

Phenology, Growth and Yield of Three Wheat (*Triticum aestivum* L.) Varieties as Affected by High Temperature Stress

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Abstract

Wheat is the most important cereal in the world. However, due to an increasing trend of rising temperatures around the world, wheat may be exposed to greater thermal stress in the near future. Therefore, the identification and development of suitable wheat varieties is an important step to resolve this threat to production and to achieve high yield, even under high temperature stress. In this context, phenology, growth and yield of three elite varieties of wheat ('Gourab', 'BARI Gom-25' and 'BARI Gom-26') were evaluated under two sowing conditions: optimum (sown on November 15) and late heat stress condition (sown on December 27). All wheat varieties, when sown late, faced severe temperature stress that significantly affected phenology, growth and finally yield. Taking into consideration phenological variation, dry matter (fresh and dry weight) partitioning and grain yield, variety 'BARI Gom-26' performed better both in optimum and late heat stress, followed by 'BARI Gom-25'; 'Gourab' performed the least. On the basis of heat tolerance parameters [relative performance (RP) and heat susceptibility index (HSI)], 'BARI Gom-25' (RP-79%; HSI-0.7) was the best performing variety followed by 'BARI Gom-26' (RP-74%; HSI-0.9) under heat stress while 'Gourab' (RP-61%; HSI-1.3) was sensitive to heat.

Keywords: Bangladesh, spring wheat, yield and yield components

Introduction

Accounting for a fifth of humanity's food, wheat is second after rice as a source of calories in the diets of consumers in developing countries and is first as a source of protein (Braun *et al.*, 2010). Wheat is an especially critical "staff of life" for the approximately 1.2 billion "wheat-dependent" to 2.5 billion "wheat-consuming" poor-men, women and children-who live on less than \$US 2/day (FAOSTAT, 2010). The International Food Policy Research Institute (IFPRI) projections indicate that the world demand for wheat will rise from 552 million tons in 1993 to 775 million tons by 2020, and 60% in total by 2050 (Rosegrant *et al.*, 1997; Rosegrant and Agcaoili, 2010). At the same time, climate change-induced temperature increases are likely to reduce wheat production in developing countries (where around 66% of all wheat is produced) by 20-30% (Esterling *et al.*, 2007; Lobell *et al.*, 2008; Rosegrant and Agcaoili, 2010). The IPCC (2007) noticed that global climate change (GCC) will have a major impact on crop production.

Regarding agriculture and food security, overall crop yield (wheat, maize and rice) could decrease in South Asia by up to 30% by the end of this century (compared with an increase as much as 20% in East and South East Asia) (Anonymous, 2012). In cereal production alone, the most conservative climate change projections suggest a mini-

mum decline of 4-10% across South Asia. In Bangladesh, rice production could fall by 8% and wheat production by 32% as early as 2050 (Anonymous, 2012). CIMMYT-ICARDA (2011) estimated that 20-30% of wheat yield losses will occur by 2050 in developing countries as a result of an assumed temperature increase of 2-3°C on a global scale, but these yield losses will not be fully compensated by yield gains in high latitude regions, estimated at 10-15% (OECD-FAO, 2009).

The annual mean temperature of Bangladesh is 25.75°C, which is expected to rise about 0.21°C by 2050 (Karmakar and Shrestha, 2000). The Organization for Economic Cooperation and Development (OECD) (2003) estimated a rise in temperature of 1.4°C by 2050 and 2.4°C by 2100 in Bangladesh. Islam (2009) estimated, from 34 meteorological climate sites in Bangladesh, that temperature increases over the past 100 years-for all Bangladesh-of 0.62°C (maximum) and 1.54°C (minimum) occurred in February. Poulton and Rawson (2011) reported that temperature in Bangladesh increased over the past two decades by 0.035°C/year. If this trend continues, temperatures will have increased 2.13°C more than 1990 levels by 2050.

Substantial losses in rain-fed wheat are also anticipated: studies in India suggest that a 0.5°C rise in winter temperature would reduce wheat yield by 0.45 tones/ha while a similar rise in temperature of > 2.5°C would reduce non-irrigated wheat and rice farm revenue by 9-25%

Tab. 1. Recent studies related to heat, drought and low temperature stress, primarily in wheat, from different countries around the world

Country	Tested cultivars	Main research findings	Reference
Denmark	Tested 2,255 Mexican wheat landraces	Landraces were evaluated on the basis of canopy temperature depression (LCC), and 1000-kernel weight. Three landrace cultivars with superior and consistent LCC values were identified. These accessions are potentially useful sources for improving heat tolerance in cultivated wheat.	Hede <i>et al.</i> (1999)
Australia	Wheat 'Lyallpur'	Despite favourable day/night temperature (18/13°C), drought reduced kernel dry weight at anthesis.	Wardlaw (2002)
Sudan	Wheat 'Debira', 'El Nelein' and 'Donki'	A 2-year field study in two regions showed that 'El Nelein' performed best when sown late (air temp. 17-24°C).	Ahmed <i>et al.</i> (2003)
China	Spring wheat 'Ningchun18'	Soil water deficit both during the middle vegetative stage (jointing) and the late reproductive stages (filling and maturity or filling) and no-soil-water-deficit both during the late vegetative stage (booting) and the early reproductive stage (heading) had the highest yield increase of 25 and 14%.	Zhang <i>et al.</i> (2006)
Egypt	Wheat cultivars 'Sakha8', 'Sakha93', 'Sakha61' 'Chinese spring'	Based on drought susceptibility index 'Sakha8' and 'Sakha93' were found to tolerant, and 'Sakha61' and 'Chinese spring' were found to susceptible.	El-Fadly <i>et al.</i> (2007)
Turkey	20 wheat cultivars (16 bread wheat, <i>Triticum aestivum</i> ; four durum wheat, <i>Triticum durum</i> cultivars)	Considering drought sensitivity indices over 2 years, the bread wheat cultivars 'Yayla-305', 'Gerek-79', 'Dagdaz-94' and 'Bolat-2973' were found to be more drought-tolerant than the other cultivars.	Bagci <i>et al.</i> (2007)
Argentina	Wheat, barley and Triticale	Wheat, barley and a triticale cultivar were evaluated in three season under three thermal condition: control and two timing of heating before anthesis and found stem elongation stage is most sensitive to high temperature stress (yield reduction 46%)	Ugarte <i>et al.</i> (2007)
Hungary	Wheat 'GK-Elet' and 'Mv-Emese'	Pot culture experiment in growth chamber indicated that 'Mv-Emese' was good drought stress tolerance than GK-Elet	Lukacs <i>et al.</i> (2008)
Bulgaria	Two drought tolerant wheat ('Katya' 'Zlatitza') and two sensitive 'Sadovo' and 'Miziya')	The obtained results showed that the drought tolerant varieties 'Katya' and 'Zlatitza' had higher levels of these proteins, especially RBP and Clp proteases.	Demirevska <i>et al.</i> (2008)
USA	Spring wheat variety 'Sinton'	It was noticed that cool air temperature (65°F) lengthened the life span and high temperature (79°F) shortened the life span	Frank <i>et al.</i> (2009)
Portugal	Four <i>triticum</i> genotypes ('Golia', 'Sever', 'Acalou' and 'TE9306')	It was concluded that under heat stress (day/night 31/20°C), during the grainfilling period, Fe and Mn helped to overcome stress.	Dias <i>et al.</i> (2009)
Iran	Wheat cultivars 'Azar-2', 'Sardari', 'Frankia' and 'Trakia'	It was observed that variety 'Frankia' performed better in various level of terminal drought stress	Dalirie <i>et al.</i> (2010)
Azerbaijan	Two bread wheat ('Giymatli-2/17', 'Azamatli-95') and two durum wheat ('Garagylchyg-2', 'Barakatli-95')	It was found that drought tolerant genotypes 'Azamatli-95' and 'Barakatli-95' this decrease was less pronounced compared to genotypes 'Garagylchyg-2' and 'Giymatli-2/17', which are sensitive to drought.	Bayramov <i>et al.</i> (2010)
Pakistan	Four wheat genotypes viz., 'LU-26s', 'Bhattai', 'Roshan', 'Taifu'	The genotypes 'LU-26s' was found to have best performance under drought condition, with minimum decrease in the growth parameters i.e., plant height, number of tillers and shoot dry weight.	Shirazi <i>et al.</i> (2010)
Pakistan	Five wheat cultivars ('TJ-83', 'Imdad-2005', 'Abadgar-93', 'Moomal-2000', 'Mehran- 89')	'Moomal-2000' and 'Mehran- 89' (better performed under 20-30°C air temperature) heat stress. Cultivars 'TJ-83', 'Imdad-2005' and 'Abadgar-93' were heat-sensitive	Buriro <i>et al.</i> (2011)
Saudi Arabia	Tested 3 cultivars ('KSU-105', 'KSU-106' and 'Yecora Roja')	'KSU-105' performed better in late heat stress condition (temperature 25-30°C). Cultivars 'KSU-106' and 'Yecora Roja' were heat-sensitive.	Refay (2011)
Russia	Eight wheat genotypes	Genotypes 'Zlata' showed sensitivity to low air temperature (-3°C) and 'Ester' and 'Yubileynaya' showed tolerance to low temperature.	Karmanenko <i>et al.</i> (2011)
Ethopia	18 wheat cultivars 'B5-5B', 'S-17B', and 'WA-13', 'Asassa, Bekelcha', 'Boohai, Egersa', 'Foka, Gerardo', 'Ilani, T Kilinto', 'Obsa, Oda', 'Quamy', 'Tob-66' and 'Yeror', 'CDSS93Y107' 'CD94523'	Water deficit significantly affected gas exchange and chlorophyll fluorescence parameters. It reduced the net photosynthesis rate, transpiration rate and stomatal conductance measured both at anthesis and grain-filling stages.	Bogale <i>et al.</i> (2011)
India	Wheat cultivars 'HD2851', 'HI8498', 'HDR77', 'PBW343' and 'HD2936'	Low temperature (<18°-20°C air temperature) during reproductive stage causes sterility of pollen grains. Cultivars, 'HD2851', 'HI8498' and 'HDR77' were highly affected by low temperature (<15°C). Other two cultivars 'PBW343' and 'HD2936' were found low temperature (air temperature 11.6 to 15°C) tolerant.	Chakrabarti <i>et al.</i> (2011)
United Kingdom	Wheat 'Damani', 'Gomal-8', 'Hashim-8', 'DN-73', 'Zam-04', 'Dera-98'	Among these cultivars 'Hashim-8' was found drought tolerant.	Khakwani <i>et al.</i> (2011)
Jordan	Sixteen wheat cultivars	Cultivars Waha-1, Omrabi-5, and Massara-1 genotypes performed better in Mediterranean climate among genotypes studied.	Al-Karaki (2012)

(Anonymous, 2012). The Intergovernmental Panel on Climate Change (IPCC) estimates that by 2050, there will be changing rainfall patterns with increasing temperatures, flooding, droughts and salinity that would cause rice production to decline in Bangladesh by 8% and wheat by 32%, against 1990 as the base year (CCC, 2009).

Several research findings noticed that temperature below ($<10^{\circ}\text{C}$) or above ($>25^{\circ}\text{C}$) the optimum (12 to 25°C) alter phenology, growth and development and finally reduce the yield of existing Bangladeshi wheat varieties (Hakim *et al.*, 2012; Hossain *et al.*, 2009, 2011, 2012a, 2012b, 2012c; Nahar *et al.*, 2010; Rahman *et al.*, 2009). Thus, heat is the greatest threat to food security in Bangladesh where wheat is the second most important food grain and where population is rapidly increasing (Indexmundi, 2011). The IPCC (2007), CIMMYT-ICARDA (2011), CGIAR (2009) and OECD (2003) reported that world wheat production will decrease due to global warming and developing countries, like Bangladesh, will be highly affected. Heat stress in wheat can be mitigated in two ways: heat management or the development of heat-tolerant cultivars. Breeding for cultivars that are tolerant to post-anthesis high temperature stress is an effective strategy to overcome this problem. There is a concerted effort by researchers around the world to develop stress (heat and drought)-tolerant cultivars (Tab. 1). As a sub-set of this global effort, and in the light of future global warming forecasting for the country, Bangladeshi researchers, including our group, are also trying to develop heat-tolerant wheat varieties. Therefore, the study was conducted to identify heat-tolerant and -susceptible wheat varieties from existing varieties for future breeding programmes.

Materials and methods

Experimental site

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 (FAO/UNDP, 1988). It is situated in northern part of Bangladesh and geographically, the area lies between $25^{\circ}38'$ N, $88^{\circ}41'$ 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).

Treatments and design

Three existing elite wheat varieties ('Gourab', 'BARI Gom-25' and 'BARI Gom-26') from WRC, Bangladesh were used as experimental materials. The characteristics of these varieties are presented in Tab. 2. 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., late sowing (LS) (sown on 27 December). The experiment was conducted in a randomized complete block design (RCBD) with a split plot arrangement and three replications. Sowing dates comprised the main plot and elite varieties of wheat comprised the subplot.

Experimental procedure

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 agrochemical company engaged in crop protection and seed treatment, in association with Chemtura Corp., USA. Seeds were sown at 120 kg/ha. Unit plot size was 1.6×4 m [4 m long 8 rows and row to row distance 20 cm (i.e., 9.6 g seeds/row)]. Fertilizer was applied at doses recommended by the WRC: 100-27-40-20-1 kg/ha of N (nitrogen), P (phosphorus), K (potassium), S (sulfur), and B (boron). Two-thirds of N and a full amount of the other fertilizers were applied as a basal amount during final 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.

Data collection and their procedure

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 un-

Tab. 2. Characteristics of tested wheat varieties of Bangladesh

Variety	Duration (Days)	Yield (kg ha ⁻¹)	Suitable area for cultivation	Year of release	Sowing time	Harvest time	Major diseases and pests
'Gourab'	102-108	3500-4600	All over the country except in saline areas	1998	Nov.15-30	Mar.-Apr.	Tolerant to <i>Bipolaris</i> leaf blight and resistant to leaf rust
'BARI Gom-25'	102-110	3600-5000	Suitable for southern region (8-10 dS/m salinity level)	2010	Nov.15-30	Mar.-Apr.	Highly tolerant to <i>Bipolaris</i> leaf blight and resistant to leaf rust diseases.
'BARI Gom-26'	104-110	3500-5000	Possible to grow throughout the country except in areas with salinity level >6 dS/m	2010	Nov.15-30	Mar.-Apr.	Tolerant to <i>bipolaris</i> leaf blight and resistant to leaf rust diseases (stem rust) race, Ug 99

der bright sunshine until fully dried, then weighed and threshed.

Phenological data on days to germination (DG), booting (DB), first visible awn (DFAV), heading (DH), anthesis (DA), physiological maturity (DPM) and harvest maturity (DHM); biomass data on 30-culm fresh weight (FW) and dry weight (g) (DW), and yield (GY) data on 30-culm grain weight (g) were recorded. To obtain the actual yield of all varieties, grain yield 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.

Heat tolerant data of relative performance (%) and heat susceptibility index were calculated by following equations. Relative performance (RP%) for yield was calculated as described by Asana and Williams (1965) and was expressed as a percentage:

$$RP (\%) = \frac{\text{Stress performance}}{\text{Optimum performance}} \times 100$$

Heat susceptibility index (HSI) was calculated for each genotype according to the formula of Fischer and Maurer (1978):

$$HSI = \frac{1 - \frac{Y}{Y_p}}{1 - \frac{X}{X_p}}$$

Where

Y = mean grain yield of a genotype under a stress environment

Y_p = mean yield of the same genotype under a stress-free environment

X = mean Y of all genotypes

X_p = mean Y_p of all genotypes

If $HSI < 0.5$, the crop is highly tolerant to high temperature stress, if $HSI > 0.5 < 1.0$, it is moderately tolerant, and if $HSI > 1.0$, it is susceptible to high temperature stress.

Temperature data was recorded regularly by HOBO U12 Family of Data Loggers (MicroDAQ.com) at the meteorological station, WRC, Dinajpur, Bangladesh and is presented in Fig. 1.

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

Results and discussion

Temperature is a modifying factor in all stages of wheat development including germination, tillering, booting, ear emergence, anthesis and maturity since it can influence the rate of water supply and other substrates necessary for growth, but varies with plant species, variety and phenological stages (Wahid *et al.*, 2007). Under high temperature, the crop completes its life cycle much faster than under normal temperature conditions (Fischer, 1985; Hakim *et al.*, 2012; Hossain *et al.*, 2009, 2011, 2012a, 2012b, 2012c; Nahar *et al.*, 2010; Rahman *et al.*, 2009). Delayed planting in a sub-tropical region such as Pakistan, India, Bangladesh, etc. reduced plant height, DH, days to maturity and the duration of grain filling and ultimately reduced yield and yield components (Din and Singh, 2005; Mahboob *et al.*, 2005).

Days to germination

Low temperature is one of the most important environmental parameters of late-sown wheat in sub-tropical environments. Chakrabarti *et al.* (2011) conducted a field experiment in India and found that air temperature $< 15^\circ\text{C}$ was not suitable for the growth and development (germination, seedling stand establishment and tillering) of spring wheat. Timmermans *et al.* (2007) reported that seedling emergence and establishment in *Solanum sisymbriifolium*, when planted late, were negatively affected by low temperature during germination. At the time of our present research, the maximum temperature during the germination period was > 26 to 28°C , sometimes nearing 30°C , while the minimum temperature was between 12 and 13°C , in OS. However, at LS, the average maximum and minimum temperatures were near 23 and 10°C , and

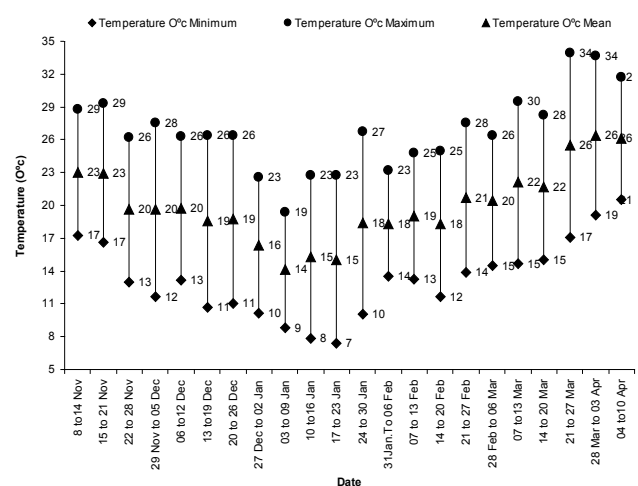


Fig. 1. Temperature ($^\circ\text{C}$) during the wheat growing period. Source: Meteorological Station, Wheat Research Centre, Nashipur, Dinajpur, Bangladesh

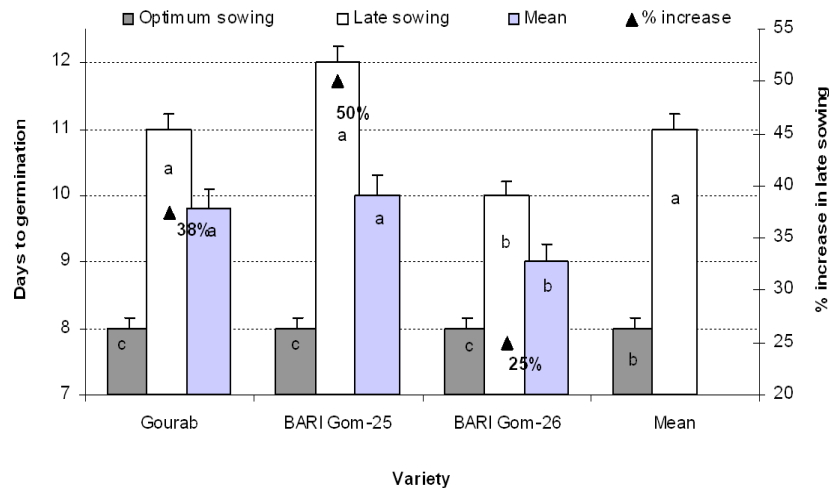


Fig. 2. Days passed to germination of 3 wheat varieties sown under optimum and very late conditions. Mean (\pm SD) was calculated from three replicates for each treatment. Bars with different letters are significantly different at $p \leq 0.05$ (LSD test)

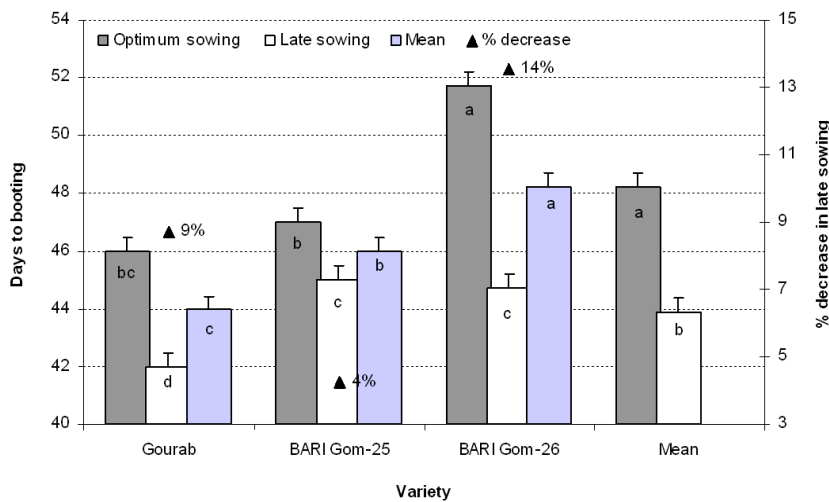


Fig. 3. Days passed to booting of 3 wheat varieties when sown under optimum and very late conditions. Mean (\pm SD) was calculated from three replicates for each treatment. Bars with different letters are significantly different at $p \leq 0.05$ (LSD test)

sometimes minimum and maximum temperature ranged between 8-9°C and 20-19°C, respectively (Fig. 1). The required DG was earlier when temperature was higher (in OS) but germination was later in LS due to low temperatures (Fig. 2). This claim is supported by Fig. 1 and previous results reported by Hossain *et al.* (2011, 2012c), who conducted a field experiment in Bangladesh and noted that low temperature (<10°C) at the germination stage delayed the time taken for grain to germinate. Significant differences in DG were found among the three varieties with respect to OS and LS. Among them, 'BARI Gom-25' took more time to germinate in LS than other varieties, closely followed by 'Gourab'. On the other hand, 'BARI Gom-26' took least time to germinate. In OS, all three varieties took statistically similar time to germinate (Fig. 2). In our study, the required DG increased by 50% in 'BARI Gom-25' followed by 38% in 'Gourab' and 25% in 'BARI Gom-26' in LS, due to low temperature stress.

Days to booting

Reproductive phases like booting, fertilization and gametogenesis (8-9 days before anthesis) are most sensitive to high temperature in various plants (Foolad, 2005; Tarchoun *et al.*, 2012), as also observed with our present research findings, which noted that DB of the three evaluated varieties were significantly different in OS and LS. Among the varieties 'BARI Gom-26' took the most time for booting while 'Gourab' took the least time under both OS and LS (Fig. 3). In LS, required DB was reduced the most, by 14% in 'BARI Gom-26' and the least in 'BARI Gom-25' by 4%. Hakim *et al.* (2012) evaluated 20 wheat cultivars in same agro-climatological conditions and noticed that the life span of all wheat cultivars were reduced in LS due to high temperature stress (> 25°C) at the reproductive stage.

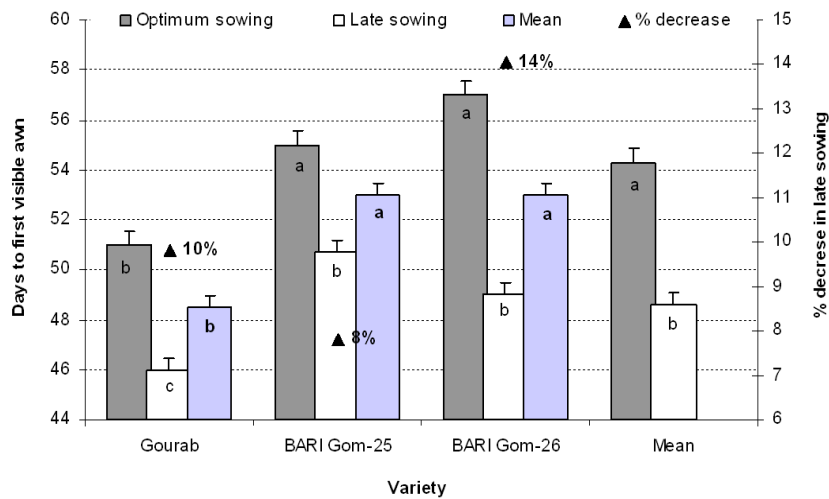


Fig. 4. Days passed to the first visible awn of 3 wheat varieties when sown under optimum and very late conditions. Mean (\pm SD) was calculated from three replicates for each treatment. Bars with different letters are significantly different at $p \leq 0.05$ (LSD test)

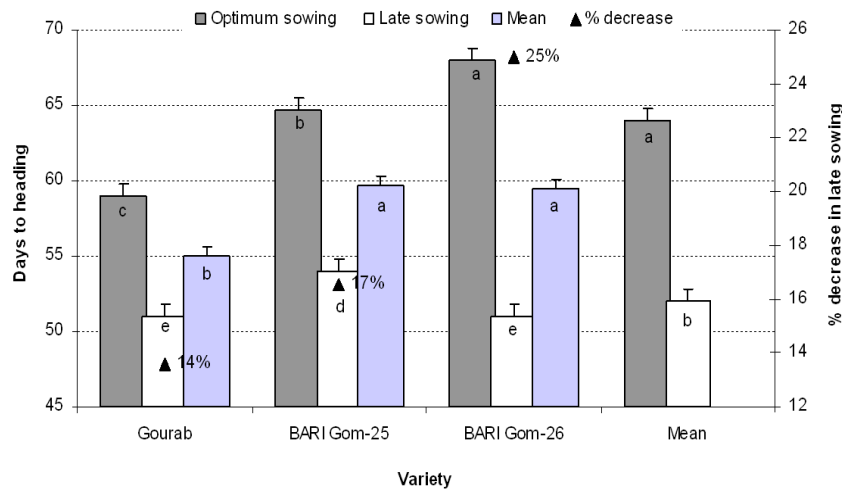


Fig. 5. Days passed to heading of 3 wheat varieties when sown under optimum and very late conditions. Mean (\pm SD) was calculated from three replicates for each treatment. Bars with different letters are significantly different at $p \leq 0.05$ (LSD test)

Days to first visible awn

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 our present findings, due to heat stress in LS, all three evaluated varieties had a shorter life span than OS, which ultimately affected final GY (Fig. 1, 4 and 10). Both in OS and LS, 'BARI Gom-26' and 'BARI Gom-25' took more time than 'Gourab' to reach the first visible awn. Under high temperature stress, the required DFAV was reduced by 14% in 'BARI Gom-26' and by 8% in 'BARI Gom-25'. Nahar *et al.* (2010) also observed a decrease in the life span of wheat varieties in LS but not in OS, due to high temperature stress; in their study, maximum temperature at vegetative and reproduction stages were 25 to 27°C and 30 to 32°C, respectively.

Days to ear emergence/heading

The developmental stage in which the spike or ear partially or fully appears to emerge from its enclosing sheath is also called ear emergence or heading (Acevedo *et al.*, 2002). However, the time taken for the spike or ear to emergence from the enclosing sheath is entirely dependent on growth conditions. In our study, the three varieties evaluated needed most time for heading in OS and less time in heat stress (LS) (Fig. 5). Among them, 'BARI Gom-26' and 'BARI Gom-25' took statistically similar and longest time while 'Gourab' required the least time to reach heading due to heat stress in LS (Fig. 1, 5). Due to heat stress, the reduction in required DH was highest in 'BARI Gom-26' (25% reduction) and lowest in 'Gourab' (14% reduction). Hossain *et al.* (2011, 2012b, 2012c), Nahar *et al.* (2010), Rahman *et al.* (2009) and Ubaidullah *et al.*

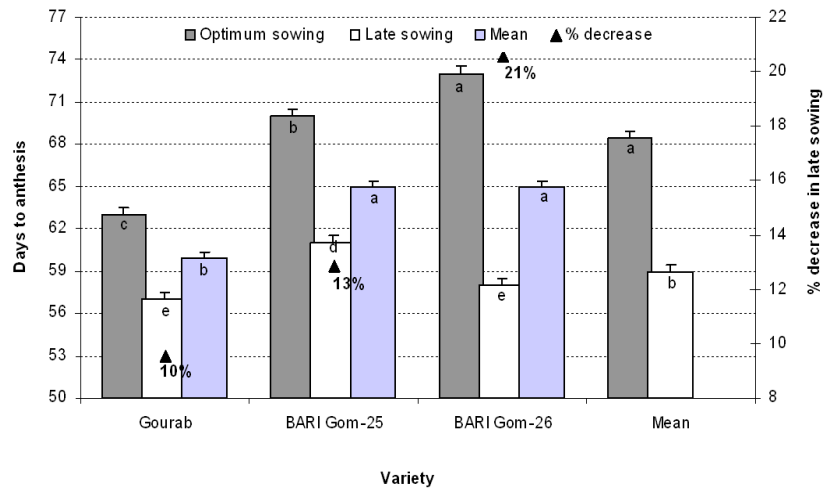


Fig. 6. Days passed to anthesis of 3 wheat varieties when sown under optimum and very late conditions. Mean (\pm SD) was calculated from three replicates for each treatment. Bars with different letters are significantly different at $p \leq 0.05$ (LSD test)

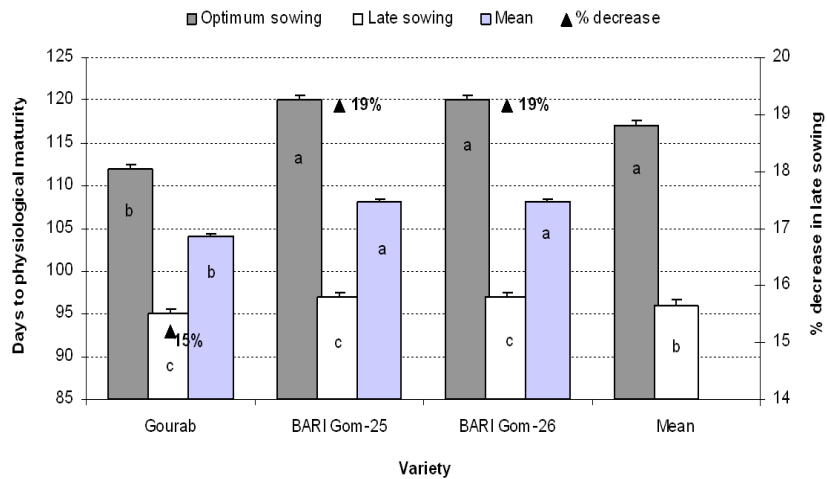


Fig. 7. Days passed to physical maturity of 3 wheat varieties when sown under optimum and very late conditions. Mean (\pm SD) was calculated from three replicates for each treatment. Bars with different letters are significantly different at $p \leq 0.05$ (LSD test)

(2006) also observed that delayed sowing in wheat shortened the duration of each developmental phase due to a rise in temperature. They also reported up to 23 days difference between OS and LS for heading. Al-Karaki (2012), investigating 16 wheat cultivars in a Mediterranean climate, showed long pre-heading periods, followed by short periods and high rates of grain filling to avoid terminal drought and high temperature stress (25-31°C). Among them, 'Waha-1', 'Omrahi-5' and 'Massaa-1' were tolerant to stress (drought and high temperature).

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). In the present experiment, it was found that all three varieties showed a different duration to reach anthesis, both in LS and OS, due to temperature

differences. 'BARI Gom-26' and 'BARI Gom-26' took more but statistically similar time both in LS and OS while 'Gourab' took less time to reach anthesis. In LS, all three varieties showed a reduced life span to complete anthesis due to heat stress. Among them, 'BARI Gom-26' took less time (21% reduction) than 'Gourab' (10% reduction) to reach anthesis (Fig. 6). Hakim *et al.* (2012) also noticed that 20 wheat cultivars took 14 to 19% less time in LS than OS to reach days to flowering, due to high temperature stress (> 25°C).

Days to physiological maturity

The DPM of wheat cultivars varies due to inherent differences between cultivars (Shahzad *et al.*, 2007), but is influenced by different environmental conditions (Spink *et al.*, 1993). They also observed that delayed sowing shortens the duration of each developmental phase due to

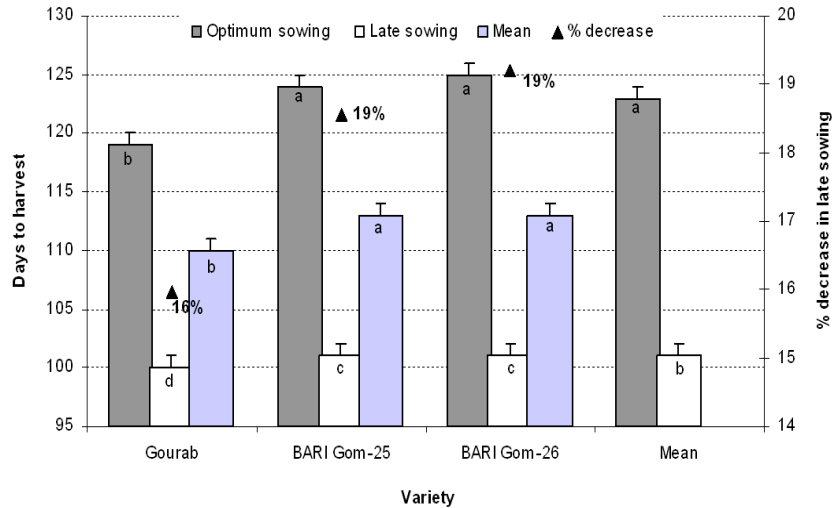


Fig. 8. Days passed to harvest of 3 wheat varieties when sown under optimum and very late conditions. Mean (\pm SD) was calculated from three replicates for each treatment. Bars with different letters are significantly different at $p \leq 0.05$ (LSD test)

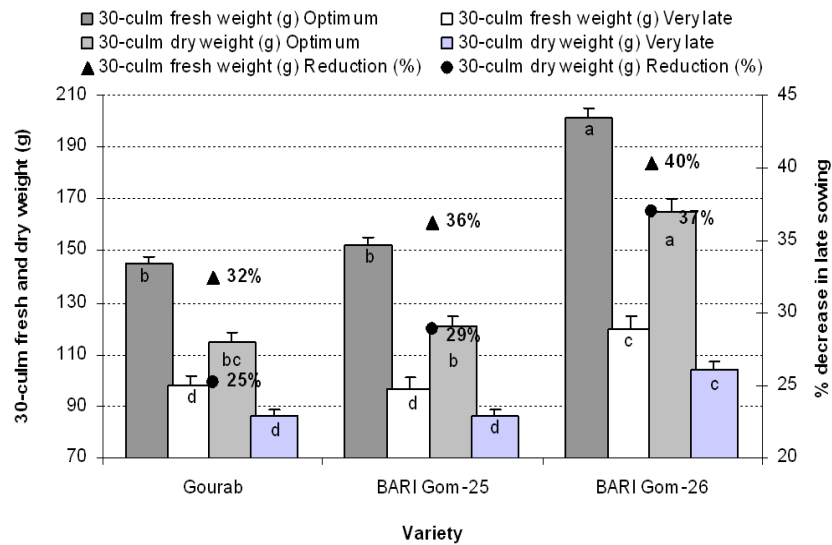


Fig. 9. 30-culm fresh and dry weights of 3 wheat varieties, sown under optimum and very late conditions. Mean (\pm SD) was calculated from three replicates for each treatment. Bars with different letters are significantly different at $p \leq 0.05$ (LSD test)

a rise in temperature. This observation is similar to that of our present research findings. In our research, DPM of all three varieties decreased significantly from OS to LS (Fig. 7). Among the 3 tested varieties, 'BARI Gom-26' and 'BARI Gom-25' were statistically similar but took the most time to reach PM in both OS and LS while 'Gourab' needed fewer days. However, in LS, all 3 varieties had a reduced life span from germination to physiological maturity. Among them, 'BARI Gom-26' and 'BARI Gom-25' needed 19% less time to reach PM than 'Gourab' which needed 15% less time as a result of heat stress during this period of LS (Fig. 7). Hakim *et al.* (2012); Hossain *et al.* (2011, 2012b, c) and Rahman *et al.* (2009) also observed that LS shortened the duration of each development phase due to high temperature stress at the reproductive stage.

Days to harvest maturity

Environmental factors affect the number of days required to reach or achieve different growth stages in wheat, but that this varies with genotype due to their different genetic makeup (Araus *et al.*, 2007). In the present study all 3 varieties matured earlier in LS than in OS. Among them, 'Gourab' matured earlier both in OS and LS while the two other varieties needed statistically more time to mature, 'Gourab' finally yielding lower GY (Fig. 8, 10). The temperature during the grain-filling or grain-maturing period was near 22°C in OS and >30°C in LS, which ultimately forced the life span to become complete (Fig. 1). There is also a similarity between this result and that of a 2-year study by Ubaidullah *et al.* (2006) in which heading, grain filling and grain maturity were 23, 3 and 29 days earlier

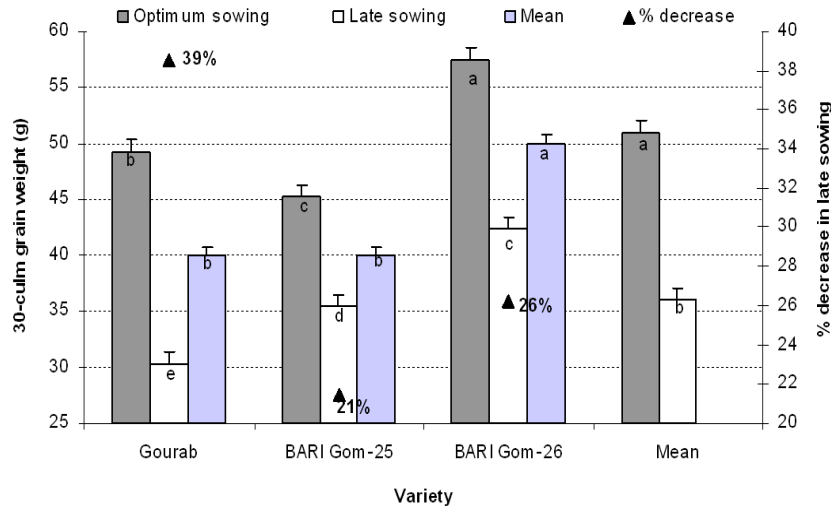


Fig. 10. Grain yield of 3 wheat varieties when sown under optimum and very late conditions. Mean (\pm SD) was calculated from three replicates for each treatment. Bars with different letters are significantly different at $p \leq 0.05$ (LSD test)

when wheat was sown late than when sown normally due to heat stress during LS. Due to heat stress in LS, 19% less time was required to reach DHM in 'BARI Gom-26' and 'BARI Gom-25' and 16% less time in 'Gourab'. Nahar *et al.* (2010) also observed a reduction in the number of required days to maturation in LS due to high temperature stress.

Fresh weight and dry weight

Under optimal conditions, 80 to 90% of the carbohydrates translocated to the wheat grain are assimilates from current photosynthesis and 10 to 20% from the plant's reserve (Spiertz and Vos, 1985). However, under stress conditions such as drought and high temperature, crops do not translocate carbohydrates to grain because in this situation the crop basically survives without production (Hall, 2001) or resource allocation (Martiniello and Teixeira da Silva, 2011). Hasan and Ahmed (2005) conducted a field experiment in Bangladesh (sub-tropical climate) and found that post-anthesis heat stress ($>26^{\circ}\text{C}$) reduced maximum dry matter accumulation due to a reduction in wheat kernel dry matter, mirroring our experimental results. In LS, all 3 tested varieties were highly affected by heat stress, expressed as a reduction in dry matter (FW and DW) and GY (Fig. 9; 10). For these parameters, 'BARI Gom-26' performed better, followed by 'BARI Gom-25' while 'Gourab' performed worst in LS. Due to heat stress in LS, the highest reduction in FW and DW was 40 and 37% in 'BARI Gom-26', followed by 'BARI Gom-25' (29 and 36%) and the least reduction was 25 and 32% in 'Gourab' (Fig. 9). Ahamed *et al.* (2010) evaluated 5 existing wheat varieties of Bangladesh under two growing conditions (optimum and late) and showed that dry matter partitioning and production in all 5 varieties was affected at LS due to heat stress (30 to 32°C), resulting in reduced GY.

Grain yield

Sowing time is the most important for temperature-sensitive cereals such as wheat, barley, sorghum, etc., but the time of planting and their effectiveness on a plant varies from region to region. In Kansas, USA, planting during OS encourages tillering during fall and spring, reduces competition among tillers, and promotes a high harvest index (HI). Early planting causes excessive tillering, increases competition, and leads to a low HI. LS wheat decreases tillering during fall and spring and causes tillers that develop during spring to be small with a low HI (Thiry *et al.*, 2002). In Bangladesh, early wheat faces high temperature stress at the vegetative stage and LS wheat is affected at two stages: germination by low temperature stress ($<10^{\circ}\text{C}$) and at the reproductive stage by high temperature ($>25^{\circ}\text{C}$), which ultimately affects GY (Hossain *et al.*, 2011; 2012c). Every 1°C rise in temperature above the optimum (15°C) reduces yield by 3-4% per spike (Wardlaw *et al.*, 1989a, 1989b).

In our present study, all 3 varieties were highly affected by heat stress in LS than in OS, which finally drastically reduced GY. Among the 3 varieties, 'BARI Gom-26' produced statistically highest GY both in OS and LS, followed by 'BARI Gom-25' while 'Gourab' produced least GY. However, the rate of reduction varied from genotype to genotype. Among 3 varieties, 'Gourab' (39% yield reduction in LS) was highly affected by high temperature stress in LS than 'BARI Gom-25' (21% yield reduction in LS) and 'BARI Gom-26' (26% yield reduction in LS) (Fig. 10). In our research, fluctuations in weather conditions (Fig. 1) were reflected in phenology, crop growth and development (Fig. 2 to 9) and ultimately GY (Fig. 10), which is common to several crops (Martiniello and Teixeira da Silva, 2011). Previous research findings also indicated that high temperature significantly decreased all traits, especially GY (by 46.63%), 1000-kernel weight (by 20.61%)

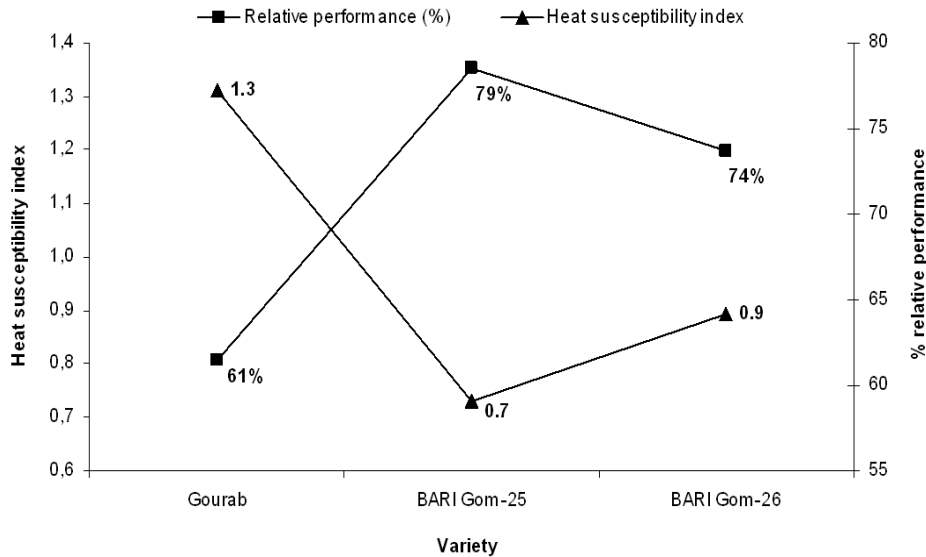


Fig. 11. Relative performance (%) and heat susceptibility index of 3 wheat varieties in very late heat stress condition, as compared with optimum sowing

and grain filling duration (by 20.42%) under high temperature stress (>25 to 30°C) (Modarresi *et al.*, 2010).

Relative yield performance and heat susceptibility index

The performance of different genotypes under stress may be observed by calculating RP% (Asana and Williams, 1965) and HSI (Fischer and Maurer, 1978). Rahman *et al.* (2009) also reported genotypic variation in RP% of sensitive and tolerant genotypes, and a higher RP% indicated that the genotype was tolerant to stress. There is a similarity between the above findings and the present study: in LS, the RP% of all genotype ranged from 61 to 79% (Fig. 11) Among the 3 varieties, higher RP% was found in 'BARI Gom-25' (79%), lowest in 'Gourab' (61%). Considering the HSI value, 'Gourab' (1.3) was higher than 1.0 in LS, indicating that this genotype had no tolerance to high temperature. The HSI of 'BARI Gom-25' (0.7) and 'BARI Gom-26' (0.9) showed moderate heat stress tolerance (Fig. 11). Among the 3 varieties, 'BARI Gom-25' (RP% = 79; HSI = 0.7) was moderately heat tolerant, followed by 'BARI Gom-26' (RP% = 74; HSI = 0.9) while 'Gourab' was heat sensitive (RP% = 61; HSI = 1.3).

Conclusions

From the above results and discussion, due to high temperature stress in LS, duration of life cycle stages of our tested wheat varieties was reduced. OS (i.e. optimum sowing on November 15) resulted in better performance of all varieties than late sowing (i.e., LS on December 27). From overall performance (phenology, growth, yield and heat tolerance parameters), 'BARI Gom-25' and 'BARI Gom-26' were considered to be the best performing varieties under heat stress while 'Gourab' was found to be sensitive to heat.

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