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EXPLORING HEAT TOLERANCE IN BREAD WHEAT: IMPLICATIONS FOR CLIMATE RESILIENCE

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ABSTRACT

The present investigation was carried out to study of heat stress tolerance in two varying environments created by two different dates of sowing *viz.*, normal and late sowing for yield and its contributing traits by performing diallel analysis (Griffing Method II, Model 1) and Hayman's graphical analysis. To achieve the objectives of the present investigation, eight genetically diverse parents namely; HD 2864, MP 3336, Raj 3765, HD 2932, Raj 4238, Raj 3777, CG 1029 and HI 1634 were crossed in diallel fashion excluding reciprocals in *rabi* 2022-23. These eight parents along with their 28 F_1 progenies were evaluated in a randomized block design with three replications during rabi 2023-24 at Instructional Farm of Sri Karan Narendra College of Agriculture, Jobner (Rajasthan).

The assessment of crosses Indicated that HD 2932 x Raj 4238 in E_1 and HD 2864 x Raj 3765, MP 3336 x HI 1634 and Raj 4238 x Raj 3777 in E_2 environment showed the superiority under heat stress environment for grain yield and more than two characters on the basis of heat susceptibility index (HSI) and heat tolerance (TOL).

Introduction

Wheat best adopts to cool growing conditions (Chowdhary and Wardlaw, 1978), while moderately high temperatures (25 -32ºC) for longer duration and very high temperature (33-40ºC) for a shorter period are very common in subtropical environments of South East Asia including India (Paulsen 1994; Stone and Nicolas, 1994). Although wheat production in much warmer areas is technically feasible, heat stress is a common constraint, especially during anthesis and grainfilling in many temperate environments in South and West Asia (Reynolds *et al*., 1994). Therefore, heat stress is one of the major constraints of wheat production in arid, semiarid, tropical and subtropical regions of the world (Ashraf and Harris, 2005).

The genus *Triticum* is composed of diploid, tetraploid, and allohexaploid species. So, polyploidy has played a major role in wheat evolution. The diploid species (2n=2x=14) (commonly known as' einkorn wheats') as *Triticum monococcum* and *Triticum urartu* is usually found in the wild, and its grains are hulled. *Triticum monococcum* is also grown in small quantities for consumption in some areas. The tetraploid species (2n=4x=28) contain both hulled and hulless. The wild species *Triticum turgidum* subsp. *dicoccoides* and domesticated *Triticum turgidum* subsp. *dicoccum* (now designated as *Triticum dicoccum* or *Triticum dicoccon*) is hulled, commonly referred to as emmer wheat and *Triticum turgidum* subsp. *durum* (now designated as *Triticum durum*) is hulless and commonly referred as macroni wheat. The hexaploid hulled wheat (2n=6x=42) species are *Triticum aestivum* subsp. *spelta* and *Triticum aestivum* subsp. *macha*. *Triticum aestivum* subsp. *aestivum* presently referred as bread wheat (Gustafson *et al.*, 2009).

Heat stress at late growth stages is a problem in 40% of wheat areas in the temperate environments (Reynolds *et al*., 2001). A brief period of exposure to high ambient temperature (>35ºC) can drastically reduce grain yield in wheat (Hawkerand Jenner, 1993) because of induction of early senescence and acceleration of grain filling activities in wheat (Paulsen, 1994) due to shortening of grain filling duration and constriction of carbon as similation (Stone, 2001). Grain weight is affected by high temperatures, especially those above 34ºC, that reduce the duration of grain filling owing to the limited photosynthesis (Al Khatib and Paulsen, 1984) and inhibits tarchbiosyn thesis in the endosperm (Keeling *et al.*, 1994; Jenner, 1994).

Heat stress during post-anthesis and grain-filling stage affects availability and translocation of photosynthates to the developing kernels and starch synthesis and deposition within the kernel, thus resulting in lower grain weight and altered grainquality (Bhullar and Jenner, 1985; Mohammadi *et al*., 2004). It has been observed that each degree rise in ambient temperature reduces the yield by 3-4% (Mishra, 2007). Wheat breeders are seeking to incorporate late heat tolerance in the wheat germ plasm and to develop genotypes that are early in maturity in order to escape the terminal heat stress and, thus suit well in the rice-wheat as well as in soybean-wheat cropping systems. According to Levitt (1980) abiotic stress is, any change in environmental conditions that reduces or adversely affects plant growth and development.

Materials and Methods

Eight genetically diverse genotypes of wheat were selected on the basis of broad range of genetic and heat tolerance diversity for most important yield components from the germplasm maintained in All India Coordinated Wheat and Barley Improvement Project (AICW & BIP) at Rajasthan Agricultural Research Institute, Durgapura. These eight parental genotypes namely; HD 2864, MP 3336, Raj 3765, HD 2932, Raj 4238, Raj 3777, CG 1029 and HI 1634 were crossed in a half diallel fashion (without reciprocals) using hand emasculation.

In order to create heat stress condition at post anthesis, the sowing in the heat stress environment (E_2) was delayed by about 30 days later than the normal sowing (E_1) during *rabi* 2023-24. Thus, late sowing created post anthes is heats tress environment as it exposed the crop to heat stress after anthesis.

Heat susceptibility index (HSI)

Heat susceptibility index (HSI) was calculated for grain yield and other attributes by using the formula as suggested by Fischer and Maurer (1978).

$$HSI = \left[1 - \left(\frac{Y_D}{Y_P}\right)\right] / D$$

Where,

Y_D = Mean of the genotype in stress environment (E_2)

Y_P = Mean of the genotype undernon-stress environment (E_1)

D =Heat stress intensity

D = 1- [mean of all genotypes instress environment (E_2) / mean of all genotypes undernon-stress environment (E_1)]

The HSI values were used to characterize the relative tolerance of genotypes based on minimization of yield losses compared to normal environmental conditions.

Heat tolerance (TOL)

Rosielle and Hamblin (1981) defined heat tolerance (TOL) as the differences in yield between the heat stress (Y_D) and non-stress (Y_p) environment.

$TOL = Y_P - Y_D$

Where,

Y_P = Yield of a genotype under non-stress environment (E_1)

Y_D = Yield of a genotype under heat stress environment (E_2)

Results

The heat susceptibility index (HSI) measures the reduction in the performance of test genotypes under stress (heat stress) conditions and is used to identify heat-tolerant genotypes. The results of present study demonstrated reduction in the mean performance of parents and F_1's under heat stress (E_2) environment in comparison to normal sown environment (E_1) for all the

Table 1: Mean of all genotypes under normal (E_1) and heat stress environment (E_2) and heat stress intensity (D-value) for different characters.

Characters	Mean of all genotypes in		D-value
	E_1	E_2	
Days to 75% heading	94.31	87.07	0.08
Days to maturity	129.64	116.99	0.10
Flag leaf area (cm^2)	27.71	25.84	0.07
Effective tillers per plant	7.04	4.62	0.34
Grains per spike	45.31	42.67	0.06
1000-Grain weight(g)	48.70	40.84	0.16
Biological yield per plant (g)	54.45	40.88	0.25
Grain yield per plant (g)	23.33	17.64	0.24
Harvest index (%)	41.72	41.93	-0.01
Protein content (%)	11.03	10.93	0.01
Proline content (µg/ 100mg fresh weight)	65.36	75.37	-0.15
Total chlorophyll content (mg/g fresh weight)	1.87	1.64	0.12
Membrane stability index (%)	58.23	52.26	0.10

Table 2: Heat susceptibility index (HSI) for days to 75% heading, days to maturity, flag leaf area, effective tillers per plant, grains per spike, 1000-grain weight and biological yield per plant.

Parents	Days to 75% heading	Days to Maturity	Flag leaf area (cm^2)	Effective tillers per plant	Grains per spike	1000-Grain weight (g)	Biological yield per plant (g)
HD 2864	0.39	0.49	3.16	1.65	1.80	0.77	0.78
MP 3336	0.98	1.01	4.32	0.96	0.84	1.12	0.82
Raj 3765	0.88	0.32	-1.59	1.49	5.35	1.43	1.41
HD 2932	1.67	0.60	-3.40	1.18	1.82	0.06	0.32
Raj 4238	1.01	1.22	-2.53	1.66	1.85	1.93	0.29
Raj 3777	1.65	0.82	3.50	1.20	5.30	0.35	0.74
CG 1029	1.50	1.53	-4.07	1.51	1.65	0.48	0.97
HI 1634	0.87	1.11	-7.02	1.29	2.01	1.50	1.06
F_1 crosses							
HD 2864 x MP 3336	0.59	1.45	-0.05	0.98	1.32	0.97	0.70
HD 2864 x Raj 3765	1.53	0.91	1.64	0.98	1.39	1.52	0.59
HD 2864 x HD 2932	0.61	0.85	-3.59	0.93	0.32	0.81	1.12
HD 2864 x Raj 4238	1.00	0.93	2.35	1.38	0.38	1.57	1.25
HD 2864 x Raj 3777	0.53	0.99	0.09	0.93	0.71	1.19	0.79
HD 2864 x CG 1029	0.59	0.89	2.68	0.91	0.53	0.60	0.75
HD 2864 x HI 1634	0.05	0.75	1.90	1.13	0.88	1.31	0.49
MP 3336 x Raj 3765	0.69	0.94	4.14	0.72	2.89	1.21	1.42
MP 3336 x HD 2932	0.62	1.37	1.74	1.27	1.15	0.62	1.43
MP 3336 x Raj 4238	0.94	0.62	1.47	0.54	0.52	1.58	1.19
MP 3336 x Raj 3777	1.26	0.97	3.72	1.11	0.00	0.74	0.98
MP 3336 x CG 1029	1.54	1.09	2.81	1.03	1.68	1.36	0.66
MP 3336 x HI 1634	0.09	1.16	1.80	0.72	0.84	0.80	0.75
Raj 3765 x HD 2932	1.95	1.11	3.39	0.25	1.62	1.18	1.13
Raj 3765 x Raj 4238	0.04	1.08	0.11	0.48	1.10	1.39	1.19
Raj 3765 x Raj 3777	0.30	1.12	-0.97	1.04	0.46	0.64	1.10
Raj 3765 x CG 1029	1.31	0.94	-2.88	0.89	0.63	1.24	1.07
Raj 3765 x HI 1634	1.79	1.06	-0.09	0.39	0.71	1.65	1.21
HD 2932 x Raj 4238	0.86	1.05	5.21	0.81	2.21	1.30	1.15
HD 2932 x Raj 3777	1.38	0.90	-1.69	0.93	0.87	1.10	1.29
HD 2932 x CG 1029	1.11	1.18	3.57	0.99	1.14	0.45	1.27
HD 2932 x HI 1634	0.74	1.19	1.00	0.99	0.22	0.98	0.81
Raj 4238 x Raj 3777	0.35	0.98	-1.86	0.90	1.40	0.34	0.95
Raj 4238 x CG 1029	1.54	1.12	0.88	0.95	2.41	0.51	1.10
Raj 4238 x HI 1634	0.60	0.80	5.26	1.33	0.63	0.87	1.55
Raj 3777 x CG 1029	1.20	0.90	1.16	0.96	0.21	0.77	0.85
Raj 3777 x HI 1634	1.21	0.92	-2.28	0.87	0.02	1.16	1.01
CG 1029 x HI 1634	1.62	0.83	-0.66	1.23	0.07	0.82	1.07

characters except proline content. The heat susceptibility index was calculated for each character. On the basis of HSI, the parents and F_1's were classified into four different categories arbitrarily *i.e.* highly heat tolerant (HSI < 0.50), heat tolerant (HSI: 0.51-0.75), moderately heat tolerant (HSI: 0.76-1.00) and heat susceptible (HSI > 1.00) [Table 4.29- 4.30]. The genotypes with high positive HSI values are susceptible to higher temperature and *vice versa.*

On the basis of HSI, it appeared that the parents HD 2864 and HI 1634 for days to 75% heading; HD 2864, Raj 3765 and HD 2932 for days to maturity; Raj 3765, HD 2932, Raj 4238, CG 1029 and HI 1634 for flag leaf area; MP 3336 for effective tillers per plant; MP 3336 for grains per spike; HD 2932, Raj 3777 and CG 1029 for 1000-grain weight; HD 2932, Raj 4238 and Raj 3777 for biological yield per plant; Raj 4238 and CG 1029 for grain yield per plant: HD 2932, Raj 3777 and HI 1634 for harvest index; Raj 3765, Raj 3777, CG 1029 and HI 1634 for protein content; HD 2864 and Raj 4238 for proline content; HD 2932, Raj 4238 and CG 1029 for total chlorophyll content; HD 2864 and HI 1634 for membrane stability index were least affected under heat stress. An

Table 3: Heat susceptibility index (HSI) for grain yield per plant, harvest index, protein content, proline content, total chlorophyll content, and membrane stability index.

Parents	Grain yield per plant (g)	Harvest index (%)	Protein content (%)	Proline content (µg/100 mg fresh weight)	Total chlorophyll content (mg/g fresh weight)	Membrane stability index (%)
HD 2864	0.83	-7.97	1.83	0.39	0.73	0.78
MP 3336	1.12	-4.43	0.78	3.46	0.73	0.93
Raj 3765	1.29	-0.02	0.00	1.05	0.77	1.37
HD 2932	0.87	-11.34	0.77	1.92	0.48	0.88
Raj 4238	0.69	25.16	0.69	-0.06	0.00	1.08
Raj 3777	1.11	-11.43	0.45	1.25	0.77	0.90
CG 1029	0.45	17.78	0.09	5.02	0.70	0.99
HI 1634	1.36	-10.95	0.00	1.34	2.34	0.53
F_1 crosses						
HD 2864 x MP 3336	0.65	-0.13	0.64	0.73	1.99	1.40
HD 2864 x Raj 3765	0.85	-3.72	1.67	1.21	0.49	0.89
HD 2864 x HD 2932	1.25	-0.24	0.18	0.85	2.18	0.95
HD 2864 x Raj 4238	1.46	-5.15	0.56	1.85	0.61	1.31
HD 2864 x Raj 3777	1.02	-2.69	0.33	2.51	0.79	0.71
HD 2864 x CG 1029	1.01	-3.69	0.00	1.11	0.60	1.35
HD 2864 x HI 1634	1.14	-16.78	0.18	0.77	1.89	0.68
MP 3336 x Raj 4238	1.48	-10.9	0.17	0.40	0.65	1.23
MP 3336 x Raj 3777	0.73	6.63	-0.09	1.35	1.06	0.50
MP 3336 x CG 1029	1.09	-10.68	0.09	0.02	1.68	1.13
MP 3336 x HI 1634	0.43	10.99	0.80	2.96	1.55	0.98
Raj 3765 x HD 2932	1.06	5.21	-0.43	1.47	0.51	1.20
Raj 3765 x Raj 4238	1.07	12.36	2.73	1.20	0.19	0.72
Raj 3765 x Raj 3777	1.13	1.03	0.90	0.31	0.65	0.95
Raj 3765 x CG 1029	0.79	12.12	2.13	2.78	1.34	1.28
Raj 3765 x HI 1634	1.42	-1.82	1.32	2.33	0.87	0.80
HD 2932 x Raj 4238	0.99	6.19	0.52	1.01	0.98	1.39
HD 2932 x Raj 3777	0.95	15.85	1.76	2.99	0.54	0.98
HD 2932 x CG 1029	0.70	18.15	0.72	0.98	0.74	0.46
HD 2932 x HI 1634	1.29	-12.71	1.31	2.68	2.08	1.00
Raj 4238 x Raj 3777	0.58	17.13	2.08	2.55	0.80	1.28
Raj 4238 x CG 1029	0.82	9.05	0.18	0.60	0.77	0.57
Raj 4238 x HI 1634	1.25	10.25	3.18	2.86	0.68	0.69
Raj 3777 x CG 1029	0.86	-6.46	2.60	1.51	0.85	0.51
Raj 3777 x HI 1634	1.11	1.57	1.98	1.87	1.74	1.19
CG 1029 x HI 1634	0.95	-7.75	2.53	0.21	2.32	0.95
MP 3336 x Raj 3765	1.56	-6.12	2.17	0.33	1.31	0.58
MP 3336 x HD 2932	1.69	-15.13	0.18	0.85	0.36	0.63

overall assessment of parents indicated that HD 2864, Raj 3777, CG 1029 and HI 1634 were found to be desirable for grain yield and most of its attributes on the basis of heat susceptibility index (Table 4.29-4.30).

Perusal of heat susceptibility index (HSI) revealed that the crosses HD 2864 x MP 3336, MP 3336 x HI 1634 and Raj 4238 x Raj 3777 for days to 75% heading; HD 2864 x HI 1634 and MP 3336 x Raj 4238 for days to maturity; HD 2864 x HD 2932, HD 2864 x Raj 3777, Raj 3765 x Raj 4238 and Raj 3777 x HI 1634 for flag leaf area; Raj 3765 x HD 2932, Raj 3765 x Raj 4238 and Raj 3765 x HI 1634 for effective tillers per plant; HD 2864 x HD 2932, MP 3336 x Raj 3777, Raj 3777 x HI 1634, CG 1029 x HI 1634 and HD 2932 x HI 1634 for grains per spike; HD 2864 x CG 1029, Raj 4238 x Raj 3777 and Raj 4238 x CG 1029 for 1000-grain weight; HD 2864 x MP 3336, HD 2864 x Raj 3765 and MP 3336 x CG 1029 for biological yield per plant; HD 2864 x MP 3336, MP 3336

Table 4: Heat tolerance (TOL) for days to 75% heading, days to maturity, flag leaf area, effective tillers per plant, grains per spike, 1000-grain weight and biological yield per plant.

Parents	Days to 75% heading	Days to Maturity	Flag leaf area (cm^2)	Effective tillers per plant	Grains per spike	1000-Grain weight (g)	Biological yield per plant (g)
HD 2864	3.00	6.33	5.01	4.23	5.27	6.04	9.66
MP 3336	7.34	13.34	6.96	2.16	2.16	8.37	10.62
Raj 3765	6.67	4.00	-3.61	4.33	16.56	11.63	19.63
HD 2932	13.34	7.67	-5.49	2.80	4.23	0.47	3.81
Raj 4238	7.67	16.33	-5.28	4.13	4.17	16.36	3.17
Raj 3777	13.00	10.66	8.23	3.06	16.53	2.58	10.30
CG 1029	11.33	20.00	-6.83	3.27	3.76	3.61	11.76
HI 1634	6.66	15.00	-10.78	2.84	5.00	11.93	14.83
F_1 crosses							
HD 2864 x MP 3336	4.66	20.00	-0.08	2.23	3.47	7.80	9.21
HD 2864 x Raj 3765	12.00	12.00	2.87	2.33	-3.53	12.92	7.80
HD 2864 x HD 2932	4.67	11.33	-6.45	2.26	0.74	6.45	16.27
HD 2864 x Raj 4238	7.66	12.33	4.10	3.60	1.00	13.65	19.27
HD 2864 x Raj 3777	4.00	13.00	0.16	2.14	2.06	9.89	11.81
HD 2864 x CG 1029	4.67	12.00	4.20	2.20	1.57	4.39	10.75
HD 2864 x HI 1634	0.34	9.67	3.21	2.77	2.57	10.08	6.15
MP 3336 x Raj 3765	5.33	12.67	7.92	1.73	8.94	10.01	22.66
MP 3336 x HD 2932	5.00	18.66	3.21	3.30	3.33	5.29	20.94
MP 3336 x Raj 4238	7.34	8.00	2.96	1.34	1.50	14.07	16.67
MP 3336 x Raj 3777	10.00	13.00	9.17	2.80	0.00	6.22	13.21
MP 3336 x CG 1029	12.00	14.67	7.03	2.64	4.86	11.15	9.39
MP 3336 x HD 2932	5.00	18.66	3.21	3.30	3.33	5.29	20.94
Raj 3765 x HD 2932	15.67	15.00	7.86	0.64	4.73	9.78	17.41
Raj 3765 x Raj 4238	0.33	14.34	0.26	1.17	3.20	11.69	18.78
Raj 3765 x Raj 3777	2.34	15.00	-2.08	2.57	1.37	4.86	15.72
Raj 3765 x CG 1029	10.00	12.67	-5.70	2.30	1.80	9.53	14.78
Raj 3765 x HI 1634	14.33	14.34	-0.18	0.93	2.06	13.30	19.35
HD 2932 x Raj 4238	6.67	14.00	11.89	1.93	6.36	10.59	16.77
HD 2932 x Raj 3777	11.00	12.00	-3.11	2.34	2.40	8.95	19.99
HD 2932 x CG 1029	8.67	16.00	8.50	2.50	3.37	3.47	17.12
HD 2932 x HI 1634	5.67	16.00	2.01	2.50	0.66	7.90	11.08
Raj 4238 x Raj 3777	2.67	13.00	-3.38	2.16	4.03	2.52	14.11
Raj 4238 x CG 1029	12.00	15.33	1.81	2.40	6.74	3.92	14.94
Raj 4238 x HI 1634	4.67	10.67	12.05	3.30	1.60	7.30	25.04
Raj 3777 x CG 1029	9.33	12.34	2.79	2.44	0.57	6.10	11.51
Raj 3777 x HI 1634	9.34	12.34	-4.38	2.10	0.07	9.37	13.87
CG 1029 x HI 1634	12.67	11.00	-1.51	3.00	0.20	6.50	14.83

x HI 1634 and Raj 4238 x Raj 3777 for grain yield per plant: HD 2864 x HI 1634, MP 3336 x HD 2932 and HD 2932 x HI 1634 for harvest index; HD 2864 x HD 2932, HD 2864 x CG 1029, MP 3336 x CG 1029 and Raj 4238 x CG 1029 for protein content; MP 3336 x Raj 3765, MP 3336 x CG 1029 and CG 1029 x HI 1634 for proline content; HD 2864 x Raj 3765, MP 3336 x HD 2932 and Raj 3765 x Raj 4238 for total chlorophyll content; MP 3336 x Raj 3777 and HD 2932 x CG 1029 for membrane stability index exhibited comparatively more tolerance among 28 F_1's crosses under heat stress environment (Table 4.29 - 4.30).

On the basis of HSI the crosses *viz.*, HD 2864 x MP 3336, HD 2864 x Raj 3765, MP 3336 x Raj 3777, MP 3336 x HI 1634, Raj 3765 x CG 1029, HD 2932 x Raj 4238, HD 2932 x Raj 3777, HD 2932 x CG 1029, Raj 4238 x Raj 3777, Raj 4238 x CG 1029, Raj 3777 x CG 1029 and CG 1029 x HI 1634 showed the superiority under heat stress environment for grain yield and more than two characters.

Table 5: Heat tolerance TOL) for grain yield per plant, harvest index, protein content, proline content, total chlorophyll content, and membrane stability.

Parents	Grain yield per plant (g)	Harvest index (%)	Protein content (%)	Proline content (µg/100 mg fresh weight)	Total chlorophyll content (mg/g fresh weight)	Membrane stability index (%)
HD 2864	4.37	3.51	0.21	-5.91	0.17	4.67
MP 3336	5.68	1.80	0.08	-29.23	0.14	6.08
Raj 3765	7.99	0.01	0.00	-10.11	0.09	8.39
HD 2932	3.99	4.60	0.09	24.52	0.10	4.57
Raj 4238	3.30	-9.25	0.08	0.67	0.00	7.22
Raj 3777	6.67	5.11	0.05	18.67	0.22	5.05
CG 1029	2.10	-7.19	-0.01	-36.68	0.08	6.09
HI 1634	7.49	4.48	0.00	-12.86	0.53	3.54
F_1 crosses						
HD 2864 x MP 3336	3.16	0.05	0.07	-10.57	0.56	8.70
HD 2864 x Raj 3765	5.01	1.73	0.19	-11.53	0.08	6.07
HD 2864 x HD 2932	7.92	0.11	0.02	-7.80	0.75	6.62
HD 2864 x Raj 4238	9.98	2.37	-0.06	26.76	0.14	8.54
HD 2864 x Raj 3777	6.31	1.15	0.04	-31.04	0.28	4.08
HD 2864 x CG 1029	6.46	1.71	0.00	-16.74	0.22	8.54
HD 2864 x HI 1634	5.85	7.16	-0.02	-9.43	0.22	4.21
MP 3336 x Raj 3765	10.60	2.73	0.25	-4.78	0.22	3.63
MP 3336 x HD 2932	10.44	6.71	-0.02	-5.93	0.10	4.11
MP 3336 x Raj 4238	9.31	5.12	0.02	-3.65	0.10	7.21
MP 3336 x Raj 3777	4.10	-2.90	-0.01	-14.06	0.20	2.31
MP 3336 x CG 1029	6.56	4.72	0.01	-0.13	0.59	6.66
MP 3336 x HI 1634	2.36	-4.78	0.09	-31.07	0.32	6.41
Raj 3765 x HD 2932	6.64	-2.21	-0.05	-13.08	0.06	7.60
Raj 3765 x Raj 4238	6.58	-5.03	0.34	-11.39	0.02	3.53
Raj 3765 x Raj 3777	6.71	-0.45	0.10	-3.61	0.15	5.90
Raj 3765 x CG 1029	4.21	-4.92	0.25	-25.57	0.43	7.29
Raj 3765 x HI 1634	9.12	0.76	0.16	-13.52	0.27	4.04
HD 2932 x Raj 4238	6.02	-2.69	0.06	-10.18	0.15	9.47
HD 2932 x Raj 3777	5.67	-6.38	0.19	-17.17	0.10	6.01
HD 2932 x CG 1029	3.69	-7.40	0.08	-5.97	0.24	2.14
HD 2932 x HI 1634	7.66	5.77	0.14	-28.01	0.72	5.09
Raj 4238 x Raj 3777	3.37	-6.99	0.24	-16.19	0.17	8.00
Raj 4238 x CG 1029	4.54	-3.85	0.02	-4.42	0.13	3.32
Raj 4238 x HI 1634	7.84	-4.16	0.35	-21.82	0.24	4.45
Raj 3777 x CG 1029	4.64	2.72	0.31	-14.58	0.24	2.63
Raj 3777 x HI 1634	6.26	-0.67	0.22	-18.80	0.39	7.53
CG 1029 x HI 1634	5.62	3.50	0.30	1.84	0.53	5.66

The magnitudes of heat stress intensity (D-value) are presented in Table 4.31. Low value of heat stress intensity (D-value) *i.e.* less than 0.20, indicated that the parameters *viz.*, days to 75% heading (0.08), days to maturity (0.10), flag leaf area (0.07), grains per spike (0.06), 1000-grain weight (0.16), harvest index (-0.01), protein content (0.01), proline content (-0.15), total chlorophyll content (0.12) and membrane stability index (0.10) showed more tolerance whereas effective tillers per plant (0.34), biological yield per plant (0.25), and grain yield per plant (0.24) with high heat stress intensity (D-value) *i.e.* 0.21 to 0.35, suffered more under heat stress environment (E_2).

Heat tolerance (TOL)

Heat tolerance indices were calculated for each character. The greater TOL value indicated larger yield reduction under heat stress conditions and the higher heat sensitivity. Therefore, a smaller value of TOL indices is

Table 6: Heat susceptibility index and heat tolerance of significant heterobeltiotic crosses for grain yield per plant under normal (E_1) and heat stress environment (E_2).

Ens.	Crosses	HSI	TOL
E_1	HD 2864 x HD 2932	1.25	7.92
	HD 2864 x Raj 4238	1.46	9.98
	HD 2864 x CG 1029	1.01	6.46
	MP 3336 x HD 2932	1.69	10.44
	MP 3336 x Raj 4238	1.48	9.31
	MP 3336 x CG 1029	1.09	6.56
	HD 2932 x Raj 4238	0.99	6.02
	Raj 4238 x HI 1634	1.25	7.84
E_2	HD 2864 x Raj 3765	0.85	5.01
	HD 2864 x CG 1029	1.01	6.46
	MP 3336 x HI 1634	0.43	2.36
	Raj 4238 x Raj 3777	0.58	3.37

favoured.

On the basis of TOL, it appeared that the parents HD 2864, HI 1634 and Raj 3765 for days to 75% heading; Raj 3765, HD 2864 and HD 2932 for days to maturity; HI 1634, CG 1029 and HD 2932 for flag leaf area; MP 3336, HD 2932 and Raj 3777 for effective tillers per plant; MP 3336, CG 1029 and Raj 4238 for grains per spike; HD 2932, Raj 3777 and CG 1029 for 1000-grain weight; Raj 4238, HD 2932 and HD 2864 for biological yield per plant; CG 1029, Raj 4238 and HD 2864 for grain yield per plant: Raj 4238, CG 1029 and Raj 3765 for harvest index; CG 1029, Raj 3765, and HI 1634 for protein content; CG 1029, MP 3336 and HI 1634 for proline content; Raj 4238, CG 1029 and Raj 3765 for total chlorophyll content; HI 1634, HD 2932 and HD 2864 for membrane stability index were least affected under heat stress. An overall assessment of parents indicated that HD 2864, HD 2932, Raj 4238, Raj 3765 and CG 1029 were found to be desirable for grain yield and most of its attributes on the basis of heat tolerance (Table 4.32-4.33).

Perusal of heat tolerance (TOL) revealed that the crosses HD 2864 x HI 1634, MP 3336 x HI 1634 and Raj 3765 x Raj 4238 for days to 75% heading; HD 2864 x HI 1634, MP 3336 x Raj 4238 and Raj 4238 x HI 1634 for days to maturity; HD 2864 x HD 2932, Raj 3765 x CG 1029 and Raj 3777 x HI 1634 for flag leaf area; Raj 3765 x HD 2932, Raj 3765 x Raj 4238 and Raj 3765 x HI 1634 for effective tillers per plant; HD 2864 x Raj 3765, MP 3336 x Raj 3777 and Raj 3777 x HI 1634 for grains per spike; HD 2932 x CG 1029, Raj 4238 x Raj 3777 and Raj 4238 x CG 1029 for 1000-grain weight; HD 2864 x MP 3336, HD 2864 x Raj 3765 and HD 2864 x HI 1634 for biological yield per plant; HD 2864 x MP 3336, MP 3336 x HI 1634 and Raj 4238 x Raj 3777 for grain yield per plant: HD 2932 x Raj 3777, HD 2932 x CG 1029 and Raj 4238 x Raj 3777 for harvest index; HD 2864 x Raj 4238, MP 3336 x HD 2932 and Raj 3765 x HD 2932 for protein content; MP 3336 x HI 1634, Raj 3765 x CG 1029 and HD 2932 x HI 1634 for proline content; HD 2864 x Raj 3765, Raj 3765 x HD 2932 and Raj 3765 x Raj 4238 for total chlorophyll content; MP 3336 x Raj 3777, HD 2932 x CG 1029 and Raj 3777 x CG 1029 for membrane stability index exhibited comparatively more tolerance among 28 F_1's crosses under heat stress environment (Table 4.32-4.33).

On the basis of heat tolerance (TOL) the crosses *viz.*, HD 2864 x MP 3336, MP 3336 x Raj 3777, MP 3336 x HI 1634, Raj 3765 x CG 1029, HD 2932 x CG 1029, Raj 4238 x Raj 3777, Raj 4238 x CG 1029 and Raj 3777 x CG 1029 showed the superiority under heat stress environment for grain yield and more than two characters.

Discussion

Heat stress is a common abiotic factor responsible for reducing yield and there is a necessity to identify heat stress tolerant genotypes. Heat stress during post-anthesis or grain-filling stage affects availability and translocation of photosynthates to the developing kernels and starch synthesis and deposition with in the kernel, consequently resulting in lower grain weight and altered grain quality (Mohammadi *et al.*, 2004). Heat stress is a key task to wheat productivity in India. The effect of climate change is clearly evident from recent vagaries across areas in India. Therefore; breeding aimed at selecting genotypes with high temperature stress tolerance is one of the most vital objectives of the wheat breeder.

Keeping the above facts in view, the current study was conducted to magnify the yield level of wheat in high temperature areas by selecting stress tolerant parents and cross combinations for future breeding programme.

The results of current study confirmed that in comparison to normal sown condition (E_1), mean performance of parents and F_1's declined under late sown or heat stress condition (E_2) for all the characters except proline content. It is fairly accepted that yield is a complex character and a final product of the action and interaction of a number of component characters. Thus, selection based on yield *per se* will not be much effective. Therefore, in order to determine the tolerance of different parents and crosses for heat stress, the heat susceptibility index and heat tolerance indices were estimated based upon the values and direction of desirability of different characters used in the study. The genotypes with high positive HSI values are susceptible to higher temperature and *vice versa*. On the basis of HSI, the parents and

F_1's were classified into four different categories *i.e.*, highly heat tolerant (HSI < 0.50), heat tolerant (HSI: 0.51-0.75), moderately heat tolerant (HSI: 0.761.00) and heat susceptible (HSI > 1.00).

Perusal of Table 5.5 revealed that among crosses namely, HD 2932 x Raj 4238 in E_1 and HD 2864 x Raj 3765, MP 3336 x HI 1634 and Raj 4238 x Raj 3777 in E_2 environment showed the superiority under heat stress environment for grain yield and more than two characters on the basis of heat susceptibility index and heat tolerance.

Low value of heat stress intensity (D-value) *i.e.* less than 0.20, indicated that the parameters *viz.,* days to 75% heading (0.08), days to maturity (0.10), flag leaf area (0.07), grains per spike (0.06),1000-grain weight (0.16), harvest index (-0.01), protein content (0.01), proline content (-0.15), total chlorophyll content (0.12) and membrane stability index (0.10) showed more tolerance whereas effective tillers per plant (0.34), biological yield per plant (0.25), and grain yield per plant (0.24) with high heat stress intensity (D-value) *i.e.* 0.21 to 0.35, suffered more under heat stress environment (E_2). Similar results were also observed by Hossain *et al.,* (2013), Ramani *et al.,* (2014), Choudhary (2018) and Kumar *et al*., (2018b).

Conclusion

The assessment of heat susceptibility index and heat tolerance indicated that among the crosses, HD 2932 x Raj 4238, HD 2864 x Raj 3765, MP 3336 x HI 1634 and Raj 4238 x Raj 3777 were most desirable for heat stress tolerance.

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