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The Effect of High Temperature Stress on the Phenology, Growth and Yield of Five Wheat (*Triticum aestivum* L.) Varieties

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ABSTRACT

The phenology, growth and yield of five elite varieties of wheat were evaluated under two sowing conditions to identify heat-tolerant and heat-susceptible varieties for future breeding. The first condition was optimum (sown on November 15) while the other was a very late heat stress condition (sown on December 27). In the grain-filling stage, temperature was 20-22°C under optimum conditions but was 28-30°C or higher under very late heat stress. When sown late, all varieties faced severe temperature stress that significantly affected phenology, growth and finally yield. Due to heat stress, the highest yield reduction observed was 46% in 'Sourav' followed by 43% in 'Sufi' and the lowest reduction was 27% in 'Shatabdi' followed by 32 and 35% in 'Bijoy' and 'Prodip'. When taking into consideration the reduction in phenological, growth and yield attributes, 'Shatabdi' performed best under heat stress, followed by 'Bijoy' and 'Prodip', while 'Sourav' and 'Sufi' was most sensitive to heat, among the 5 elite varieties.

Keywords: genotypes, high temperature, phenology, wheat, yield

INTRODUCTION

Global climate change will pose a serious challenge to crop production across the world. One of the important components of global climate change is an increase in the Earth's near-surface temperatures. This increase in temperature is often associated with increases in the concentrations of atmospheric carbon dioxide (CO_2) and other heat-trapping greenhouse gases such as methane, nitrous oxide, ozone and water vapor. At the present rate of greenhouse gas emissions, atmospheric CO_2 is predicted to double by the end of this century (IPCC 2001) which could increase the surface temperatures in a range of 1.8–5.8°C (IPCC 2001). These changes in climate would have enormous influence on the productivity of important food crops, such as wheat, in various regions of the world.

Wheat is the most important cereal crop in the world and is a major source of nourishment. In Bangladesh it occupies second place in terms of grain production after rice (BBS 2008), but its yield is low compared to other wheat-growing countries around the world (FAO 1999). According to research findings, the potential yield of existing wheat varieties is 3.0-3.5 t ha^{-1} (Hossain *et al.* 2009; Hossain *et al.* 2011; Hakim *et al.* 2012), but in farmers' fields, it is < 3 t ha^{-1} (BBS 2010). The reason for this low yield may be due to the lack of awareness among farmers about the use of proper agronomic management such as choice of variety, sowing time, seed rate, balanced dose of fertilizers, and other associated crop production factors (Quayyum 1994). In the northern part of Bangladesh, where highlands generally remain fallow after aus rice or jute cultivation, wheat can be seeded in early November (heat stress condition) and in some areas where wheat is followed by the transplant of aman rice or where soil remains wet due to excessive

Table 1 Studies related to heat-tolerant and heat-sensitive cultivars in different countries around the world.

Country	Tested temperatures	Results		References
		Heat-tolerant cultivars	Heat-sensitive cultivars	
Pakistan	Tested 5 cultivars under different sowing conditions (10 to 30°C)	'Moomal-2000' and 'Mehran- 89' (better performed under 20-30°C) heat stress	Cultivars 'TJ-83', 'Imdad-2005' and 'Abadgar-93' were heat-sensitive	Buriro *et al.* 2011
Iran	Tested two cultivars under different temperature regimes (10 to 30°C) to observe germination	'Hourani-27' (showed higher germination % at 20-30°C)	Cultivar 'F-8' was heat-sensitive with lower germination	Al-Qasem *et al.* 1999
Saudi Arabia	Tested 3 cultivars under early and late heat stress condition	'KSU-105' performed better in late heat stress condition	Cultivars 'KSU-106' and 'Yecora Roja' were heat-sensitive	Refay 2011
Bangladesh	Tested 10 genotypes under control heat stress condition (day /night temperature, 15/10 to 25/20°C)	Among 10 genotypes 3 were moderately stress-tolerant ('MW-8', 'BW-4'and 'BW-3')	Cultivar 'ZW-10' was highly susceptible	Rahman *et al.* 2009
Italy	Tested 3 genotypes under three temperature conditions; at sowing to anthesis and anthesis to maturity (from 11.3 to 30°C)	Cultivar 'Colosseo' showed better performance in high temperature condition.	Cultivars 'Simeto' and 'Creso' were susceptible to high temperature	Motzo *et al.* 2007

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Original Research Paper

Table 2 Threshold high temperatures for select crop plants.

Crop plants	Threshold temperature (°C)	Growth stage	References
Wheat	26	Post-anthesis	Stone and Nicolás 1994
Corn	38	Grain filling	Thompson 1986
Cotton	45	Reproductive	Rehman *et al.* 2004
Pearl millet	35	Seedling	Ashraf and Hafeez 2004
Tomato	30	Emergence	Camejo *et al.* 2005
Brassica	29	Flowering	Morrison and Stewart 2002
Winter pulses	25	Flowering	Siddique *et al.* 1999
Groundnut	34	Pollen production	Prasad *et al.* 2000
Cowpea	41	Flowering	Patel and Hall 1990
Rice	34	Grain yield	Morita *et al.* 2004

rainfall, seeding is continued up until January (also heat stress condition) (BARI 2006). As a result of the variation in sowing date, ambient temperature varies widely, which affects crop phenology. Literature related to high temperature stress and its effects on different wheat cultivars in different countries around the world is presented in **Table 1**. Temperatures below or above the normal alter plant functions and productivity. For example, low temperature (< 12°C) applied during germination and seedling emergence in *Solanum sisymbriifolium* (Timmermans *et al.* 2007) and spring wheat (Hossain *et al.* 2011; Hakim *et al.* 2012; Hossain *et al.* 2012a) resulted in poor and uneven emergence, while spring wheat exposed to high temperature (20-24°C) resulted in a decrease in time to flowering, grain set, and physiological maturity, ultimately reducing grain yield (Prasad *et al.* 2008). Wahid *et al.* (2007) reported that transitory or constantly high temperatures cause an array of morpho-anatomical, physiological and biochemical changes in plants, which affect plant growth and development and may lead to a drastic reduction in economic yield. This rate of reduction of temperature-affected crops depends fully on threshold level temperature and varies with plant species, but for cool season crops, 0°C is often the best-predicted base temperature (Miller *et al.* 2001). The threshold temperature refers to a value of daily mean temperature at which a detectable reduction in growth begins. In tomato, for example, when ambient temperature exceeds 35°C, seed germination, seedling and vegetative growth, flowering and fruit set, and fruit ripening are adversely affected. For other plant species, the threshold temperature may be lower or higher than 35°C. Upper threshold temperatures for some major crop species are indicated in **Table 2**. Knowledge of threshold level temperatures is important in physiological research as well as for crop production.

On the other hand, the current assessment for Bangladesh by the Intergovernmental Panel on Climate Change (IPCC 2007) predicts warming of 1.5-2.0°C by 2050, with increased rainfall of 10-15% by 2030 and a 12% increase in evaporation. Poulton and Rawson (2011) reported that temperature in Bangladesh has increased over the past two decades at 0.035°C/year and if this trend continues, temperatures will have exceeded 1990 levels by 2.13°C in 2050.

The adverse effect of temperature could be minimized by adjusting sowing time to an optimum date and by developing crop plants with improved thermo-tolerance using various genetic approaches. For this purpose, however, a thorough understanding of physiological responses of plants to high temperature, mechanisms of heat tolerance and possible strategies for improving crop thermo-tolerance is imperative. In such a context, this study was conducted to identify heat-tolerant and -susceptible wheat varieties for future breeding programmes.

MATERIALS AND METHODS

The study was conducted at the experimental field of the Wheat Research Center (WRC), Dinajpur, Bangladesh during November, 2010 to April, 2011. The area falls under the Old Himalayan Piedmont Plain designated as Agro Ecological Zone 1. Geographically, the area lies between 25° 38′ N, 88° 41′ E and 38.20 m above sea level. The soil is sandy-loam and strongly acidic (pH ranges from 4.5 to 5.5) (WRC, 2009). Five existing elite wheat varieties (**Table 3**) (‘Sourav’, ‘Shatabdi’, ‘Sufi’, ‘Bijoy’, and ‘Prodip’) from WRC, Bangladesh were used as experimental materials. Their performance was evaluated under two growing environments: the first was an optimum sowing (OS) environment (sown on 15 November) while the other was a post-anthesis heat stressed environment i.e., very late sowing (VLS) (sown on 27 December). OS and VLS for this study were based on previous research findings of Hossain *et al.* (2009). Temperature data of the experimental site during the study period was recorded and is presented in **Fig. 1**.

The experiment was conducted in a randomized complete block design (RCBD) with three replications. Before sowing, seeds were treated with Provax-200 WP, a seed-treated fungicide containing Carboxin and Thiram. Research conducted at the WRC (2009) indicated that Provax-200 WP is a perfect match for controlling fungi in Bangladesh soil, for achieving excellent seed germination and for protecting wheat cultivars from fungal attacks during the seedling stage. This fungicide is marketed by Hossain Enterprise CC Bangladesh Ltd., an agro-chemical company engaged in crop protection and seed treatment, in association with Chemtura Corp., USA.

Seeds were sown at 120 kg ha^{-1}. Unit plot size was 1.6 × 4 m {4 m long 8 rows and row to row distance 20cm (i.e., 9.6 g seeds row^{-1})}. Fertilizer was applied at doses recommended by the WRC: 100-27-40-20-1 kg ha^{-1} of N (nitrogen)-P (phosphorus)-K (potassium)-S (sulphur)-B (boron). Two-thirds of N and a full amount of the other fertilizers were applied as a basal land preparation. The remaining N fertilizer was applied immediately after the first irrigation {21 days after sowing (DAS)}. Second and third irrigations were applied at booting (47 DAS) and grain-filling (78 DAS) stages. Intercultural operations were done properly according to treatments. The crop was harvested plot-wise at full maturity according to treatments. Sample plants were harvested separately from an area of 3 × 1.2 m (i.e., 3 m long middle 6 rows), avoiding border effects. The harvested sample crop of each plot was bundled separately, tagged and taken to a threshing floor. The bundles were thoroughly dried in bright sunshine until fully dried, then weighed and threshed.

Phenological data on days to germination, booting, heading, anthesis, physiological maturity and harvest maturity, biomass data on 30-culm fresh weight and dry weight (g) and yield data on 30-culm grain weight (g) were recorded.

Temperature data was recorded regularly by HOBO U12 Family of Data Loggers (MicroDAQ.com) at the meteorological station, WRC, Dinajpur, Bangladesh. Different phenological growth stages (days to germination, booting, heading, anthesis, physiological maturity and harvest maturity) were observed carefully and recorded. To obtain the actual yield of all varieties, grain yield and 1000-grain weight was adjusted at 12% moisture by the following equation (Hellevang 1995):

$$Y(M_2) = \frac{100 - M_1}{100 - M_2} \times Y(M_1)$$

where $Y(M_2)$ = weight of grain at expected moisture percentage (generally 12% for wheat); $Y(M_1)$ = weight of grain at present moisture percentage; M_1 = present moisture percentage; M_2 = expected moisture percentage.

Data was analyzed using MSTAT-C (Russell, 1994). Treatments means were compared for significance by the least significant difference (LSD) test at $P = 0.05$.

Table 3 Five tested existing wheat varieties of Bangladesh and their characters.

Varieties	Characteristics and other information
Sourav	Identifying characters: This is a semi-dwarf high yielding wheat variety. It is highly tolerant to lodging due to its strong stem. Flag leaf is broad and recurved. Strong waxiness is present in spike and culm, while it is very strong in flag leaf sheath. The lower glume beak is long (about 5-10 mm) and lower glume shoulder shape is slightly slopping. Developed by (Centre/Division): Wheat Research Centre, BARI. Year of release: 1998. Crop duration: 102-110 days. Yield (kg/ha): 3500-45000. Suitable area: All over the country except in saline areas. Sowing time: November 15-30. Harvesting time: March-April. Major diseases and Management: Tolerant to *Bipolaris* leaf blight and resistant to leaf rust diseases.
Shatabdi	Identifying characters: It is a semi-dwarf variety with good tillering ability and high yield. The leaves are broad, recorded and light green in color. Flag leaves are also broad and droopy. The plants are light green in color with very weak glaucosity in the spike, culm and flag leaf sheath. Lower glume beak is long and the lower glume shoulder shape is elevated. Developed by (Centre/Division): Wheat Research Centre, BARI. Year of release: 2000. Crop duration: 105-110 days. Yield (kg/ha): 3600-5000. Suitable area: All over the country except in saline areas. Sowing time: November 15-30. Harvesting time: March-April .Major diseases and Management: Highly tolerant to *Bipolaris* leaf blight and resistant to leaf rust diseases.
Sufi	Identifying characters: It is a semi-dwarf variety with good tillering ability. The leaves are broad, recurved and light green in color. Flag leaves are also broad and droopy. The plants are light green in color with very weak glaucosity in the spike, culm and flag leaf sheath. Lower glume beak is long and the lower glume shoulder shape is elevated. Developed by (Centre/Division): Wheat Research Centre, BARI. Year of release: 2005. Crop duration: 105-110 days. Yield (kg/ha): 3600-5000. Suitable area: All over the country except in saline areas. Sowing time: November 15-30. Harvesting time: March – April. Disease: Highly tolerant to *Bipolaris* leaf blight and resistant to leaf rust diseases.
Bijoy	Identifying characters: It is a semi-dwarf variety with good tillering ability. The leaves are broad, recurved and light green in color. Flag leaves are also broad and droopy. The plants are light green in color with moderate glaucosity in the spike, culm and flag leaf sheath. Lower glume beak is very short and the lower glume shoulder shape is square and wide. Thousand-grain weight is very high (47-52g). Developed by (Centre/Division): Wheat Research Centre, BARI. Year of release: 2005. Crop duration: 103-112 days. Yield (kg/ha): 4300-5000. Suitable area: All over the country except saline areas. Sowing time: November 15-30. Harvesting time: March – April. Major diseases and Management: Highly tolerant to *Bipolaris* leaf blight and resistant to leaf rust diseases.
Prodip	Identifying characters: It is a semi-dwarf high yielding ability and heat tolerant variety. The leaves are broad, recurved and light green in color. Flag leaves are also broad and droopy. The plants are light green in color with weak glaucosity in the spike, culm and flag leaf sheath. Lower glume beak is very long (>15.0 mm) and the lower glume shoulder shape is elevated and broad with numerous spicules on the beak. Thousand-grain weight is very high (48-55 g). Developed by (Centre/Division): Wheat Research Centre, BARI. Year of release: 2005.Crop duration: 102-110 days, Yield (kg/ha): 4300-51000, Suitable area: All over the country except in saline areas, Sowing time: November 15-30, Harvesting time: March – April, Major diseases and Management: Highly tolerant to *Bipolaris* leaf blight and resistant to leaf rust diseases.

Sourav **Shatabdi** **Sufi** **Bijoy** **Prodip**

RESULTS AND DISCUSSION

Physiologically, the following are usually distinguished stages of development for cereals: germination, emergence, tillering, floral initiation or double ridges, terminal spikelet, first node or beginning of stem elongation, booting, spike emergence, anthesis, physiological maturity and harvest maturity. The time span of each development phase depends on genotype, temperature, day length and sowing date. Various environmental stresses, particularly heat, may shorten these growth phases in wheat (Acevedo *et al.* 2002).

Days to germination

Normally, germination may occur between 4 and 37°C, optimal temperature being from 12 to 25°C, and delays in germination adversely affect crop establishment, when temperature is typically low (Evans *et al.* 1975). These facts are related to our present research, because the duration of germination of all wheat genotypes in VLS was longer than in OS. This might also be due to low temperatures at VLS (**Fig. 1, 2**). In our study, significant differences in days to germination were found among the varieties with respect to OS and VLS. 'Shatabdi' took more time to germinate in OS than other varieties, closely followed by 'Sourav' and 'Sufi'. In VLS, 'Sourav', 'Shatabdi' and 'Sufi' took statistically similar and more time to germinate. On the other hand, 'Bijoy' 'Prodip' took less and statistically similar time to germinate (**Fig. 2**).

In OS, the maximum temperature during the germination period was > 28°C, sometimes near 30°C while the minimum temperature was between 15 and 17°C (**Fig. 1**). However, at VLS, the average maximum and minimum temperatures were near 23 and 10°C, respectively. If we compare the required time for germination, it is clear that germination was earlier when temperature was higher (in OS) but germination was later in VLS due to low temperatures (**Fig. 2**). This germination-temperature link was also noted by Timmermans *et al.* (2007), who reported that seedling emergence and establishment in *Solanum sisymbriifolium*, when planted late, were negatively affected by low temperature during germination. Sultana *et al.* (2000) experienced similar results for pearl millet and maize: maximum germination percentage was 98% at 24°C. In our study, the required days to germination of all varieties increased in VLS, due to low temperature. 'Prodip' (increased 33%) showed the greatest increase followed by 'Sourav' and 'Sufi' (31%), and 'Bijoy' (increased 20%) showed the least increase in time required for days to germination in VLS. Chakrabarti *et al.* (2011) and Hakim *et al.* (2012) also found that air temperature < 15°C was not suitable for the growth and development (germination, seedling stand establishment and tillering) of spring wheat. Low temperature increases days to germination, also reported by Nahar *et al.* (2010). A detailed comparison of this study with that study is presented in **Table 4**.

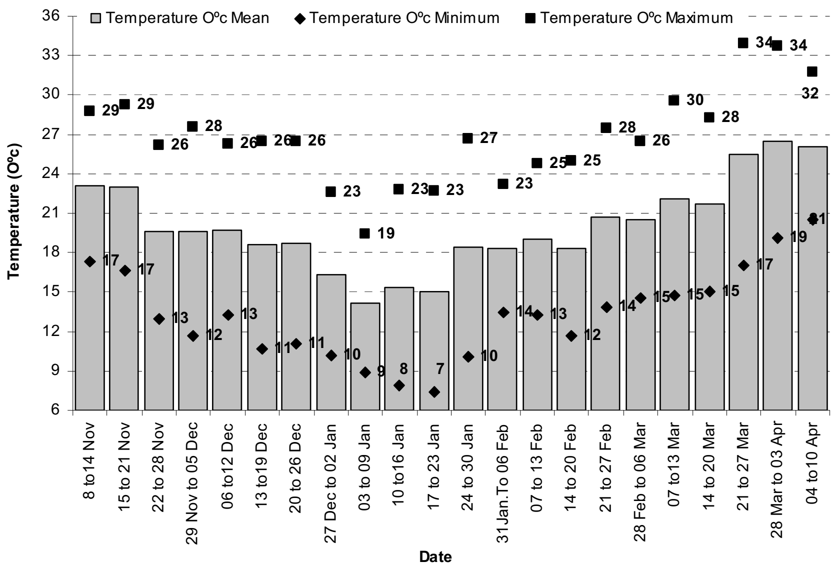

Fig. 1 Weather information during the wheat growing period. Source: Meteorological Station, Wheat Research Centre, Nashipur, Dinajpur, Bangladesh.

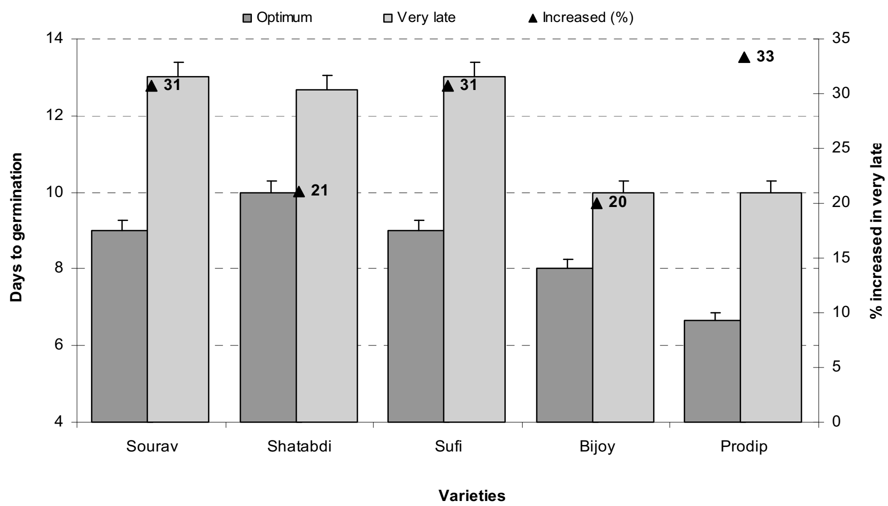

Fig. 2 Days to germination of 5 wheat varieties when sown under optimum and very late conditions. Mean (±SD) was calculated from three replicates for each treatment, which are significantly different at $P \leq 0.05$ (LSD test).

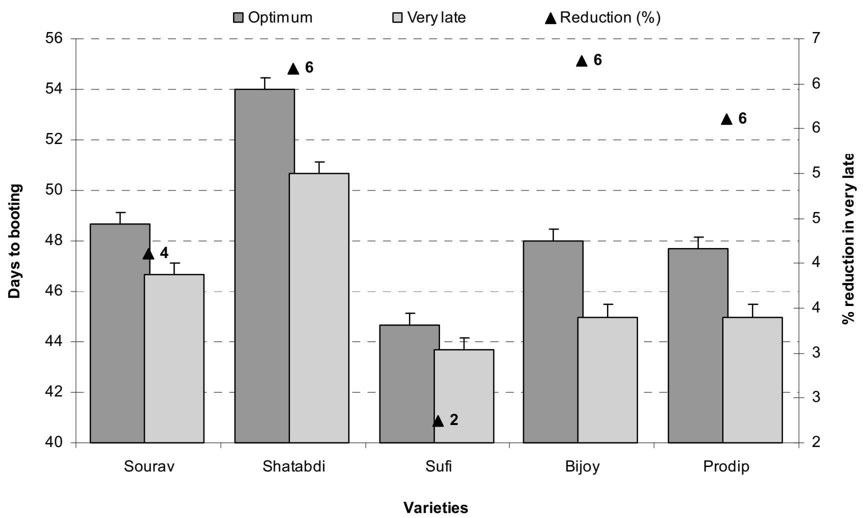

Fig. 3 Days to booting of 5 wheat varieties when sown under optimum and very late conditions. Mean (±SD) was calculated from three replicates for each treatment, which are significantly different at $P \leq 0.05$ (LSD test).

Days to booting

As the young spike expands inside the leaf sheaths it can eventually be felt and finally seen after the flag leaf stage as a sheath swelling or boot. This becomes most obvious shortly before its awns start to protrude out of the top of the last sheath (Acevedo *et al.* 2002). Reproductive phases, which are most sensitive to high temperature, are booting,

Table 4 Varietal ('Sourav', 'Shatabdi', 'Sufi', 'Bijoy', 'Prodip') differences between the present study and a previous study (Nahar *et al*. 2010) due to different agro-climatological variation.

Parameters	Present research findings	Previous research finding (Nahar *et al*. 2010)
Experimental site	Northern part of Bangladesh, Dinajpur (25°38′ N, 88°41′ E and 38.20 m above sea level)	Central region of Bangladesh, Dhaka (24°75′ N and 90°50′ E and 18 m the sea level)
Year and duration	November, 2010 to April, 2011	November, 2008 to April, 2009
Sowing date	Optimum sowing environment (sown on 15 November) while the other was a post-anthesis heat stressed environment (sown on 27 December).	Normal growing environment (sowing on November 30) and the other was post anthesis heat stressed environment (sowing on 30 December).
Soil	The soil is sandy-loam and strongly acidic (pH ranges from 4.5 to 5.5)	The soil was silty-loam having non-calcarious properties and shallow red brown terrace.
Temperature	**Optimum sowing:** Maximum, minimum and mean temperatures were, at germination, between 26-27, 11-13 and 19-20°C), at the vegetative stage 18-20, 9-11 and 14-16°C, and at the reproductive stage 20-24, 10-12 and 15-17°C. **Very late sowing:** Maximum, minimum and mean temperatures were, at germination, 18-20, 8-9 and 13-14°C), at the vegetative stage 20-22, 10-12 and 15-18 °C, and at the reproductive stage 26-29, 15-17 and 22-23°C.	**Optimum sowing:** Maximum, minimum and mean temperatures were, at germination, 25-30, 15-20 and 20-25°C), at the vegetative stage 25-27, 12-15 and 16-20°C, and at the reproductive stage 24, 10 and 17°C. **Very late sowing:** Maximum, minimum and mean temperatures were, at germination, 25-26, 12-15 and 17-20°C), at the vegetative stage 25-27, 15-27 and 19-22°C, and at the reproductive stage 30-32, 20-22 and 25-27°C.
Days to germination	In our study var. 'Shatabdi' took more time to germinate both in optimum and late conditions, followed by 'Sourav' and 'Sufi' while 'Prodip' took least time followed by 'Bijoy'.	In this study no significance difference was observed between varieties in early and late conditions. Among them, 'Sourav' took more time both in early and late conditions. On the other hand, in late sowing, 'Shatabdi' and Bijoy took least time to germinate, followed by 'Sufi'.
Days to booting	'Shatabdi' took more time both in optimum and late conditions, followed by 'Sourav', 'Bijoy' and 'Prodip' and 'Sufi' took the least time to reach booting.	In early sowing, all varieties took statistical similar time, but in the late condition they differed significantly. Among them, 'Sourav' and 'Prodip' took more time to booting, followed by 'Shatabdi', 'Bijoy' and 'Sufi'.
Days to anthesis	'Shatabdi' took more time in both optimum and late conditions, followed by 'Sourav', 'Prodip' and 'Bijoy', and 'Sufi' took the least time to reach anthesis.	In early sowing, all varieties took statistical similar time (about 81 days), but in late condition they differed significantly. Among them, 'Sourav' and 'Prodip' took more time to booting, followed by 'Shatabdi', 'Bijoy', and 'Sufi' took least time.
Days to harvest	In our present experiment, 'Sourav' and 'Shatabdi' took most time to mature in optimum condition, followed by Bijoy and 'Sufi', which took the least time followed by 'Prodip'. Under late heat stress, 'Shatabdi' took the most time, followed by 'Sourav' and 'Bijoy' and 'Sufi' took the least time followed by 'Prodip'.	In early sown condition, 'Shatabdi' took more time to reach ripe harvest, followed 'Bijoy' and 'Sourav', which took the least time, followed by 'Sufi' and 'Prodip'. On the other hand, in late condition, 'Bijoy' took the most time followed by 'Shatabdi' and 'Sourav' took the least time to mature followed by 'Sufi' and 'Prodip'.
Grain yield	Considering yield performance, 'Shatabdi' was the highest yielder, followed by 'Prodip' both in early and late conditions. 'Sourav' was the second highest yielder in early condition and 'Bijoy' in late condition.	'Bijoy' was the highest yielder, followed by 'Shatabdi' while 'Sourav' was the lowest both in early and late conditions.
Unique parameters measured	In our research, we measured three different parameters {days to heading, days to physiological maturity and green biomass and dry biomass weight (g)} that were not examined in the Nahar *et al*. (2010) study to better understand physiological variation, its relation with dry matter-partitioning, and finally yield under heat stress.	
Conclusion from two studies	From the above comparison of two research findings, it can be concluded that temperature in the northern part of Bangladesh at the time of wheat growing was lower than the central part, which ultimately had an effect on phenology, growth and development of wheat plants. In the previous experiment, which took place in central Bangladesh, crop duration was 86-97 days in late and 88-108 optimum sowing conditions, respectively. On the other hand, in the northern part, it was 101-103 days in late and 122-128 days in optimum condition, respectively. As a result, the yield of all varieties was lower in the central part than in the north. Among all the varieties, 'Shatabdi' performed the best in the north and 'Bijoy' in the central part.	

fertilization and gametogenesis (8-9 days before anthesis) in various plants (Foolad 2005; Hossain *et al.* 2012a; Tarchoun *et al.* 2012). In the present study, significant differences were found for days to booting in OS and VLS treatments. 'Shatabdi' took the most time (54 days) for booting while 'Sufi' took the least time under both OS and VLS (**Fig. 3**). However, due to heat stress, booting took less time in VLS. 'Shatabdi' needed most time for booting. Unlike OS, in VLS, 'Sufi' took more time (reduction 2%) to reach booting from germination (**Fig. 3**). A detailed comparison of this study with a study by Nahar *et al.* (2010), which used the same cultivars, is presented in **Table 4**.

Days to ear emergence/heading

A developmental stage when the head, spike or ear emerges from its enclosing sheath is called ear peep. The stage from partial to full appearance is also called ear emergence or heading (Acevedo *et al.* 2002). Tewolde *et al.* (2006) stated that under high temperature stress, earlier heading is advantageous since more green leaves are retained at anthesis, leading to a smaller reduction in yield. In our study, compared to other varieties, 'Shatabdi' (72 days) and 'Sourav' (69 days) needed most time for heading while other varieties did not show any significant differences to days to heading in OS (**Fig. 4**). But, in VLS, Sufi required the longest time (reduction 14.45%) while 'Shatabdi' required the least time (reduction 18.43%) to reach heading due to heat stress in VLS (**Fig. 4**). Ubaidullah *et al.* (2006) and Spink *et al.* (1993) also observed that delayed sowing shortened the duration of each developmental phase in wheat due to a rise in temperature. They also reported up to 23 days difference between early and late sowing for heading. Al-Karaki (2012) conducted a field experiment in Jordan (Mediterranean climate) with 16 wheat cultivars to know their potential under heat stress. Under field observation, he noticed that Mediterranean-adapted cultivars had long preheading periods, followed by short periods and high rates of grain filling to avoid terminal drought and high temperature stress (25-31°C). Among the 16 cultivars, 'Waha-1', 'Omrabi-5' and 'Massaa-1' performed best in stress conditions.

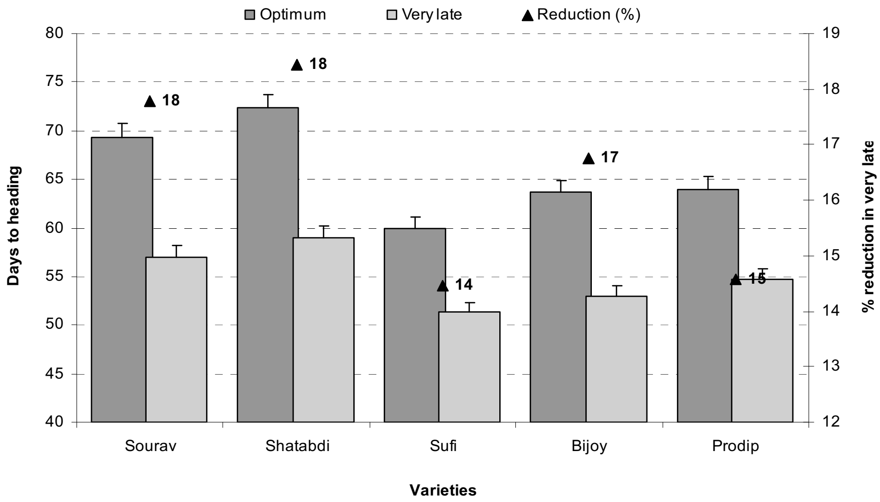

Fig. 4 Days to heading of 5 wheat varieties when sown under optimum and very late conditions. Mean (±SD) was calculated from three replicates for each treatment, which are significantly different at $P \leq 0.05$ (LSD test).

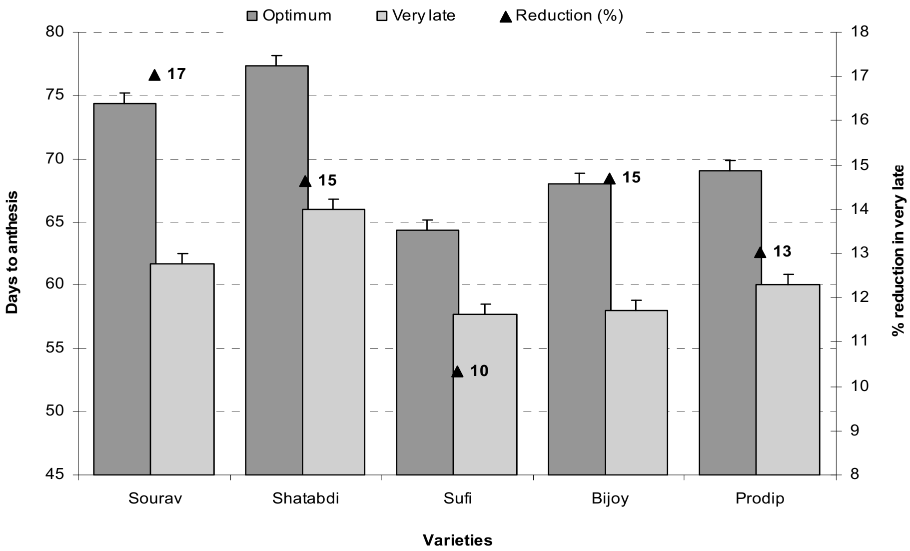

Fig. 5 Days to anthesis of 5 wheat varieties when sown under optimum and very late conditions. Mean (±SD) was calculated from three replicates for each treatment, which are significantly different at $P \leq 0.05$ (LSD test).

Days to anthesis/flowering

The main developmental stage when yellow anthers are clearly visible on spikes is termed anthesis or flowering (Acevedo *et al.* 2002). Growth chamber and greenhouse studies suggested that high temperature is most deleterious when flowers are first visible and sensitivity continues for 10-15 days (Foolad 2005). In the present experiment, 'Shatabdi' (77 days) took more time while 'Sufi' took less time to reach anthesis in OS, compared to the other varieties. In VLS, all the varieties showed a reduced life span to complete anthesis due to heat stress. Among these, 'Sourav' took less time (reduction 17.03%) than 'Sufi' (reduction 10.35%) to reach anthesis (**Fig. 5**). A study by Nahar *et al.* (2010), which used the same cultivars, is compared in detail in **Table 4**.

Days to physiological maturity

Physiological maturity is usually assumed as the period when the flag leaf and spikes turn yellow (Hanft and Wych 1982). Days to physiological maturity decreased significantly from OS to VLS. From **Fig. 6**, it can be observed that OS needed maximum days while VLS needed minimum days to reach physiological maturity. This might be due to an increase in temperature from OS to VLS, which reduced the life span of the VLS crop. 'Shatabdi' and 'Sourav' in OS needed the most days (122 days) to reach physiological maturity, while 'Sufi' (111.70) needed fewest days. However, in VLS, all 5 varieties had a reduced life span from germination to physiological maturity. Among them, 'Sourav' showed a 19.94% reduction in time to complete physiological maturity more than 'Sufi' (14.35%) as a result of heat stress during this period (**Fig. 6**). Spink *et al.* (1993) also observed that delayed sowing shortened the duration of each development phase due to high temperature.

Days to harvest maturity

It is a common fact that the duration of maturity of any crop is reduced by stress. Asana and Williams (1965) found in wheat that each degree increase in temperature during the grain-filling period resulted in about a 3-day decrease in the duration of grain-filling, regardless of cultivar. Hossain *et al.* (2011, 2012a) and Hakim *et al.* (2012) also found that duration of maturity of spring wheat cultivars reduced by high temperature stress in northern Bangladesh. The findings from the present study mirror those from the literature. For example, in OS, 'Shatabdi' and 'Sourav' took most time (127.70 days) while 'Sufi' took least time (122 days) to reach maturation (**Fig. 7**). On the other hand, under VLS, crop duration was longest in 'Shatabdi' (103.7 days) while the other varieties had a similar duration to days to maturity. 'Sourav' took 20.13% less time from germination to reach

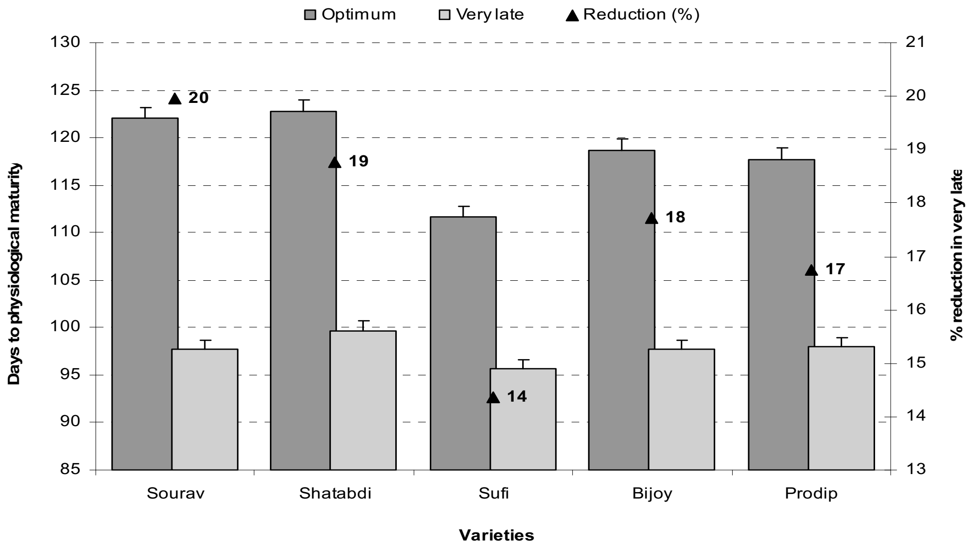

Fig. 6 Days to physical maturity of 5 wheat varieties when sown under optimum and very late conditions. Mean (±SD) was calculated from three replicates for each treatment, which are significantly different at $P \leq 0.05$ (LSD test).

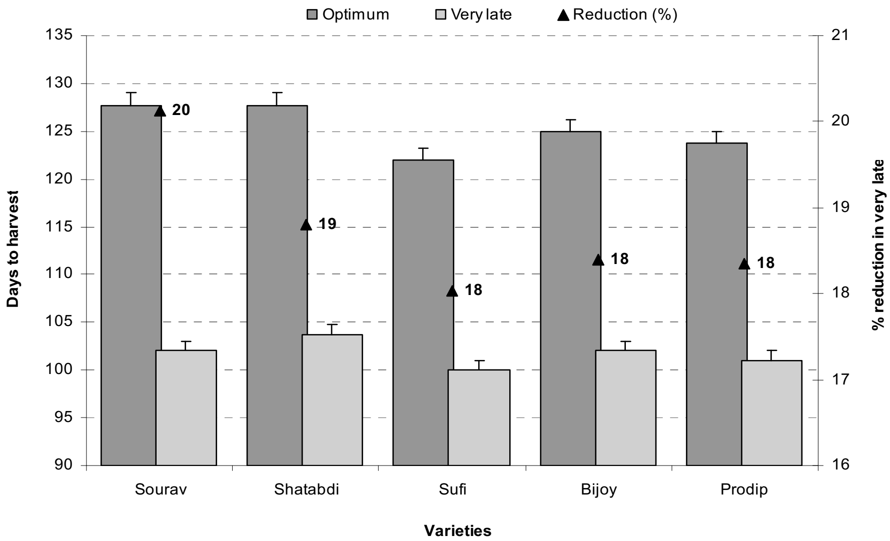

Fig. 7 Days to harvest of 5 wheat varieties when sown under optimum and very late conditions. Mean (±SD) was calculated from three replicates for each treatment, which are significantly different at $P \leq 0.05$ (LSD test).

harvest as a result of high temperature stress unlike others which took 15.97% more time (**Fig. 7**). Nahar *et al.* (2010) also noticed that 'Sourav' took less time to harvest than other varieties (**Table 4**). There is also a similarity between the result of the present study and a 2-year study by Ubaidullah *et al.* (2006) in which heading, grain filling and grain maturity were 23, 3 and 29 days early when wheat was sown late than when sown normally due to heat stress during late sowing.

In the present study all 5 varieties matured earlier in VLS than in OS: the temperature during the grain-filling or grain-maturing period was near 22°C in OS and > 30°C in VLS. Wheat cultivars that can fill their grain quickly may have an advantage in environments with short, hot and dry grain-filling periods. So, to avoid stress, they complete their life cycle earlier (Whan *et al.* 1996), confirmed by the findings of our study. Bavei *et al.* (2011) conducted a field experiment in Iran with 10 advanced spring barley cultivars ('L1' to 'L10') and noticed that the physiological status of plants was remarkably affected by terminal heat stress, which ultimately reduced grain yield. From overall 10 genotypes, cultivars 'L6' and 'L8' performed better in stress conditions.

Fresh weight and dry weight

Toru and Wardlaw (1988) found that the duration of grain growth and dry matter accumulation were reduced as temperature increased above 26.7°C. Kumer *et al.* (1994) reported straw yield to decrease, probably due to an unfavorable environment (high temperature) at the vegetative stage; as a result, crops became thin and produced less tillers which in turn decreased straw yield. In our experiment, 'Shatabdi' and 'Prodip' produced the highest fresh and dry weight both in OS and VLS (**Fig. 8**). Other varieties did not show any significant difference in both sowing conditions. In VLS, all varieties were highly affected by heat stress, expressed as reduced dry matter (fresh and dry weight) and grain yield. The highest reduction in fresh and dry weight was 35.47% in 'Shatabdi' and the least reduction was 23.75% in 'Bijoy' (**Fig. 8**). Hasan and Ahmed (2005) also found that post–anthesis, under heat stress (>26°C), maximum dry matter accumulation was reduced due to a reduction in wheat kernel dry matter. Buriro *et al.* (2011) conducted a field experiment with 5 wheat cultivars ('TJ-83', 'Imdad-2005', 'Abadgar-93', 'Moomal-2000', 'Mehran-89') to assess which were heat-tolerant and which heat-sensitive. Among them, 'Moomal-2000' and 'Mehran- 89' performed better at 20-30°C (air temperature), i.e., heat stress. 'TJ-83', 'Imdad-2005' and 'Abadgar-93' were found to be heat-sensitive.

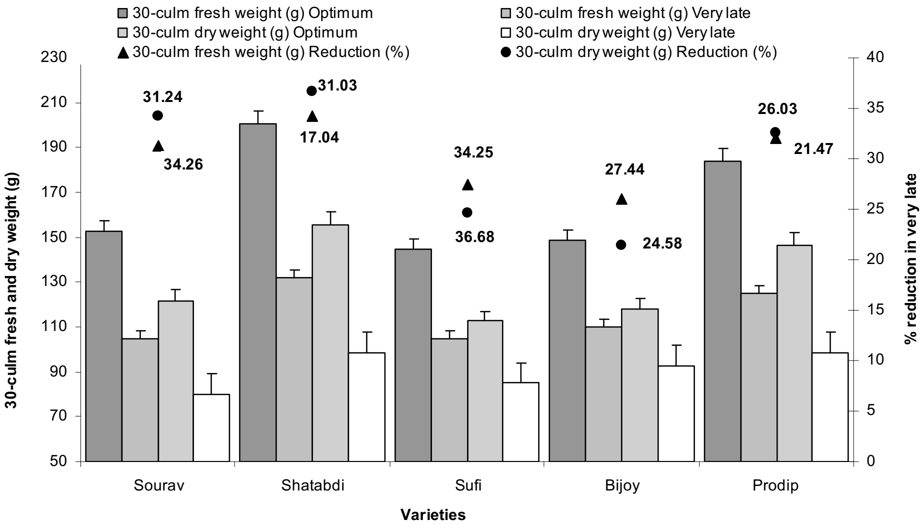

Fig. 8 30-culm fresh and dry weights of 5 wheat varieties when sown under optimum and very late conditions. Mean (±SD) was calculated from three replicates for each treatment, which are significantly different at $P \leq 0.05$ (LSD test).

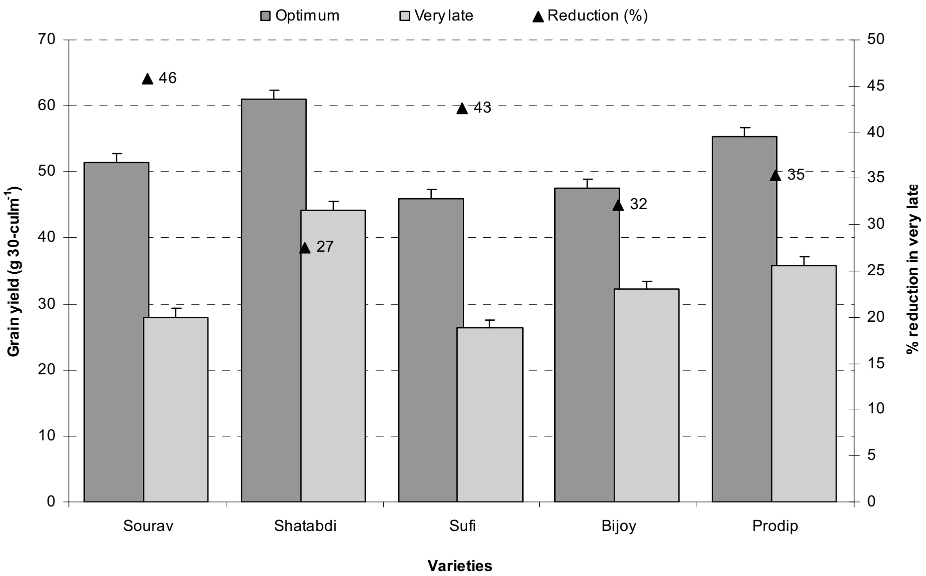

Fig. 9 Grain yield of 5 wheat varieties when sown under optimum and very late conditions. Mean (±SD) was calculated from three replicates for each treatment, which are significantly different at $P \leq 0.05$ (LSD test).

Grain yield

Guilioni *et al.* (2003) found that heat stress, singly or in combination with drought, is a common constraint during anthesis and grain-filling stages in many cereal crops of temperate regions. For example, heat stress reduced the duration of grain filling with a parallel reduction in kernel growth leading to losses in kernel density and weight by up to 7% in spring wheat.

In our study, all 5 varieties were highly affected by heat stress in VLS, which finally drastically reduced grain yield. However, the rate of reduction varied from genotype to genotype. Hasan (2002) also reported grain yield to be reduced by about 2.6 to 5.8% in heat-tolerant genotypes and by 7.2% in heat-sensitive genotypes for each 1°C rise in average mean air temperature during anthesis to maturity compared to the normal growing condition (<26°C), which was very closely to normal temperatures of 22-26°C required for reproductive growth in wheat (Asana and Williams 1965; Campbell and Read 1968). Among our varieties, 'Shatabdi' (60.95 and 43.15 g) produced the highest grain yield both in OS and VLS (**Fig. 9**) while other varieties produced statistically similar yield in OS. However, in VLS, the performance of 'Sufi' was worst, yielding only 26.33 g, which was statistically similar to 'Sourav' (27.92 g). In VLS, the highest reduction in yield was 45.80% in 'Sourav' and the least reduction was 27.50% in 'Shatabdi. The performance of 'Shatabdi' was the best in terms of yield and yield reduction in OS and VLS while 'Sourav' and 'Sufi' were the worst yielding variety in VLS (**Fig. 9**).

Consequently, among the 5 varieties, the yield of 'Shatabdi' was highest both in OS and VLS, followed by 'Prodip' and 'Bijoy' (**Fig. 9**). Therefore, it can be said that there is a relationship between the duration of maturity and yield of wheat varieties. Sikder *et al.* (1999) found that in OS (November 30), tolerant {relatively heat tolerant (e.g. 'Ananda', 'Pavon', 'Agrani' and 'Barkat') and moderately heat tolerant (e.g. 'Akbar', 'Kanchan' and 'Protiva')} and sensitive wheat varieties (e.g. 'Balaka', 'Sawgat' and 'Sonora') had a similar duration of grain filling (i.e., 40 days) but when these varieties were sown on December 30, the heat-tolerant varieties took more days for grain filling (32 days) than the heat-sensitive varieties (28 days). When considering the variation of different phenological stages in relation to growth and yield, 'Shatabdi' also performed best, followed by 'Bijoy' in VLS; its yield and dry matter reduction was also least among all 5 varieties. 'Shatabdi' is more tolerant to heat stress than all other varieties, followed by 'Sourav' and 'Sufi', which performed worst in VLS, i.e., heat stress. In our research, fluctuations in weather conditions (**Fig. 1**) were reflected in phenology, crop growth and development (**Figs. 2-8**) and ultimately by yield (**Fig.**

9), which is common among several crops (Martiniello and Teixeira da Silva 2011; Hossain *et al.* 2011; Hakim *et al.* 2012; Hossain *et al.* 2012a, 2012b). Nahar *et al.* (2010) also observed a different order of yield by the same varieties (**Table 4**).

CONCLUSION

From our study, it can be concluded that heat stress significantly changes the phenology of wheat varieties, ultimately affecting growth and yield. Generally, due to high temperature stress, the duration or length of one or more life cycle stages are reduced. OS (i.e. early sowing on November 15) resulted in better performance of all varieties than late sowing (i.e., VLS on December 27). 'Shatabdi' was considered to be the best performing variety under heat stress since the reduction in phenological stages was least while yield was highest among all 5 varieties. On the other hand, 'Sourav' and 'Sufi' are heat sensitive when phenology, growth and yield are all considered.

'Shatabdi' performed best under heat stress, followed by 'Bijoy' and 'Prodip', while 'Sourav' and 'Sufi' were most sensitive to heat, among the 5 elite varieties.

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