Academia Journal of Agricultural Research 3(3): 000-000, March 2019
DOI: 10.15413/ajar.2019.0401
ISSN: 2315-7739

Research Paper

Growth, yield and physiological response of wheat cultivars to terminal heat stress in north-west India

Accepted 6th March, 2019

ABSTRACT

Terminal heat, that is, an abrupt rise in temperature during grain filling stage in wheat adversely affects wheat yield in north-west India. A field experiment was conducted with six wheat (*Triticum aestivum* L.) cultivars to examine the effect of terminal heat stress on growth, yield and yield attributing characters. Irrespective of cultivars, heat stress, which pronounced with late (December, 15th) and very late (January, 15th) sowing, registered significant reduction in grain yield (20 and 50%) owing to maximum reduction in number of grains per spike (18 and 45%) followed by biological yield (20 and 40%), leaf area index (17 and 29%), 1000 grain weight (6 and 26%) and harvest index (2 and 19%). However, number of spikes per m^2 was enhanced by 5 and 11% of one and two months late sowing, respectively. One month delay from normal date of sowing (November, 15th) caused reduction in mean days to flowering, grain filling duration and days to maturity by 10, 10 and 20 days and for two months delay in sowing shortened the respective durations by 25, 15 and 40 days. Late (30 days) and very late (60 days) sown crop manifested around 1.7 and 2.6 times higher biomass, respectively than that of normal sown crop at 50 days after sowing which was also accompanied with greater leaf area index, specific leaf weight and early flowering and maturity. Among the cultivars, the high yielding semi-tall cultivars failed to exhibit significant difference in their grain as well as, biological yield, whereas the traditional tall cultivar C 306 manifested significantly lower grain yield and higher biomass under normal and late sown conditions as well. In general, long duration cultivars proved to be better under normal date of sowing, while medium and short-duration cultivars performed well under late and very late sown condition, respectively. Grain yield reduced at 40 and 50 kg ha^{-1} day^{-1} under one and two months delay of sowing, respectively. The number of grains m^{-2} and yield reduced drastically with increase in mean temperature during crop growing season and early exposure to heat stress under late sown condition. Thermal duration varied with cultivars, but least affected by different dates of sowing. Both the irradiance and mean temperature during crop growing period was markedly enhanced with delayed sowing.

S.D. Singh* and A. Yadav

Center for Environment Science and Climate Resilient Agriculture, Indian Agricultural Research Institute, New Delhi 110 012, India.

*Corresponding author. E-mail:

Key words: Terminal heat, harvest index, spike, specific leaf weight, leaf weight ratio, wheat.

INTRODUCTION

Wheat (*Triticum aestivum* L.) crop is generally grown in India during winter-spring season (mid-November to mid-April) after the harvesting of kharif (July to October) crops. Thus, delay in monsoon and subsequently delay in the harvesting of kharif crops such as rice forces wheat to be sown late until middle of January. As a result the reproductive (spike initiation to anthesis) and ripening (anthesis to maturity) growth phases of late sown wheat crops are generally exposed to hyper thermal stress during March to April.

This terminal heat stress reduces the growth and yield of wheat crop mainly by shortening the reproductive and ripening growth phases (Nagarajan, 2002), enforced leaf and spike senescence (Lobell et al., 2012), reduced the number of shoots per plant and per unit land area and number of grains per spike, and 1000 grain weight (Singh et al., 2003; Zacharias et al., 2010) without showing adverse effect on grain growth rate and harvest index (Nagarajan, 2002; Singh et al., 2003). Besides, the late sown crop receives less photosynthetically active radiation (PAR) than its early sown counterparts resulting in significant reduction of biomass and grain yield (Penelia et al., 1993). The grain filling duration is relatively more affected than the period from sowing to anthesis and occasionally the crop is prematurely ripened (Al-Khatib and Paulsen, 1984).

Several researchers Nagarajan (2002), Singh et al. (2003) and Lobell et al. (2012) reported adverse effect of hyper thermal stress on growth, yield and yield attributes of wheat cultivars mainly through changes in their physiological and biochemical characters.

The present study aimed to assess the effect of heat stress caused by late sowing (30 and 60 days) on growth, yield and yield attributes of wheat cultivars in order to identify some morpho-physiological traits associated with growth and productivity under higher thermal regimes for development of promising wheat cultivar for late sown conditions of northwest India.

MATERIALS AND METHODS

Field experiments were conducted with six wheat (*Triticum aestivum* L) cultivars namely C 306 (traditional tall), HD 2285, HD 2329, Kundan, HD 2643 and PBW 343 (modern semi-tall) under three dates of sowing: D1 (November, 15th: normal date of sowing), D2 (December, 15th: 30 days delayed from D1) and D3 (January, 15th: 60 days delayed from D1) during Rabi season of 2009 to 2010 at the experimental farm of Indian Agricultural Research Institute, New Delhi. Seeds were sown at 20 × 10 cm distance using dibbler in field pre-fertilized with 25% of total dose of N (120 kg ha^{-1}) and full doses of P and K (60 and 40 kg ha^{-1}, respectively). The remaining 75% of nitrogen was applied in two splits at crown root stage (50%) and maximum tillering stage (25%). The experiment was conducted in split plot design with three replications. Various growth characters such as height, leaf area index (LAI), leaf area/shoot, specific leaf area (SLA), specific leaf weight (SLW), leaf weight ratio (LWR) and crop growth rate (CGR) were measured at vegetative growth stage (50 days after sowing) and flowering, and yield and yield attributes namely number of spikes per m^2, number of grains per spike, 1000 grain weight and harvest index recorded at maturity using the formulas:

Leaf area index (LAI) = Leaf area /Ground area (1)

Specific leaf area (SLA, cm^2 g^{-1}) =Leaf area/Leaf weight (2)

Specific leaf weight (SLW, mg cm^{-2}) = Leaf weight/Leaf area (3)

Crop growth rate (CGR, g m^{-2} day^{-1}) = (W_2-W_1)/(Ground area)(t_2-t_1) (4)

Thermal sensitivity index (TSI) = (1- Stress/Normal) × 100 (5)

RESULTS AND DISCUSSION

Wheat crop exposed to medium and high thermal stresses owing to late (December, 15th) and very late sowing (January, 15th), respectively registered higher growth (biomass) at vegetative growth stage (50 days after sowing) (Table 1), however, it showed significant reduction at flowering stage (Table 2). Higher biomass of wheat plants recorded at 50 days after sowing under late and very late sown conditions might be due to conducive temperature and clean-longer sunshine hours during middle January to first week of March as compared to low temperature and foggy weather during middle December to January which coincide with vegetative growth phase of normal date of sowing (November, 15th).

The extent of reduction in growth, yield and their associated characters pronounced with the intensity of thermal stress occurred with late sowing. The days of maturity decreased in comparison to the normal sowing date (D1) as date of sowing delayed (Figures 1 and 2). It may be attributed to the lesser time available for photosynthesis and other physiological activities of the plants. Irradiance per hour increased as date of sowing delayed and it reduced the biological activities as well as, grain yield significantly for all the wheat cultivars for the cropping season 2009 to 2010 (Figure 4). Delay in sowing by one month (D1) and two months (D2) reduced the height of plant by 13 and 22%, leaf area/shoot by 20 and 32%, leaf area index by 18 and 21%, specific leaf area by 2 and 3 %, stem weight ratio by 11 and 15%, biomass by 19 and 34% and days to anthesis by 8 and 25 days, respectively. Longer growth duration of wheat crop under normal date of sowing (D1) provided an opportunity to accumulate more biomass as compared to late sowing and hence, manifested higher grain and biological yields.

Table 1: Effect of late sowing on growth characters of wheat cultivars at vegetative growth stage (50 days after sowing).

Cultivar/ Sowing date	Plant height (cm)	No. of shoots m^{-2}	Leaf area /shoot (cm^2)	Leaf area index	Specific leaf wt. (mg cm^{-2})	Specific leaf area (cm^2 g^{-1})	Leaf weight ratio	Stem weight ratio	Biomass (g m^{-2})
November 15th									
C 306	53	478	44	2.81	3.20	316	0.33	0.30	127
HD 2285	54	420	49	2.10	2.80	361	0.32	0.36	90
HD 2329	46	395	40	1.60	3.20	315	0.35	0.33	76
Kundan	44	483	61	2.95	2.40	415	0.42	0.30	102
HD 2643	44	450	43	1.94	2.75	363	0.47	0.30	76
PBW 343	35	450	35	1.56	3.25	310	0.45	0.31	74
Mean	46	446	45	2.16	2.93	347	0.39	0.32	91
December 15th									
C 306	64	518	57	2.95	3.57	280	0.52	0.48	204
HD 2285	58	494	40	2.35	3.50	286	0.53	0.47	154
HD 2329	54	656	38	2.54	3.62	276	0.58	0.42	158
Kundan	53	525	43	2.30	3.83	260	0.57	0.39	145
HD 2643	42	562	36	2.04	3.73	268	0.62	0.38	122
PBW 343	45	625	34	2.11	3.70	270	0.60	0.40	131
Mean	53	563	41	2.38	3.67	273	0.57	0.42	152
Effect (%)	+15	+26	-9	+10	+25	-21	+46	+31	+67
January 15th									
C 306	64	625	61	3.83	4.33	230	0.53	0.47	311
HD 2285	65	545	46	3.50	4.22	237	0.48	0.62	277
HD 2329	50	662	48	3.20	3.87	258	0.47	0.53	261
Kundan	60	562	57	3.21	3.91	255	0.50	0.50	251
HD 2643	46	500	42	3.08	4.61	216	0.61	0.39	159
PBW 343	42	588	39	2.91	5.20	192	0.63	0.36	157
Mean	54	580	49	3.28	4.35	231	0.54	0.48	236
Effect (%)	+17	+30	+8	+52	+48	-34	+38	+50	+160
LSD at 5%									
Cultivar (C)	8	125	8	0.60	0.50	45	0.04	NS	25
Sowing date (D)	6	45	10	0.50	0.60	35	0.06	0.06	65
C × D	10	156	13	0.70	0.70	54	0.10	0.08	110

Terminal heat stress during anthesis and grain filling period accelerates maturity and significantly reduces grain size and weight (Kosima et al., 2007). Exposure of crop to higher than optimal temperatures reduces the yield and decreases the quality of cereals (Fokar et al., 1998; Maestri et al., 2002). This may be attributed to the early arrival of heat stress in the late sown varieties as compared to the sowing at the optimum time of wheat cultivars (15th November). The heat stress temperature (>34°C) was attained on the 87th, 79th and 48th day for D1, D2 and D3, respectively. The arrival of heat stress for second and third sown wheat crops was earlier by 8 and 39 days than that of normal date of sowing, which reduced the biological grain yield significantly.

The enhanced number of shoots/m^2 by 5 and 8% at flowering under late and very late sown conditions respectively may be attributed to the conducive temperature to grow in the rizosphere (Table 2). Reduction in growth of wheat cultivars by late sowing was mainly due to marked reduction in their growth duration (days to flowering and maturity) owing to relatively higher thermal regime that prevailed during the critical growth stages (Table 1). Lower biomass production of wheat cultivars at flowering under late sown condition was probably due to significant reduction in photosynthetic efficiency owing to decrease in photosynthetic surface, that is, leaf area/shoot,

Table 2: Effect of heat stress on growth characters of wheat cultivars at flowering.

Cultivar/ Sowing date	Plant height (cm)	Number of shoots m-2	Leaf area /shoot (cm2)	Leaf area index	Specific leaf wt. (mg cm-2)	Specific leaf area (cm2 g-1)	Leaf weight ratio	Stem weight ratio	Biomass (g m-2)
November 15th									
C 306	125	375	100	3.8	4.4	227	0.21	0.61	880
HD 2285	90	412	94	3.9	3.9	263	0.21	0.55	691
HD 2329	85	400	82	3.3	3.3	233	0.24	0.52	641
Kundan	95	450	87	3.9	4.5	187	0.24	0.54	858
HD 2643	95	395	115	4.5	3.9	238	0.24	0.53	786
PBW 343	90	425	92	4.0	4.0	218	0.20	0.56	919
Mean	97	410	95	3.9	4.0	228	0.22	0.55	796
December 15th									
C 306	110	425	85	3.2	4.7	212	0.20	0.58	771
HD 2285	85	506	71	3.6	4.3	234	0.24	0.48	618
HD 2329	75	456	70	3.2	4.5	223	0.27	0.48	565
Kundan	78	412	74	3.0	4.8	209	0.29	0.44	621
HD 2643	85	420	85	3.6	4.2	240	0.28	0.48	652
PBW 343	78	375	72	2.7	4.5	218	0.25	0.49	660
Mean	85	432	76	3.2	4.5	223	0.26	0.49	648
Effect (%)	-13	+5	-20	-18	+12	-2	+18	-11	-19
January 15th									
C 306	90	450	75	3.0	4.1	242	0.23	0.52	690
HD 2285	75	488	55	2.7	4.2	242	0.20	0.47	494
HD 2329	70	475	64	2.7	4.2	237	0.20	0.45	490
Kundan	75	425	60	2.5	5.5	181	0.24	0.45	534
HD 2643	78	431	70	3.0	4.7	214	0.20	0.49	536
PBW 343	70	406	67	2.8	4.7	213	0.21	0.46	430
Mean	76	446	65	3.1	4.6	222	0.22	0.47	529
Effect (%)	-22	+8	-32	-21	+15	-3	0	-15	-34
LSD at 5%									
Cultivar (C)	15	54	15	0.5	0.4	25	0.04	0.05	92
Sowing date (D)	10	25	20	0.4	0.3	NS	NS	0.03	102
C × D	18	145	30	0.6	0.8	32	0.05	0.6	125

leaf area index, days to flowering and maturity (Tables 2 and 3). This might also be attributed to marked reduction in the light exposure duration of crop plants owing to shortening of crop growth duration under late sown condition (Penelia et al., 1993).

All the cultivars, irrespective of their growth duration and stature, showed marked phenological response to varying dates of sowing. Regardless of varietal variation, the duration of developmental phases (sowing to anthesis, anthesis to maturity and sowing to maturity) were drastically reduced under late sown condition (Table 2). Delay of sowing by one month (D2) reduced the mean crop duration from sowing to anthesis and anthesis to maturity by 8 days each, and sowing to maturity by 16 days, while delay of sowing by two months (D3) shortened the duration of same developmental phases by 24, 16 and total of 40 days, respectively. In other words, sowing delayed by 30 days delayed the maturity of crop by 16 days, while delay in sowing by 60 days delayed the crop maturity only by 20 days as compared to normal date of sowing; thereby, resulting in delay of maturity only by 4 days with delay of sowing by 30 days after second date of sowing. This indicated the possibility of harsh heat stress under extreme delay of sowing. The extent of reduction in developmental

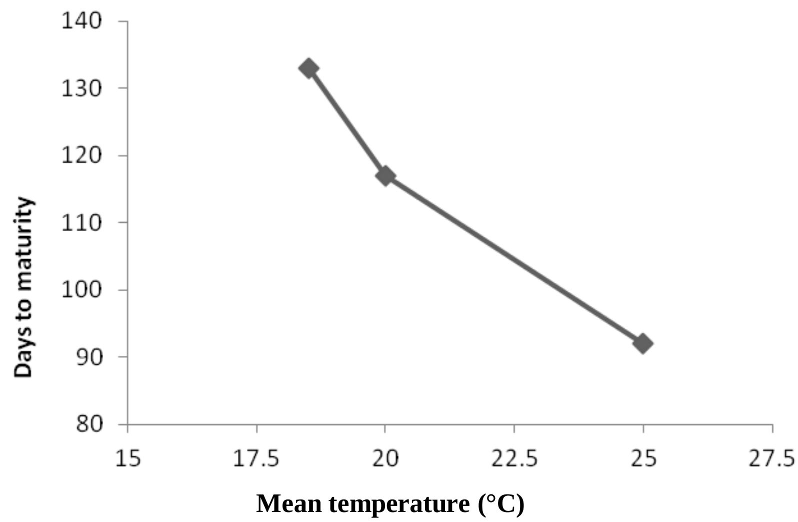

Figure 1: Days to maturity and mean temperature.

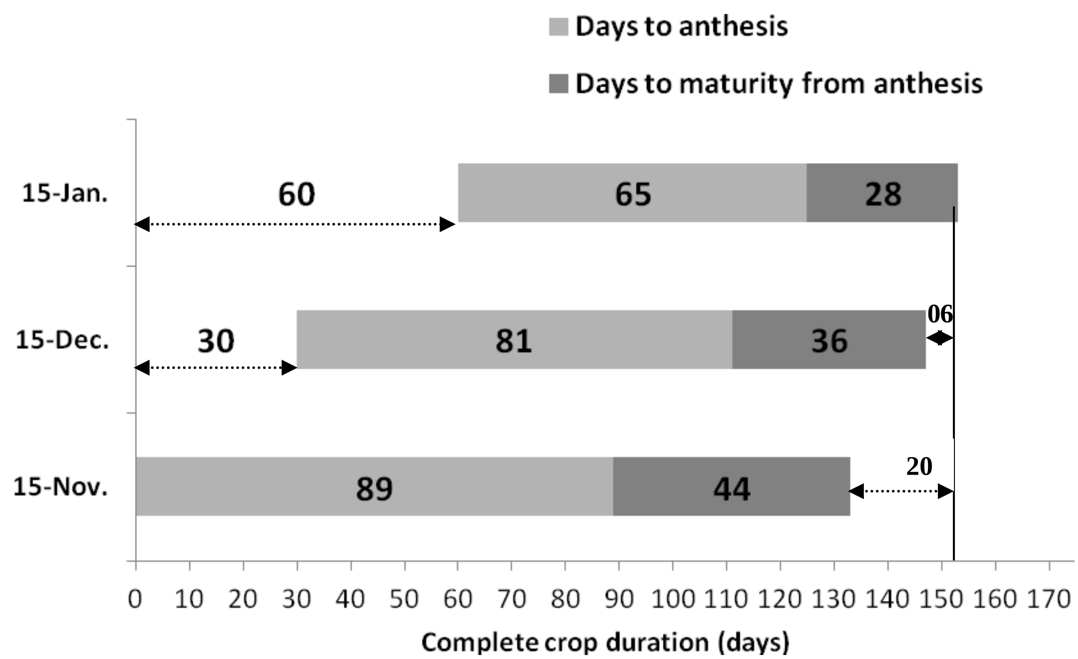

Figure 2: Effect of delayed sowing on growth phase and complete crop duration.

phases by two months late sowing (D3) was more than double to that of one month late sowing (D2). Several researchers Nagarajan (2002) and Singh et al. (2003) reported significant reduction in developmental phases of wheat crop under higher thermal regime due to late sowing.

Regardless of stature and growth duration of cultivars, delay in sowing by one and two months caused significant reduction in biological yield (21 and 42%) which accounted for significant reduction in grain yield (20 and 50%) and straw yield (22 and 36%) (Table 3). The extent of reduction in grain and straw yields was almost at par (20 and 22%) under one month delayed sowing (D2), while under extreme late sowing (D3) the magnitude of reduction was higher in grain yield (50%) than in straw yield (36%) which indicates greater thermal sensitivity of reproductive shoot (spikes) as compared to vegetative shoots (stem, leaves). Thus, further delay of sowing caused greater vulnerability in grain yield than in straw yield of wheat crop (Table 3).

Significant reduction of grain yield under D2 (20%) and D3 (50%) condition was mainly attributed to marked reduction in days to anthesis (8 and 25 days) and maturity (16 and 41 days) which in turn caused marked reduction in

Table 3: Effect of heat stress on yield and yield attributes of wheat cultivars at maturity.

Cultivar/ Sowing date	Days to anthesis (days)	Anthesis to maturity (days)	Days to maturity (days)	No. of spikes m^{-2}	No. of grains/ spike	1000 grain wt. (g)	Grain yield ($g\ m^{-2}$)	Straw yield ($g\ m^{-2}$)	Biol. yield ($g\ m^{-2}$)	Harvest Index (%)	Pre-anthesis dry matter production (%)	Post-anthesis dry matter production (%)
November 15th												
C 306	85	45	130	360	40	45.8	533	990	1523	35	58	42
HD 2285	80	45	125	390	42	42.1	610	810	1420	43	48	52
HD 2329	85	45	130	417	43	40.0	625	765	1390	45	46	54
Kundan	85	50	135	350	37	54.1	651	900	1550	42	55	45
HD 2643	100	40	140	370	39	49.0	630	820	1450	43	54	46
PBW 343	100	40	140	433	42	38.2	675	870	1542	44	59	41
Mean	89	44	133	387	41	44.8	620	860	1480	42	53	47
December 15th												
C 306	80	35	115	408	32	42.0	437	877	1314	33	58	42
HD 2285	75	35	110	426	36	40.7	500	625	1125	44	56	44
HD 2329	80	35	115	398	37	40.5	525	611	1136	46	57	43
Kundan	80	40	120	370	30	51.6	520	630	1150	45	53	47
HD 2643	85	35	120	388	30	42.1	515	650	1165	44	55	45
PBW 343	85	35	120	410	32	33.3	508	617	1125	45	54	46
Mean	81	36	117	396	34	41.7	501	668	1169	43	55	45
Effect (%)	-9	-18	-12	+2	-18	-7	-20	-2	-21	+2	+3	-4
January 15th												
C 306	60	30	90	415	24	36.5	322	636	958	34	67	33
HD 2285	60	30	90	400	26	37.0	340	511	851	40	63	37
HD 2329	65	25	90	430	25	34.8	330	495	825	40	69	31
Kundan	65	30	95	402	20	43.3	290	528	818	35	70	30
HD 2643	70	25	95	362	27	27.3	295	517	812	36	72	28
PBW 343	70	25	95	438	31	24.0	280	628	908	31	67	33
Mean	65	28	93	408	26	33.8	310	552	862	36	68	32
Effect (%)	-27	-36	-31	+5	-37	-25	-50	-36	-42	-14	+28	-32
LSD at 5%												
Cultivar (C)	5	NS	NS	45	8	13	52	65	115	4	5	4
Sowing date (D)	8	8	12	NS	12	6	68	79	170	5	8	5
C × D	12	10	15	38	18	28	115	140	215	6	9	6

Table 4: Effect of heat stress on yield associated characters of wheat cultivars.

Cultivar/ Sowing date	Grain weight/ shoot (g)	Dry wt./ Shoot (g)	Grain growth rate (gm^{-2} d^{-1})	Grain growth rate (mg/ ear d^{-1})	Crop growth rate (S - M) (gm^{-2} d^{-1})	Thermal duration (S – F) (°days)	Thermal duration (F – M) (°days)	Thermal duration (S – M) (°days)
November 15th								
C 306	1.48	4.23	11.8	33	12.5	946	762	1708
HD 2285	1.56	3.64	13.5	35	11.4	880	750	1630
HD 2329	1.50	3.33	13.8	33	10.7	946	762	1708
Kundan	1.86	5.17	13.0	43	11.5	946	840	1786
HD 2643	1.70	3.92	15.7	43	10.4	1166	822	1988
PBW 343	1.56	3.56	16.8	39	11.0	1166	822	1988
Mean	1.61	3.91	14.0	37	11.2	1008	793	1801
December 15th								
C 306	1.07	3.22	12.5	31	12.3	790	753	1543
HD 2285	1.17	2.64	14.3	34	10.2	706	750	1456
HD 2329	1.32	2.85	14.9	37	10.0	888	790	1678
Kundan	1.40	3.10	12.9	35	9.6	888	890	1778
HD 2643	1.33	3.00	14.7	38	9.7	1000	794	1794
PBW 343	1.24	2.88	14.5	37	9.4	1000	794	1794
Mean	1.25	2.95	13.9	35	10.2	878	795	1674
Effect (%)	-23	-25	-1	-6	-9	-13	0	-8
January 15th								
C 306	0.78	2.30	10.7	25	12.1	913	693	1606
HD 2285	0.85	2.13	11.3	28	9.5	913	693	1606
HD 2329	0.77	1.92	13.2	31	9.2	1000	620	1620
Kundan	0.72	2.03	9.7	22	8.6	1000	716	1716
HD 2643	0.81	2.24	11.8	32	8.5	1152	581	1733
PBW 343	0.64	2.07	11.2	26	10.4	1152	581	1733
Mean	0.76	2.11	11.3	27	9.7	1022	648	1670
Effect (%)	-53	-46	-20	-27	-13	+1	-18	-8
LSD at 5%								
Cultivar (C)	0.6	0.5	2.5	10	2.5	105	85	125
Sowing date(D)	0.7	0.6	1.5	8	NS	NS	75	85
C × D	1.2	0.8	3.4	14	3.2	126	145	175

S-M (sowing to maturity); S-A (sowing to anthesis); A-M (anthesis to maturity).

leaf area index (18 and 21%), number of grains/spike (18 and 37%) and 1000 grain weight (7 and 25%). However, number of spikes per m^2 and harvest index was least affected traits by late and very late sowing (Tables 2 and 3). Total grain weight and dry weight/shoot was reduced by 23 and 25%, respectively under D2 and 53 and 460%, respectively under D3 condition. All these may be attributed to the sensitivity of both photosynthetic activity and surface as it is highly sensitive to elevated temperature, and any reduction in this may affect growth and productivity of wheat crop (Wahid et al., 2007; Al-Khatib and Paulsen, 1990, 1999).

Heat stress also reduces photosynthesis through disruption in the structure and the function of chloroplasts and reduction in chlorophyll content (Xu et al., 1995). The inactivation of chloroplast enzymes mainly induced by oxidative stress may also reduce the rate of photosynthesis. Due to increase in the mean temperature, the number of grains per square meter was significantly reduced (Figure 3). Similarly, the grain yield per square meter of wheat cultivars reduces significantly as mean temperature increased (Figure 3). Thousand grain weight and mean

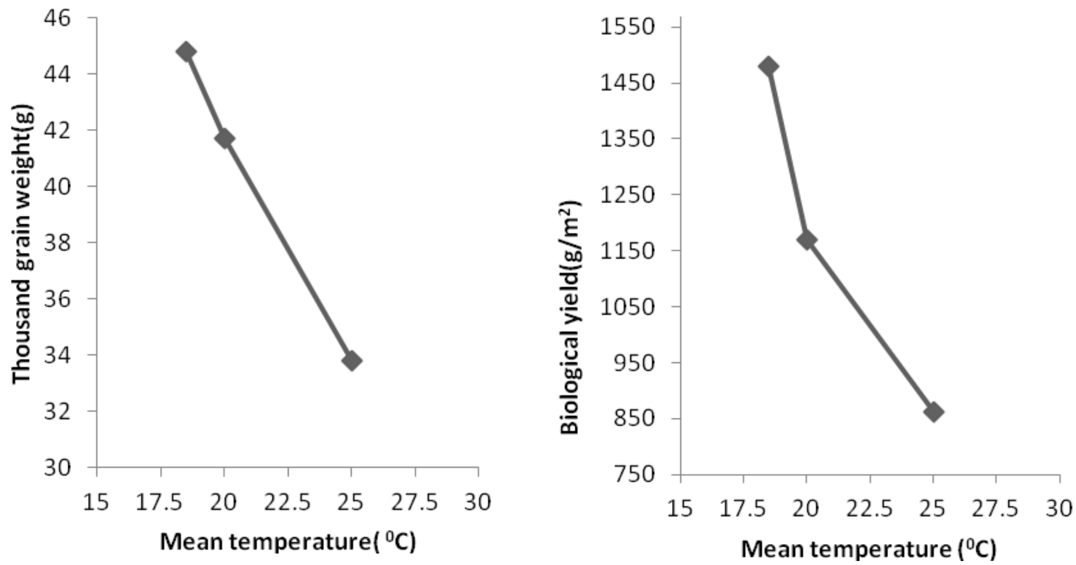

Figure 3: Effect of temperature on mean biological yield, economic yield, grains/spike and 1000 grain weight of wheat cultivars.

Table 5: Grain yield performance of different wheat cultivars under varying dates of sowing.

Cultivar/ Date of sowing	Rank of wheat cultivars under varying dates of sowing					
	I	II	III	IV	V	VI
November 15th	PBW 343	Kundan	HD 2643	HD 2329	HD 2285	C 306
December 15th	HD 2329	Kundan	HD 2643	PBW 343	HD 2285	C 306
January 15th	HD 2285	HD 2329	C 306	HD 2643	Kundan	PBW 343

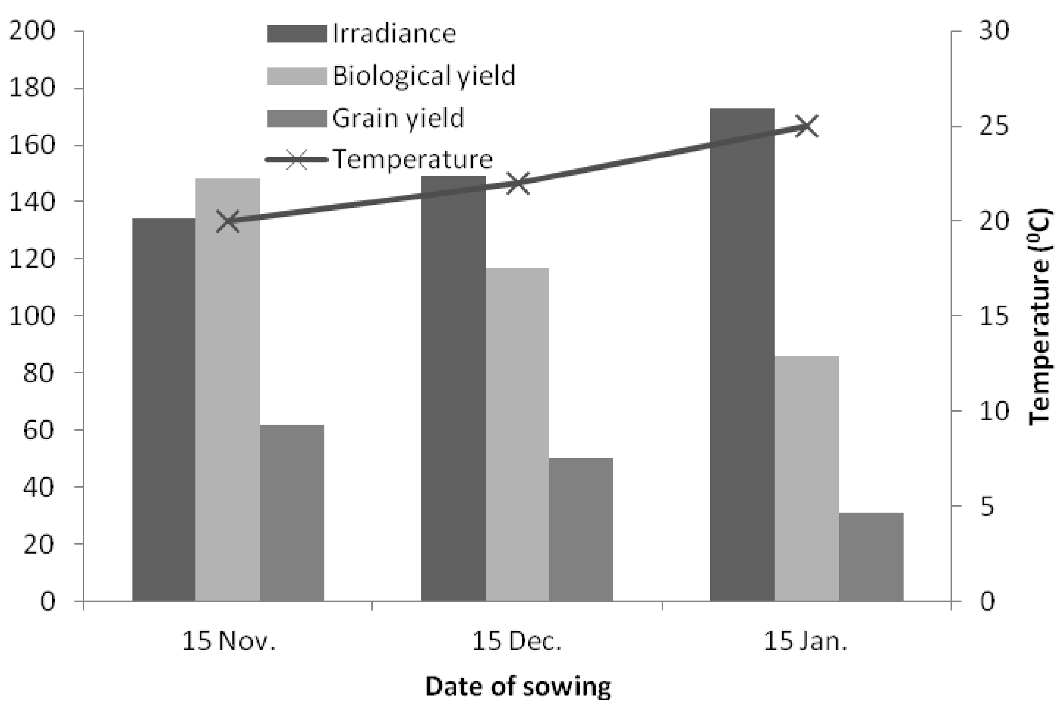

Figure 4: Influence of irradiance (kJ × $10^2/m^2$), biological yield (g/m^2 × 10), grain yield (g/m^2 × 10) and temperature (°C).

temperature also followed the same trend (Figure 3). The biological yield also reduced significantly as mean temperature increased (Figure 3). Although late (D1) and very late sowings (D2) caused marked reduction in crop maturity duration, but differences in thermal duration of wheat cultivars sown at varying dates was marginal indicating the stability of thermal duration of different varieties (Table 4).

Among the cultivars, long and medium duration cultivars, PBW 343 and Kundan recorded first and second rank, respectively under normal date of sowing (D1), while medium duration cultivars, HD 2329 and Kundan manifested first and second rank, respectively under late sowing (D2), and short and medium duration cultivars, HD 2285 and HD 2328 scored first and second rank under extreme late sown condition (D3) (Table 5).

Wheat cultivars showed marked variation in growth, yield and associated characters both under normal and late sown conditions. Among the cultivars, short duration HD 2285 and medium duration HD 2329 manifested higher grain yield under very late sown conditions as compared to long duration cultivars, HD 2643 and PBW 343. Higher grain yield recorded by short and medium duration cultivars under very late sown condition as compared to longer growth duration cultivars may be attributed to greater translocation of assimilates from either current assimilate or from pre-anthesis stored stem reserve. Heat stress affects the relative contribution of pre-anthesis stored reserves and current assimilation substantially. When photosynthetic source of assimilates is reduced by heat stress, the alternative source of grain filling is remobilized stem reserves. The stem reserves under heat stress dramatically contribute to the fulfillment of the requirement of the wheat grains.

Long duration cultivars thus showed greater thermal sensitivity as compared to short and medium duration cultivars mainly because of late flowering and grain filling. Long duration cultivars coincided with harsh heat stress condition under very late sowing, whereas the short duration cultivars managed to escape the heat stress under very late sowing. The cultivars with least effect in different yield components under late sowing may be helpful in breeding wheat cultivars for late sown condition. The late sown wheat crop generally get exposed to heat stress (35 to 40°C) during grain filling period and finally suffer from edaphic and atmospheric drought which might have enforced early maturity of crop and resulted in lower productivity. It is estimated that grain yield of wheat reduced at 270 kg ha^{-1} per °C rise in temperature (Rane et al., 2000).

Maximum extent of reduction in the number of grains/spike by delayed sowing might be due to greater sensitivity and reduction of reproductive growth phase (spike initiation to anthesis) in wheat plants (Shpiler and Blum, 1986). Reduction in 1000 grain weight under late sowing was possibly due to reduction in grain filling duration (Table 3) as well as, grain growth rate (Table 4). However, slight increase in the number of spikes m^{-2} under late sowing may be due to determination of spike bearing shoots at effective tillering stage during vegetative growth phase, which was not exposed to hyper-thermal stress even under very late sowing. The magnitude of grain yield reduction was about 40 and 50 kg ha^{-1} day^{-1} under D2 and D3, respectively.

Grain-filling rate was reported to be more thermo-sensitive than days to anthesis and grain filling duration (Zhong-hu and Rajaram, 1994), which is supported by the present findings. Higher grain weight/shoot and grain number per spike coupled with higher dry weight/ shoot at maturity under normal sown condition and gradual decline in the same delay in sowing as observed in the present study confirm the relationship between grain number/spike and dry weight per shoot (Table 4). Among the cultivars, long duration cultivars, HD 2643 and PBW 343 showed greater sensitivity than short and medium duration cultivars to heat stress caused by late sowing. The traditional tall cultivar, C 306 which registered lower grain yield under normal sown condition showed greater thermo-tolerance as compared to high yielding semi-tall cultivars under very late sown condition.

Conclusion

It is thus concluded from the findings that grain yield of all the wheat cultivars reduced significantly by heat stress under late sown conditions, which was attributed to significant reduction in growth duration, leaf area index and yield components such as grains/spike and 1000 grain weight. Under heat stress of extreme late sowing (D3), the performance of short and medium duration semi-tall cultivars HD 2285 and HD 2329, and traditional tall C 306 was relatively better than other cultivars and this is mainly due to less reduction in 1000 grain weight and greater harvest index. Thus, the cultivars characterized with early maturity, higher grain filling rate and greater assimilate partitioning could be used for cultivation under late sown condition and also utilized for breeding wheat varieties for heat tolerance.

REFERENCES

Al-Khatib K, Paulsen GM (1984). Mode of high temperature injury to wheat during grain Development. Physiol. Plant. 61(3): 363-368.

Al-Khatib K, Paulsen GM (1990). Photosynthesis and productivity during high temperature stress of wheat genotypes from mazor world regions. Crop Sci. 30(5): 1127-1132.

Al-Khatib K, Paulsen GM (1999). High temperature effects on photosynthetic process in temperature and tropical cereals. Crop Sci. 39(1): 119-125.

Fokar M, Nguyan HT, Blum A (1998). Heat tolerance in spring wheat. I. Estimating cellular thermotolerance and its heritability. Euphytica 104(1): 1-8

Kosina P, Reunolds M, Dixon J, Joshi A (2007). Stakeholder perception of wheat production constraints, capacity building needs and research partnership in developing countries. Euphytica 157:475-483

Lobell DB, Sibley A, Ortiz-Monasterio JI (2012). Extreme effects on wheat senescence in India. Nature Climate Change. DOI 10.1038/NCLIMATE1356.

Maestri E, Natalya K, Perrotta C, Gulli M, Ngunyen Marmiroli N (2002). Molecular genetics of heat tolerance and heat shock proteins in cereals. Plant Mol. Biol. 48: 667-681.

Nagarajan S (2002). Physiological traits associated with yield performance of spring wheat (*Triticum aestivum*) under late sown condition. Indian J. Agric. Sci. 72:135-140.

Penelia J, Bagga A, Wasnik KG (1993). Effect of late sown condition on productivity and nitrogen status in wheat. Indian J. Plant Physiol. 36: 178-184.

Rane J, Shoren J, Nagarajan S (2000). Heat stress environments and impact on wheat productivity in India: Estimate of losses. Indian Wheat News Lett. 6(1): 5-6.

Singh S, Kumar S, Pal M (2003). Physiological and phenological response of wheat cultivars to delayed sowing. Indian J. Plant Physiol. 3: 276-285.

Sphiler L, and Blum A (1986). Differential reaction of wheat cultivars to hot environments. Euphytica 35(2): 483-492.

Sphiler L, Blum A (1991). Heat tolerance for yield and its components in different wheat cultivars. Euphytica 51(3): 257-263.

Wahid A, Gelani S, Ashraf M, Foolad MR (2007). Heat tolerance in plants: overview. Environ. Exp. Bot. 61: 199-123.

Xu Q, Paulsen AQ, Guikema JA, Paulsen GM (1995). Functional and ultra structural injury to photosynthesis in wheat by high temperature during maturation. Environ. Exp. Bot. 35(1): 43-54.

Zacharias M, Singh SD, Kumar N, Harit R, Aggarwal PK (2010). Impact of elevated temperature at different phonological stages on growth and yield of wheat and rice. Indian J. Plant Physiol. 15(4): 350-358.

Zhong-hu, H, Rajaram S (1994). Differential response of bread wheat characters to high temperature. Euphytica 72: 197-203.