal sowing (24th November) and late sowing (24th December). Under both the conditions, recommended package of practices were followed. Each accession was planted in paired rows of 2.5m length with inter-row and inter-plant distances of 20 and 10 cm, respectively. Observations were recorded at specific stage on five randomly selected plants per accession per replication for12 morphological traits viz.,days to heading, days to maturity, grain filling duration, plant height (cm), peduncle length (cm), tillers per plant, spike length (cm), grains per spike, 1000 grain weight (g), grain yield per plant (g), biological yield per plant (g) and harvest index (%) and 6 physiological traits *viz*., normalized difference vegetation index at anthesis (NDVI 1), normalized difference vegetation index at 15 days after anthesis (NDVI 2), canopy temperature at anthesis (CT 1), canopy temperature at 15 days after anthesis (CT 2), soil plant chlorophyll development at anthesis (SPAD 1) and soil plant chlorophyll development at 15 days after anthesis (SPAD 2).

Canopy temperature was recorded instantaneously with a hand held infrared thermometer (Model AG-42, Tele temp crop, Fullerton CA).The SPAD chlorophyll content was measured at anthesis (SPAD1) and 15 days after anthesis (SPAD2) by chlorophyll meter (Model No. Minolta SPAD-502 Plus) which measure the greenness or the relative chlorophyll content of leaves.NDVI was measured at anthesis (NDVI1) and 15 days after anthesis (NDVI2) with the help of Green seeker hand held optical sensor unit (Model 505, NTech Industries, Inc., Ukiah, CA, USA).

Heat susceptibility index (HSI) of individual genotypes was calculated by the method suggested by Fischer and Maurer (1978). Heat response index (HRI) and stress tolerance

Table 1. Weekly weather data during the crop season

Year	Week No.	Temperature (^0C)		Relative humidity		Rainfall (mm)
		Max	Min	M	E	
2018	40	34.4	20.0	90	40	0.0
	41	32.5	17.9	86	43	0.0
	42	33.4	16.5	73	30	0.0
	43	31.4	14.4	84	36	0.0
	44	31.0	15.4	92	44	0.0
	45	27.4	10.1	90	41	0.0
	46	27.5	12.7	91	53	0.0
	47	27.4	10.9	87	44	0.0
	48	27.2	9.4	93	46	0.0
	49	24.9	7.5	96	45	0.0
	50	21.0	7.7	91	57	0.0
	51	20.7	2.0	93	50	0.0
	52	19.8	1.9	94	49	0.0
2019	1	18.9	5.7	95	66	7.3
	2	19.3	5.6	93	60	0.0
	3	20.4	4.9	90	55	0.0
	4	18.2	4.8	99	63	6.5
	5	17.1	5.3	96	65	0.0
	6	21.0	6.9	92	56	0.0
	7	20.0	9.7	94	67	0.0
	8	22.2	9.0	89	50	0.0
	9	20.9	8.0	93	53	14.8
	10	24.2	8.5	88	38	0.0
	11	24.9	9.1	91	48	0.0
	12	28.9	11.8	80	42	0.0
	13	32.6	13.5	81	28	0.0
	14	36.0	16.0	74	28	7.3
	15	36.9	20.0	69	27	0.0
	16	32.9	17.2	81	37	8.2
	17	40.7	20.6	56	19	0.0
	18	40.1	20.8	48	23	0.0

(TOL)were computed using the formula given by Bidinger *et al.* (1987) and Hossain *et al.* (1990), respectively. Heat tolerance index (HTI)and geometric mean productivity (GMP) were worked out as per Fernandez (1993); and Mean productivity (MP)as described by Rosielle and Hamblin (1981).

The weather parameters during the crop season are presented in Table 1. Weekly mean maximum temperature varied between 17.1 to 40.7 ^0C whereas, the weekly mean minimum temperature was between 1.9 and 20.8 ^0C. Morning RH varied from 48 to 99% while evening RH was highly variable with a range from 19 to 67%. Total amount of rainfall received during the season at Hisar was 44.1 mm.

3. Results and Discussion

The reduction in the performance of wheat accessions under terminal heat condition was expressed in terms of heat susceptibility index (HSI). The HSI of eighteen morpho-physiological traits were subjected to analysis of variance and mean sum of squares has been presented in Table 2. The results revealed hereby, the presence of significant variance among accessions for the HSI of all the traits except plant height and spike length. This implies that the magnitude of differences in accessions was enough to provide scope for selection with improved heat stress tolerance. The component of variance due to replications was found to be non significant for all the traits. These observations confirm with the findings of Bhusal *et al.* (2017).

The heat susceptibility index of different traits for forty wheat accessions and four check varieties have been depicted in Table 3. The genotypes with high positive HSI values are susceptible to higher temperature and vice versa (Fisher and Maurer, 1978). The estimates of HSI or the important traits *viz.,* grain yield per plant, biological yield per plant and harvest index can be utilized for selection of tolerant genotypes. The estimates of HSI for grain yield revealed that the accession DT 126 (0.05) followed by DT 142 (0.28), DT 102 (0.33), DT 46 (0.37) and DT 124 (0.46), exhibited minimum values of HSI, therefore, these accessions possessed low heat susceptibility and high yield stability under heat stress condition. In contrast, DT 104 (1.71) recorded with maximum value of HSI for grain yield and was identified as highly susceptible to heat. For the trait biological yield per plant, minimum HSI was shown by DT 124 (-0.21) followed by DT 142 (-0.02), WH 711 (-0.06), DT 102 (0.04) and DT 46(0.13). Similarly, for harvest index HSI was minimum for accession DT 127 (-2.90) followed by DT 126 (-2.66). All these accessions showed their superiority for tolerance to high temperature than other genotypes. HSI was also used by Islam et al. (2017) and Sareen et al. (2020) to classify genotypes into different categories i.e. heattolerant,moderatelyheattolerantandheatsusceptible.

Correlation coefficients were worked out based on HSI of different traits, to estimate the degree of association among various characters for heat tolerance (Table 4).Grain yield per plant exhibited significant positive association with biological yield per plant, harvest index, NDVI 1, tillers per plant and 1000 grain weight, showing the importance and effectiveness of these traits for detection and screening of high yielding and thermotolerant genotypes under normal and stress conditions. Significant positive correlations were also observed for days to maturity with days to heading and grain filling duration; NDVI 1 with CT 1, CT 2, grains per spike and biological yield; NDVI 2 with SPAD 2; CT 1 with grains per spike; CT 2 with plant height; spike length with biological yield; tillers per plant with 1000 grain weight and biological yield; and 1000 grain weight with grains per spike and biological yield. Similarly, signifi-

Table 2. Mean sum of squares for HSI of different traits

Source of variation	d. f.	Mean sum of squares								
		DH	DM	GFD	NDVI 1	NDVI 2	CT 1	CT 2	SPAD 1	SPAD 2
Replication	2	0.002	0.0025	0.154	4.6065	0.3255	0.452	1.027	0.1225	0.065
Treatment	43	0.028**	0.045**	0.389**	9.225**	2.754**	1.949**	12.857**	1.949**	2.819**
Error	86	0.007	0.007	0.083	1.337	0.713	0.326	1.664	0.428	0.881

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Source of variation	d. f.	Mean sum of squares								
		PH	PL	SL	TIL	GPS	TGW	BY	GY	HI
Replication	2	1.90	0.1375	0.653	0.464	0.605	0.279	0.338	0.142	1.623
Treatment	43	12.302	1.235*	0.847	2.925**	2.841**	4.61**	0.918**	0.426**	6.227**
Error	86	8.365	0.762	0.667	0.336	0.32	0.399	0.193	0.094	1.241

**, * Significant at 1 and 5 % level, respectively

(DH: Days to heading, DM: Days to maturity, GFD: Grain filling duration, NDVI 1: Normalized difference vegetation index at anthesis, NDVI 2: Normalized difference vegetation index at 15 days after anthesis, CT 1: Canopy temperature at anthesis, CT 2: Canopy temperature at 15 days after anthesis, SPAD 1: Soil plant chlorophyll development at anthesis, SPAD 2: Soil plant chlorophyll development at 15 days after anthesis, PH: Plant height, PL: Peduncle length, SL: Spike length, TIL: Tiller per plant, GPS: Grains per spike, TGW: 1000-grain weight, BY: Biological yield per plant, GY: Grain yield per plant, HI: Harvest index)

Table 3 .Heat susceptibility index of wheat accessions for different traits

Accessions	DH	DM	GFD	NDVI 1	NDVI 2	CT 1	CT 2	SPAD 1	SPAD 2	PH	PL	SL	TIL	GPS	TGW	BY	GY	HI
DT 5	0.93	0.82	0.52	-1.81	0.49	0.08	3.90	0.82	1.03	1.46	0.81	0.03	2.52	-1.11	-0.54	0.65	0.92	1.52
DT 25	1.08	1.03	0.78	-2.16	1.63	1.90	-1.96	0.31	1.18	1.29	1.42	0.94	1.14	1.31	0.20	-0.29	0.96	3.41
DT 46	0.86	0.98	1.18	-2.42	0.50	-0.16	-0.05	0.90	1.35	2.15	0.98	0.27	0.27	-0.01	1.42	0.13	0.37	0.91
DT 54	1.01	1.11	1.04	2.46	3.19	2.54	1.73	1.82	-0.29	1.95	2.41	1.75	0.77	0.54	0.23	0.58	1.43	3.37
DT 83	0.95	0.95	0.96	2.49	-0.42	1.35	2.43	0.46	0.11	3.87	1.62	1.26	1.08	2.32	1.40	0.88	1.60	3.64
DT 101	1.05	0.95	0.80	0.80	0.89	0.45	2.83	0.35	1.93	3.60	0.90	0.59	1.43	1.99	0.72	1.14	0.97	0.47
DT 102	1.14	1.22	1.39	1.02	1.01	1.48	5.06	0.24	1.64	3.85	1.25	0.27	0.59	1.01	1.66	0.04	0.33	0.78
DT 104	0.95	0.92	0.88	0.96	1.11	1.15	2.35	0.61	1.21	-0.06	0.65	-0.32	0.12	0.59	2.04	1.23	1.71	3.40
DT 106	0.85	0.96	1.33	-1.72	1.33	1.36	-0.97	0.89	1.02	0.22	1.57	1.12	0.89	1.73	2.05	1.21	1.15	1.02
DT 109	1.01	0.99	0.98	1.94	1.73	2.04	0.90	-0.18	1.65	1.82	0.38	0.90	1.47	2.37	3.33	1.27	1.24	1.14
DT 110	0.90	0.88	0.80	3.50	2.29	0.00	5.30	1.26	0.79	0.97	0.89	0.82	1.10	0.50	1.70	1.52	1.43	1.32
DT 113	0.85	1.00	1.36	4.62	-1.74	2.14	1.46	0.27	-2.35	0.14	0.68	1.02	1.09	2.42	1.52	1.37	1.47	2.05
DT 114	1.15	1.11	0.95	0.52	0.90	-0.27	1.25	2.56	-0.27	2.46	1.95	1.95	-0.39	0.24	1.11	1.36	0.99	-0.12
DT 116	1.17	1.08	0.97	3.26	1.67	2.04	4.14	0.96	1.25	1.25	0.68	1.58	2.07	0.41	-0.32	1.52	1.18	0.07
DT 122	0.98	1.06	0.96	1.05	2.22	0.10	0.53	2.35	0.51	-1.61	0.98	0.91	0.67	0.72	1.91	1.08	1.43	2.49
DT 124	1.11	1.15	1.25	-0.45	0.75	1.43	-0.91	0.37	2.15	0.87	1.26	0.58	-1.01	1.16	0.68	-0.21	0.46	1.80
DT 125	0.94	0.95	1.15	-1.46	0.05	1.40	0.27	1.17	-0.23	0.52	0.37	1.05	1.87	1.40	-0.36	0.82	0.84	0.81
DT 126	0.89	0.81	0.33	1.65	0.35	2.18	0.55	0.47	-0.03	0.26	1.19	1.47	0.13	2.63	2.20	0.95	0.05	-2.66
DT 127	1.07	1.14	1.40	-1.68	0.78	-0.02	-2.23	2.15	0.50	-1.56	1.40	1.64	1.66	0.18	-0.29	1.68	0.74	-2.90
DT 137	1.02	0.97	0.82	1.03	1.65	0.15	-1.36	0.94	1.65	-2.42	2.41	1.35	-0.20	0.90	1.59	0.51	0.85	1.63
DT 139	1.03	0.99	1.05	1.72	1.37	1.19	-1.10	1.21	1.37	-0.93	0.91	1.75	-0.10	0.79	-0.13	0.57	1.01	2.11
DT 142	0.88	1.06	1.51	0.14	0.26	1.33	0.25	1.07	1.05	-1.94	0.58	0.54	-1.81	-1.01	-2.94	-0.02	0.28	0.93
DT 147	0.96	1.01	0.93	-1.97	1.88	0.63	-1.28	0.99	1.42	-1.17	1.28	0.75	-0.04	0.31	1.37	0.56	0.71	1.01
DT 150	0.91	0.67	0.12	0.45	0.75	2.42	0.50	3.51	3.47	-0.83	0.28	1.04	1.22	0.12	1.46	1.43	1.34	1.09
DT 151	0.99	0.86	0.59	1.32	1.89	1.91	3.44	0.92	0.95	1.27	-0.33	0.30	-0.07	1.62	-1.02	0.99	0.91	0.66
DT 153	0.88	1.02	1.61	-2.25	1.28	0.84	0.95	0.89	-0.47	-1.62	1.35	0.95	0.75	0.38	0.13	1.03	0.82	0.19
DT 154	1.04	0.99	0.95	1.78	1.82	2.25	6.23	1.54	1.90	-0.15	0.96	1.35	-0.14	0.38	1.15	1.33	0.97	-0.15
DT 168	1.06	1.06	1.36	1.57	1.53	1.29	4.09	0.50	1.26	2.05	1.20	1.82	0.69	1.86	3.11	1.52	1.35	1.00
DT 169	0.87	1.13	1.71	-0.91	1.12	0.18	4.71	0.67	1.28	-0.31	-0.34	0.81	2.99	-0.24	0.27	1.01	0.95	0.75
DT 171	0.97	0.96	0.81	1.73	2.02	1.01	0.90	1.18	1.80	3.97	1.40	1.16	1.99	-0.08	1.79	1.76	1.38	0.15
DT 175	0.96	0.95	1.02	2.98	2.06	0.63	1.15	1.69	1.14	1.43	1.17	0.36	-0.04	-0.25	-1.04	0.24	0.84	2.12
DT 176	1.10	0.93	0.51	1.72	0.64	0.63	0.99	0.94	1.10	-6.38	-0.20	0.77	-0.15	0.28	-0.34	1.17	0.59	-1.38

DT 177	0.90	1.04	1.23	-1.49	0.91	1.32	-0.80	-0.12	1.25	1.32	1.12	1.28	0.17	1.90	1.28	0.71	0.51	-0.13
DT 178	0.95	0.86	0.39	0.84	1.13	1.96	-0.91	0.53	1.03	3.37	2.45	0.79	2.17	0.98	2.65	1.64	1.36	0.55
DT 181	0.96	0.77	0.25	1.61	0.15	0.07	1.38	0.60	0.59	-0.10	0.84	1.24	0.86	2.92	0.60	1.01	1.10	1.36
DT 183	1.21	1.15	1.02	1.10	0.31	2.15	1.74	-0.20	1.00	2.13	0.35	1.80	0.74	-0.03	1.83	1.22	1.27	1.42
DT 187	1.14	1.09	1.05	1.33	-0.13	1.12	2.19	0.33	-0.02	1.25	0.64	1.74	2.91	2.33	0.97	1.46	0.91	-0.91
DT 190	0.89	0.89	0.74	2.68	-0.70	2.13	2.24	2.04	1.42	1.36	0.12	0.46	1.88	0.78	2.74	0.89	0.91	0.89
DT 191	0.93	0.87	0.89	1.44	0.28	0.19	0.14	2.34	-0.31	2.76	1.83	1.04	0.71	0.29	2.49	1.88	1.31	-1.01
DT 192	1.07	1.04	0.89	3.18	-1.40	0.45	0.66	2.20	-0.98	4.41	1.27	0.45	1.94	0.35	-0.25	1.56	1.07	-0.65
WH711 (c)	1.14	1.21	1.42	0.76	0.77	0.46	0.40	0.21	1.20	0.71	0.83	0.26	1.04	0.65	1.33	-0.06	0.91	2.98
WH542 (c)	1.09	1.22	1.42	2.93	1.54	1.42	-1.36	0.48	0.06	2.47	0.86	1.30	0.99	2.59	0.73	1.01	1.26	2.06
WH1124 (c)	1.06	0.97	0.76	1.30	0.93	0.61	2.32	0.21	1.28	1.06	1.06	1.07	0.47	1.25	1.26	0.52	0.52	0.41
HD 3059 (c)	1.08	1.17	1.27	-0.30	0.22	1.24	-1.09	0.68	0.02	0.96	0.92	0.63	1.10	0.56	-0.09	0.86	0.65	-0.02

Table 4 .Correlation among HSI in wheat accessions for different traits

Traits	DH	DM	GFD	NDVI 1	NDVI 2	CT 1	CT 2	SPAD 1	SPAD 2	PH	PL	SL	TIL	GPS	TGW	BY	GY	HI
DH	1.000																	
DM	0.406**	1.000																
GFD	-0.014	0.641**	1.000															
NDVI 1	0.087	-0.018	-0.175*	1.000														
NDVI 2	0.169	0.077	-0.037	-0.038	1.000													
CT 1	0.039	-0.039	-0.085	0.221*	-0.027	1.000												
CT 2	0.042	-0.128	-0.025	0.289**	0.007	0.034	1.000											
SPAD 1	-0.121	-0.174*	-0.202*	0.124	0.043	-0.091	-0.077	1.000										
SPAD 2	0.114	-0.083	-0.236**	-0.084	0.257**	0.102	0.029	0.089	1.000									
PH	0.060	0.077	0.017	0.140	0.003	0.051	0.174*	-0.070	-0.095	1.000								
PL	-0.068	0.105	0.016	-0.030	0.039	-0.029	-0.233**	0.016	-0.094	0.079	1.000							
SL	0.153	0.081	0.005	0.116	0.078	0.155	-0.066	0.103	-0.043	0.028	0.059	1.000						
TIL	0.027	-0.085	-0.075	-0.015	-0.120	-0.022	0.170	-0.018	-0.131	0.138	-0.108	0.046	1.000					
GPS	0.057	-0.019	-0.043	0.206*	-0.085	0.205*	-0.069	-0.363**	-0.226**	0.170	-0.005	0.137	0.070	1.000				
TGW	-0.002	-0.113	-0.142	0.112	0.046	0.141	0.049	-0.077	0.102	0.096	0.121	0.077	0.177*	0.322**	1.000			
BY	-0.014	-0.222*	-0.182*	0.261**	-0.053	0.026	0.155	0.151	-0.175*	0.065	0.014	0.186*	0.381**	0.098	0.273**	1.000		
GY	-0.069	-0.134	-0.115	0.294**	0.079	0.092	0.138	0.101	-0.086	0.123	0.019	0.070	0.289**	0.087	0.268**	0.550**	1.000	
HI	-0.101	0.083	0.076	0.044	0.125	0.096	0.010	-0.106	0.088	0.041	-0.033	-0.156	-0.121	0.020	0.024	-0.460**	0.462**	1.000

*, **: Significant at 5 and 1%, respectively

Table 5. Stress indices for grain yield in wheat accessions

Accessions	Accession No.	HRI	HTI	TOL	MP	GMP
DT 5	IC 335583	-0.71	0.68	3.73	10.63	10.46
DT 25	IC 335966	-1.93	0.54	3.53	9.53	9.35
DT 46	EC 609336	0.66	0.23	0.90	6.12	6.06
DT 54	EC 276983	0.63	0.33	4.70	7.68	7.30
DT 83	IC 296756	-1.20	0.40	6.00	8.57	8.02
DT 101	IC 543401	0.64	1.13	5.13	13.73	13.49
DT 102	EC 277323	0.39	0.92	1.37	12.22	12.19
DT 104	EC 276920	0.32	0.68	8.67	11.30	10.42
DT 106	IC 534137	-0.63	0.71	5.00	11.00	10.70
DT 109	IC 402058	-0.66	0.75	5.77	11.42	11.04
DT 110	IC 276717	-0.14	0.53	5.87	9.70	9.24
DT 113	IC 542124	0.73	0.36	5.03	7.98	7.55
DT 114	EC 313735	1.20	0.27	2.77	6.72	6.53
DT 116	EC 519498	0.79	1.22	6.93	14.50	14.05
DT 122	EC 577722	0.88	0.30	4.40	7.30	6.95
DT 124	IC 47337	-0.67	0.64	1.63	10.18	10.15
DT 125	EC 609337	-0.22	0.95	4.00	12.57	12.40
DT 126	EC 445157	-1.29	0.43	0.30	8.35	8.31
DT 127	EC 609574	0.23	0.59	2.83	9.88	9.76
DT 137	IC 35143	0.60	0.40	2.80	8.23	8.07
DT 139	IC 335968	0.42	0.92	4.87	12.40	12.15
DT 142	IC 111844	-0.41	0.73	1.17	10.92	10.88
DT 147	IC 445528	0.17	0.78	2.93	11.30	11.20
DT 150	IC 535772	0.04	0.68	6.07	10.93	10.50
DT 151	IC 535518	0.23	0.99	4.60	12.87	12.63
DT 153	EC 276814	-0.33	0.32	2.37	7.25	7.12
DT 154	IC 543364	0.09	0.74	4.17	11.15	10.95
DT 168	EC 276864	0.28	0.53	5.53	9.67	9.22
DT 169	IC 547701	-0.13	0.89	4.43	12.15	11.94
DT 171	EC 295392	-0.30	0.46	5.17	8.98	8.60
DT 175	EC 478016	-0.19	0.71	3.40	10.80	10.67
DT 176	EC 299085	-0.21	0.75	2.40	11.03	10.96
DT 177	EC 573837	0.36	1.00	2.33	12.73	12.68
DT 178	IC 128664	-0.04	0.61	5.87	10.37	9.94
DT 181	EC 577619	0.75	1.01	5.70	13.12	12.80
DT 183	IC 535848	-0.32	0.59	5.30	10.12	9.74
DT 187	IC 445522	0.30	0.88	4.30	12.15	11.93
DT 190	IC 335932	0.18	1.06	4.67	13.30	13.08
DT 191	EC 519501	-0.87	0.44	4.73	8.73	8.40
DT 192	EC 13263	-1.29	0.60	4.20	10.07	9.84
WH711 (c)	-	-0.76	0.74	3.93	11.13	10.94
WH542 (c)	-	0.34	0.59	5.30	10.12	9.74
WH1124 (c)	-	1.47	1.48	2.87	15.53	15.47
HD3059 (c)	-	0.64	1.20	3.40	14.07	13.92

(HRI: Heat response index, HTI:Heat tolerance index,TOL: Stress tolerance, MP: Mean productivity and GMP: Geometric mean productivity) cant negative correlation was recorded for days to maturity with SPAD 1 and biological yield; grain filling duration with NDVI 1, SPAD 1, SPAD 2 and biological yield; CT 2 with peduncle length; number of grains per spike with SPAD 1 and SPAD 2; and biological yield with SPAD 2 and harvest index. These results corroborates with the findings of Mason *et al.* (2010), Paliwal *et al.* (2012), Sharma *et al.* (2016) and Bhusal *et al.* (2017). In order to further validate the results obtained by analysis of HSI, five other stress indices viz., heat response index (HRI), heat tolerance index (HTI), stress tolerance (TOL), mean productivity (MP) and geometric mean productivity (GMP) were worked out based on grain yield under normal and stress conditions. The estimates of stress indices for grain yield in wheat accessions have been showed in Table 4, while Fig. 1 depicts a radar graph representing the most promising accessions based on different stress indices i.e. WH 1124 based on HRI, HTI, MP and GMP; and DT 126 based on TOL.The estimate of stress tolerance (TOL) was observed minimum for DT 126 (0.30) followed by DT 46 (0.90), DT 142 (1.17), DT 102 (1.37) and DT 124 (1.63), exhibiting lower yield reduction under heat stress whereas, higher yield reduction was recorded in DT 104 (8.67) that showed high value of TOL. Similar results were also observed by Hassan *et al.* (2016) and Mohammadi *et al.* (2011). Heat response index is more useful criteria of selection as it categories the genotype based on the mechanism of heat tolerance i.e. escape, resistance or tolerance (Munjal and Dhanda, 2016). The promising accessions identified on the basis of high heat response index were WH 1124 (1.47), DT 114 (1.20), DT 122 (0.88), DT 116 (0.79), DT 181 (0.75) and DT 113(0.73). Heat response index was also used earlier by Suresh *et al.* (2018) to evaluate heat tolerance in *Triticum aestivum, Triticum durum* and triticale cultivars.The accession WH 1124 followed by DT 116, HD 3059, DT 101, DT 190 and DT 181 were found superior over the others in terms of yield, according to the estimates of heat tolerance index (HTI), mean productivity (MP) and geometric mean productivity (GMP) indices. Theseaccessions showed considerable potential to improve heat tolerance in wheat breeding programs, based on different stress tolerance indices. Various stress indices like HTI, MP and GMP have also been used by Puri et al. (2015), Mohammadi and Abdulahi (2017); and Meena et al. (2019) for evaluation and screening of heat tolerant genotypes.Based on the stress indices, viz., HSI, HRI, HTI, TOL, MP and GMP, the late sown check variety WH 1124 was found superior to other check varieties used in the study, therefore WH 1124 can serve as standard mean for these stress indices. The individual ranks of accessions for different stress indices were used to work out average and overall rank (Table 6). The accession DT 177, followed by DT 102, DT 101, DT 190 and DT 151 were found most tolerant to heat stress based on the overall ranks. The overall rank of accessions, exhibited a negative correlation of -0.863 with grain yield under stress condition, signifying that better ranked accessions had greater yield under stress condition. Further, correlation coefficient analysis among different stress indices and with grain yield was carried out and estimates are illustrated in Table 7. Grain yield under stress condition was found to be positively correlated with the indices *viz.*,HRI, HTI,MP and GMP whereas, it was negatively correlated with HSI and TOL, signifying that higher estimates of HRI, HTI, MP and GMP, and lower of HSI and TOL correspond to heat tolerance.The stress indices HTI and GMP exhibited maximum positive correlation with grain yield under stress condition; therefore, they can be regarded as the best selection criteria for heat stress tolerance.Under normal sown,grain yield recorded significant positive correlation with all the stress indices except HRI. Likewise, among the stress indices, significant positive association were observed for HSI with TOL; HTI with HRI, MP and GMP; and MP with TOL and GMP. The results also revealed significant negative association of HSI with HTI and GMP. Similar interrelationship among these stress indices reflected in the findings of Mohammadi *et al.*(2011),Suresh *et al.* (2018) and Meena *et al.* (2019). Khan *et al.* (2014) and Puri *et al.* (2015) also recorded significant positive association of MP, GMP and HTI with grain yield under normal and stress conditions. Hence, the stress indices used under study were recognized as paramount for identifying cultivars with high tolerance to heat stress.

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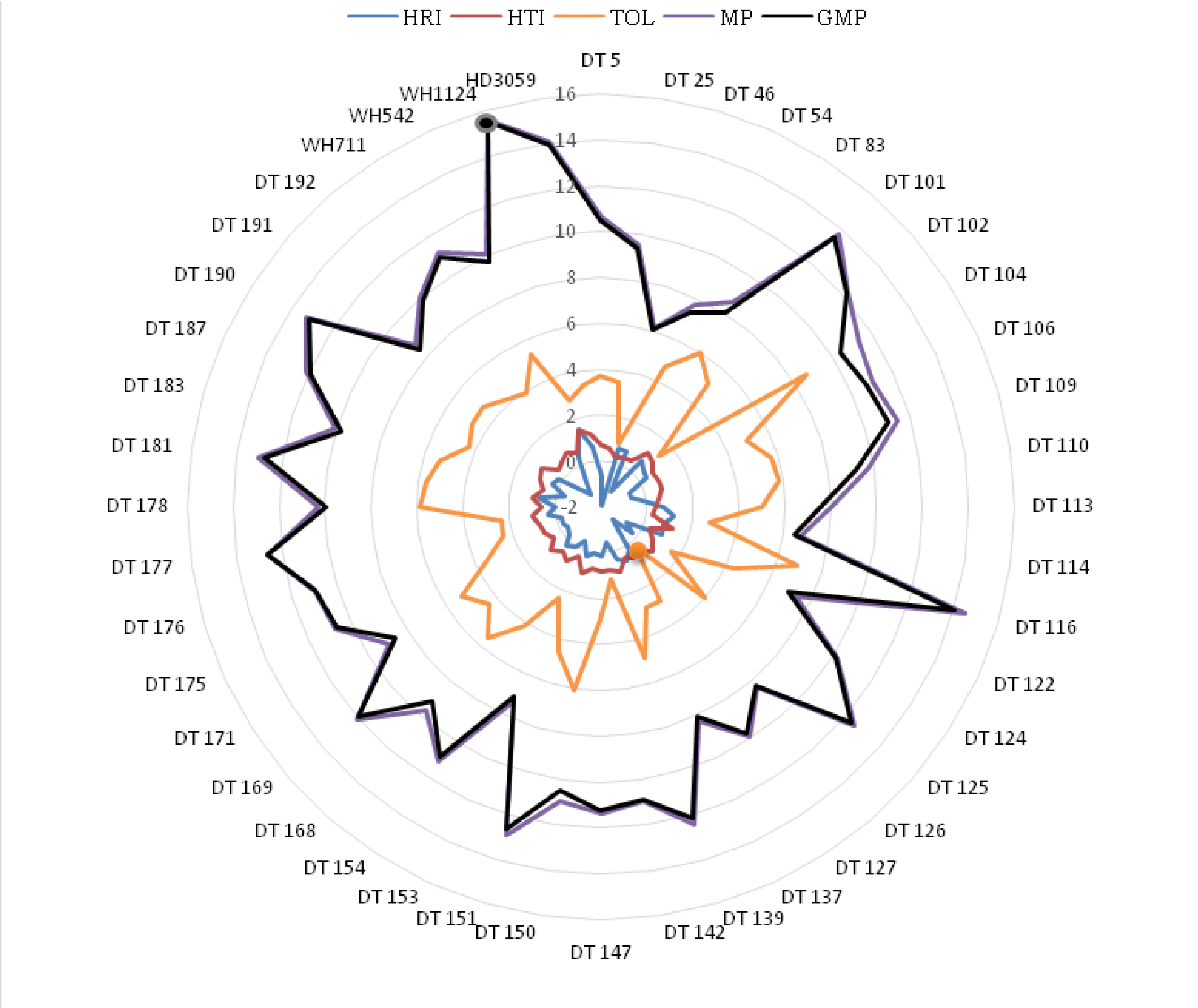

***Fig.* 1. Stress indices for grain yield in wheat accessions**

Table 6. Rank of accessions based on different stress indices

Accessions	Individual Rank						Average rank	Overall rank
	HSI	HRI	HTI	TOL	MP	GMP		
DT 5	20	38	22	17	24	23	24.00	22
DT 25	22	44	31	16	33	31	29.50	34
DT 46	4	7	44	2	44	44	24.17	23
DT 54	39	10	40	27	40	40	32.67	39
DT 83	43	41	37	41	36	38	39.33	44
DT 101	23	8	4	32	4	4	12.50	5
DT 102	3	13	10	4	11	10	8.50	4
DT 104	44	16	22	44	15	24	27.50	28
DT 106	29	35	20	30	20	20	25.67	27
DT 109	31	36	15	38	14	15	24.83	25
DT 110	39	27	32	39	31	32	33.33	41
DT 113	42	6	39	31	39	39	32.67	39
DT 114	25	2	43	9	43	43	27.50	28
DT 116	30	4	2	43	2	2	13.83	7

DT 122	39	3	42	23	41	42	31.67	38
DT 124	5	37	25	5	26	25	20.50	19
DT 125	13	30	9	19	9	9	14.83	11
DT 126	1	42	36	1	37	36	25.50	26
DT 127	11	19	28	11	30	28	21.17	21
DT 137	15	11	37	10	38	37	24.67	24
DT 139	26	12	10	29	10	11	16.33	14
DT 142	2	34	19	3	22	19	16.50	15
DT 147	10	22	14	13	15	14	14.67	9
DT 150	35	24	22	42	21	22	27.67	31
DT 151	16	19	8	25	7	8	13.83	7
DT 153	12	33	41	7	42	41	29.33	33
DT 154	23	23	17	20	17	17	19.50	17
DT 168	36	18	32	36	32	33	31.17	37
DT 169	21	26	12	24	12	12	17.83	16
DT 171	38	31	34	33	34	34	34.00	42
DT 175	13	28	20	14	23	21	19.83	18
DT 176	8	29	15	8	19	16	15.83	13
DT 177	6	14	7	6	8	7	8.00	3
DT 178	37	25	26	39	25	26	29.67	35
DT 181	28	5	6	37	6	6	14.67	9
DT 183	33	32	28	34	27	29	30.50	36
DT 187	16	17	13	22	12	13	15.50	12
DT 190	16	21	5	26	5	5	13.00	6
DT 191	34	40	35	28	35	35	34.50	43
DT 192	27	42	27	21	29	27	28.83	32
WH 711 (c)	16	39	17	18	18	18	21.00	20
WH 542 (c)	32	15	28	34	27	29	27.50	28
WH 1124 (c)	7	1	1	12	1	1	3.83	**1**
HD 3059 (c)	9	8	3	14	3	3	6.67	**2**

Table 7. Correlation among different stress indices

	Yp	Ys	HSI	HRI	HTI	TOL	MP	GMP
Yp	1.000							
Ys	0.663**	1.000						
HSI	0.228**	-0.552**	1.000					
HRI	0.137	0.155	-0.006	1.000				
HTI	0.872**	0.931**	-0.236**	0.222*	1.000			
TOL	0.560**	-0.250**	0.907**	0.005	0.097	1.000		
MP	0.926**	0.897**	-0.144	0.159	0.986**	0.204*	1.000	
GMP	0.889**	0.931**	-0.223*	0.159	0.992**	0.119	0.996**	1.000

Yp, and Ys represent grain yield under normal and stress conditions, respectively

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