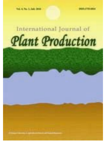

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# Evaluation of growth, yield, relative performance and heat susceptibility of eight wheat (*Triticum aestivum* L.) genotypes grown under heat stress

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## Abstract

Eight spring wheat cultivars were evaluated under three heat stress conditions (early, late and very late) in order to identify suitable cultivars to develop heat-tolerant genotypes resistant to future global warming. Results from the study indicate that stress did not negatively affect flag leaf area in ‘Prodip’ and ‘Sufi’, flag leaf dry matter partitioning in ‘Prodip’, ‘BARI Gom-26’ and ‘Shatabdi’, above-ground dry matter partitioning in ‘Shatabdi’ and ‘BARI Gom-26’, seedling emergence in ‘Sufi’ and ‘BARI Gom-26’, or tiller production in ‘Sufi’ and ‘BARI Gom-26’. With respect to lower yield reduction, relative performance and heat susceptibility index (HSI), ‘Sufi’ was highly heat stress-tolerant, followed by ‘BARI Gom-26’ and ‘Shatabdi’. On the basis of HSI values in early heat stress and extremely late heat stress (corresponding to early and extremely late sowing), ‘BARI Gom-26’ (HSI=0.10, 0.65) and ‘Shatabdi’ (0.22, 0.62) were highly tolerant to early heat stress and moderately tolerant to extremely late heat stress while ‘Sufi’ was highly tolerant (0.35) to extremely late heat stress and moderately tolerant (0.51) to early heat stress. All other genotypes were susceptible to heat stress, among which ‘Gourab’ (2.19, 1.46) was the most susceptible followed by ‘Sourav’ (1.19, 1.42), ‘Prodip’ (1.03, 1.23), ‘BARI Gom-25’ (1.61, 0.89) and ‘Bijoy’ (1.04, 1.28). Thus, ‘BARI Gom-26’, ‘Shatabdi’ and ‘Sufi’ have the greatest potential to be used as high-yielding wheat genotypes under warm to hot environments and could be used in a breeding programme to develop heat-tolerant wheat.

***Keywords:*** High-temperature; Wheat; Genotype; Growth and development.

***Running title:*** Growth and development of wheat under heat stress. Hossain et al.

## Introduction

Plant growth and crop yield depend on temperature and its extremes. The optimum temperature range for $C_3$ crops is 15-20 °C and for $C_4$ crops it is 25-30 °C (Ruan et al., 2012). The variation in temperature requirements and temperature extremes varies widely for different cultivars of the same species, and among species, it varies widely for most crops. The reproductive phase of many crop species is relatively more sensitive to heat stress than the vegetative phase (Hall, 1992; Martiniello and Teixeira da Silva, 2011). Vegetative growth and the reproductive phase in wheat differ in their sensitivity to temperature (Almeselmani et al., 2011; Chakrabarti et al., 2011; Hossain et al., 2011a; Karmanenko et al., 2011; Khakwani et al., 2011; Al-Karaki, 2012; Hakim et al., 2012; Hossain and Teixeira da Silva, 2012a; Hossain et al., 2012a; Hossain et al., 2012b; Hossain et al., 2012c; Hossain et al., 2012d; Noorka and Teixeira da Silva, 2012; Noorka et al., 2013).

A study conducted by the International Food Policy Research Institute (IFPRI) indicated that the world demand for wheat will have risen from 552 million tons in 1993 to 775 million tons by 2020 (Rosegrant et al., 1997; Hossain and Teixeira da Silva, 2012b). 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% (Lobell et al., 2008; Hossain and Teixeira da Silva, 2012b).

In Bangladesh, wheat occupies second place in terms of grain production after rice, but its yield is lower than other wheat-growing countries around the world (Hossain and Teixeira da Silva, 2012b). Poor yield in hot countries such as Bangladesh is usually blamed on high temperature, which has been confirmed by careful observations and experimentation (Hossain et al., 2009; Hossain et al., 2011a; Hakim et al., 2012; Hossain and Teixeira da Silva, 2012a; Hossain et al., 2012a; Hossain et al., 2012b; Hossain et al., 2012c; Hossain et al., 2012d). On the basis of Intergovernmental Panel on Climate Change (IPCC, 2007) and climatic data received from 34 meteorological climate sites of Bangladesh (Islam, 2009), Poulton and Rawson (2011), concluded that temperature in Bangladesh is increasing and will likely impact the future of agriculture in Bangladesh.

The adverse effect of temperature can be minimized by sowing a wheat crop within the optimum period or to breed heat-tolerant genotypes that could be sown late and very early to ensure high grain yield. Therefore, the present study was conducted to identify heat-tolerant and heat-sensitive wheat genotypes for future breeding to develop heat-tolerant cultivars.

## Materials and Methods

The study was conducted in an experimental field of the Wheat Research Center (WRC), Dinajpur, Bangladesh during November to April 2007-08 and 2008-09. The Agro-Ecological Zone (AEZ) of the area is Old Himalayan Piedmont Plain (AEZ-1) (FAO/UNDP, 1988). The geographical position of the area lies between 25° 38′ N, 88° 41′ E and lies 38.20 m above sea level. The soil of the experimental field is sandy loam and acidic having less than 1% of organic matter content. The quantity of N (nitrogen), K (potassium), S (sulphur), B (boron), Mg (magnesium) and Zn (zinc) was below the critical level, but P (phosphorus) was higher than the critical level (Hossain et al., 2011b).

Eight spring wheat varieties (‘Sourav’, ‘Gourab’, ‘Shatabdi’, ‘Sufi’, ‘Bijoy’, ‘Prodip’, ‘BARI Gom-25’ and ‘BARI Gom-26’) were used as experimental materials. The performance of these varieties was evaluated under four growing conditions: early heat stress (sown on 8 November) (EHS), optimum sowing (OS) condition (22 November), late heat stress (13 December) (LHS) and extremely late heat stress (EXLHS) (27 December).

The experiment was conducted in a randomized complete block design (RCBD) with three replications. Unit plot size was 1.6×4 m. Seeds were treated with Provax-200 WP, an effective fungicide for seeds containing Carboxin and Thiram. Seeds were sown at 120 kg ha$^{-1}$ in lines 20 cm apart. Recommended fertilizer doses, 100-27-40-20-1 kg ha$^{-1}$ of N-P-K-S-B, respectively, were applied. Plants were irrigated at the crown root initiation {21 days after sowing (DAS)}, booting (55 DAS) and grain-filling (75 DAS) stages. Intercultural operations were done when required and depending on treatments.

Data on number of seedling emergence m$^{-2}$ (NSE) at 10, 12, 14 and 16 DAS, number tillers m$^{-2}$ (NT) at 35, 40, 45, 50 DAS, flag leaf area (FLA), dry matter yield of flag (DMYFL) and dry matter partitioning of above-ground parts (DMPAGP) just after the grain-filling stage (ZS 7.1) were recorded.

ZS (Zadoks et al., 1974) was followed for these growth stages since this scale has been described as the most comprehensive and easiest scale, providing a good description for both vegetative and reproductive stages of cereals (Harrel et al., 1993).

Flag leaf area was measured by a leaf area meter (Model-CI-202, CID Inc., USA) from five flag leaves of five plants, and then averaged. Dry weight of 10 flag leaves from 5 plants and above-ground parts $m^{-2}$ were harvested then dried in an electric oven at 60 °C for 72 h and finally weighed on a digital balance.

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, 6 middle rows), avoiding border effects. The harvested sample crop of each plot was bundled separately, tagged and placed on a threshing floor. The bundles were thoroughly dried in bright sunshine until fully dried, then weighed and threshed.

Data on grain yield (g $m^{-2}$) (GY) was determined and adjusted to 12% moisture level by the following equation (Hellevang, 1995).

$$\mathrm{Y}\ (\mathrm{M}_2)= \frac{100 - M_1}{100 - M_2} \times Y(M_1)$$

Where

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

Y ($M_1$)= weight of grain at actual moisture percentage;

$M_1$=actual moisture percentage;

$M_2$=expected moisture percentage.

To compare the yield performance of a genotype, relative performance (RP%) for yield was calculated as described by Asana and Williams (1965) and was expressed as a percentage:

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

Heat Susceptibility Index (HSI) was used to measure stress tolerance in terms of minimizing the reduction in yield caused by unfavorable versus favorable environments. HSI was calculated for each genotype according to the formula of Fisher and Maurer (1978):

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

where

Y= mean grain yield of a genotype under a stressed 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.

In this experiment, stress implies high temperature combined with drought. If HSI is < 0.5, then the genotype is highly stress tolerant, if HIS > 0.5 < 1.0, it is moderately stress tolerant, and if HIS > 1.0, it is susceptible to stress.

Temperature data (Figure 1) was recorded regularly by the HOBO U12 Family of Data Loggers (MicroDAQ.com) at the Meteorological Station, WRC, Dinajpur, Bangladesh. The data of all parameters were analyzed using MSTAT-C (Russell, 1994). Treatments means were compared for significance by using the LSD test at the 5% level of probability.

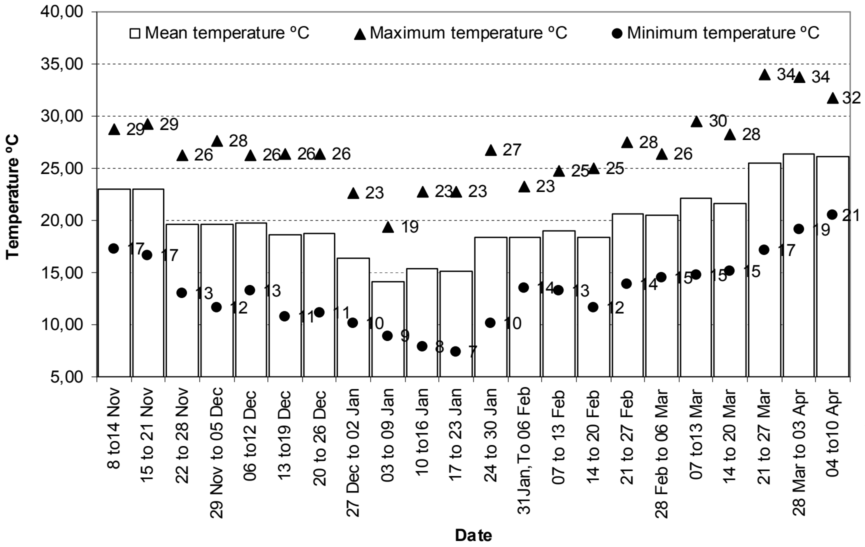

Figure 1. Temperature during the wheat growing period (Source: Meteorological Station, Wheat Research Center, Nashipur, Dinajpur, Bangladesh).

## Results

### *Weather conditions during the wheat-growing period*

It can be observed from Figure 1 that EHS (8 November) and maximum temperature in the vegetative stage was near or above 26 °C and the minimum was ≤15 °C, but at the grain-filling stage, the maximum was ≥25 °C and the minimum was 10-12 °C. The temperature at the vegetative stage was not suitable for good yield because maximum temperature was >26 °C (Figure 1). When wheat was sown on 22 November (OS), mean maximum temperature in the vegetative stage neared 25 °C and the minimum neared 10 °C, but at the grain-filling stage mean maximum temperature also neared 24 °C and minimum neared 13.5-14 °C, which is suitable for good yield in a wheat crop. Under EXLHS (27 December), i.e., at the vegetative growing stage, maximum temperature was ≥26 °C and minimum ≤10 °C, but at the grain-filling stage, maximum temperature was >30 °C and the minimum was ≤18-20 °C (March-April), which is not suitable for proper growth and good yield in wheat because it is sown late. The temperature during germination was <10 °C and in the grain-filling stage, it was >30 °C, which affected the growth and development of the ELS crop (Figure 1).

### *Number of seedling emergence m$^{-2}$*

From sowing to emergence, seedling mortality, and hence crop establishment, is a problem when soil temperatures are high. In the present study, the interaction effect of sowing time and varieties was not significant for NSE counted at 10, 12, 14 and 16 DAS (Table 1). From Figure 1 it can be observed that temperature was between 19 and 23 °C (average day + night temperature) in the germination stage of EHS, 18 to 19 °C at OS, 14 to 19 °C at LHS and 14 to 15 °C at EXLHS, which did not exceed the optimum and maximum range for germination (Table 1).

### *Number of tillers*

Tillers are an important component of wheat yield because they have the potential to develop grain-bearing heads. The NT of a developed plant is not constant and will vary because of two factors: genetic potential and environmental conditions. Some varieties have a greater potential to develop more tillers than others and may change in response to different environmental conditions. Plants are likely to produce more tillers when environmental conditions such as temperature, moisture, and light are favorable, when plant populations are low and soil fertility levels are high. In our study, the NT of wheat cultivars was significantly affected by sowing date (Table 2). Observing data recorded on different DAS, all varieties produced maximum NT in OS and minimum was in EHS, with few exceptions. Figure 1 shows that in OS, wheat faced high temperature stress from germination to the vegetative stage, resulting in reduced tillering capacity and poor crop establishment. On the other hand, in LHS and EXLHS, wheat faced low temperature stress at germination through to the seedling stage, resulting in poor germination and fewer tillers. 'Shatabdi' produced maximum NT in OS and EHS, followed by 'Gourab' and 'Sufi'. In LHS and EXLHS, 'Sufi' produced maximum NT due to better germination and stand establishment than other cultivars (Tables 1, 2). Considering all sowing times and all varieties, 'Sufi' produced higher NT followed by 'Shatabdi', while 'Bijoy' produced the least.

### *Flag leaf area*

In the present study, a higher FLA of all genotypes was found in OS compared to heat stress (Figure 2), which ultimately affected grain yield. In OS, higher FLA was found in 'Sufi', followed by 'Shatabdi' and 'Prodip'. On the other hand, no significance differences were noted in EXLHS, except for 'Gourab'. Leaf senescence may have been enhanced by higher temperature, which reduced green LA.

### *Dry matter yield of flag leaf*

In this study, the maximum values of DMYFL for all varieties were obtained under OS and the lowest values under stress conditions (EHS, LHS, EXLHS), which was due to high temperature stress (Figures 1, 3). 'Prodip' produced the highest DMYFL in all sowing conditions, except for EHS while the lowest DMYFL was found in 'Bijoy' under EHS, followed by 'Prodip' under EHS and 'Sufi' under EXLHS (Figure 3). The reduction in DMYFL was higher under EHS and EXLHS, but the reduction was genotype-dependent. Compared with OS, the reduction in DMYFL under OS and EXLHS was 34.00 and 28.28% in 'Sourav', 18.16 and 30.82% in 'Gourab', 16.30 and 26.79% in 'Shatabdi', 22.82 and 38.79% in 'Sufi', 37.98 and 19.25% in 'Bijoy', 52.79 and 34.82% in 'Prodip', 32.81 and 22.44% in 'BARI Gom-25' and 3.99 and 15.65% in 'BARI Gom-26', respectively (Figure 3).

Table 1. Seedling emergence m$^{-2}$ of wheat genotypes as affected by different levels of heat stress during different sowing times.

| Genotypes | Seedling emergence at 10 DAS | | | | Mean | Seedling emergence at 12 DAS | | | | Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| | EHS (08 Nov.) | OS (22 Nov.) | LHS (13 Dec.) | EXLHS (27 Dec.) | | EHS (08 Nov.) | OS (22 Nov.) | LHS (13 Dec.) | EXLHS (27 Dec.) | |
| Sourav | 237.33 | 232.67 | 276.00 | 273.33 | 254.83 | 229.33 | 233.33 | 279.67 | 276.67 | 254.75 |
| Gourab | 275.33 | 229.67 | 296.33 | 235.33 | 259.17 | 265.33 | 240.00 | 293.33 | 252.00 | 262.67 |
| Shatabdi | 257.33 | 272.33 | 232.67 | 259.33 | 255.42 | 246.00 | 271.33 | 231.33 | 262.67 | 252.83 |
| Sufi | 378.00 | 305.33 | 404.00 | 368.67 | 364.00 | 370.00 | 308.00 | 404.00 | 380.00 | 365.50 |
| Bijoy | 239.33 | 193.33 | 248.00 | 220.67 | 225.33 | 230.67 | 198.67 | 248.33 | 226.67 | 226.09 |
| Prodip | 234.00 | 242.67 | 274.00 | 252.67 | 250.84 | 224.00 | 238.00 | 273.00 | 250.00 | 246.25 |
| BARI Gom-25 | 228.67 | 212.00 | 273.00 | 258.00 | 242.92 | 223.33 | 212.67 | 281.33 | 270.33 | 246.92 |
| BARI Gom-26 | 223.33 | 215.33 | 290.67 | 262.67 | 248.00 | 228.00 | 218.67 | 287.33 | 284.67 | 254.67 |
| CV (%) | 11.22 | | | | | 11.07 | | | | |
| LSD $_{(0.05)}$ | ns | | | | | ns | | | | |

| Genotypes | Seedling emergence at 14 DAS | | | | Mean | Seedling emergence at 16 DAS | | | | Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| | EHS (08 Nov.) | OS (22 Nov.) | LHS (13 Dec.) | EXLHS (27 Dec.) | | EHS (08 Nov.) | OS (22 Nov.) | LHS (13 Dec.) | EXLHS (27 Dec.) | |
| Sourav | 226.67 | 240.00 | 281.33 | 280.00 | 257.00 | 250.67 | 240.67 | 276.00 | 276.67 | 261.00 |
| Gourab | 268.00 | 249.33 | 301.33 | 258.00 | 269.17 | 277.33 | 241.33 | 292.67 | 256.00 | 266.83 |
| Shatabdi | 251.33 | 395.33 | 230.67 | 266.00 | 285.83 | 258.00 | 268.67 | 226.00 | 262.00 | 253.67 |
| Sufi | 372.00 | 308.67 | 419.33 | 379.33 | 369.83 | 375.33 | 308.67 | 412.67 | 372.67 | 367.34 |
| Bijoy | 230.00 | 192.67 | 246.67 | 232.67 | 225.50 | 242.00 | 197.33 | 248.00 | 244.00 | 232.83 |
| Prodip | 228.67 | 237.33 | 280.67 | 265.33 | 253.00 | 246.00 | 232.00 | 270.00 | 264.67 | 253.17 |
| BARI Gom-25 | 227.33 | 220.67 | 273.33 | 271.00 | 248.08 | 219.33 | 220.67 | 264.00 | 268.0 | 243.00 |
| BARI Gom-26 | 244.67 | 216.67 | 300.00 | 286.00 | 261.84 | 260.00 | 218.00 | 298.00 | 266.67 | 260.67 |
| CV (%) | 18.53 | | | | | 10.47 | | | | |
| LSD $_{(0.05)}$ | ns | | | | | ns | | | | |

‘ns’=non-significant. EHS-early heat stress, OS-optimum sowing, LHS-late heat stress; EXLHS-extremely late heat stress.

Table 2. Tillers m$^{-2}$ of wheat genotypes as affected by different levels of heat stress during different sowing times.

| Genotypes | Tillers m$^{-2}$ (no.) counted at 35 DAS | | | | Mean | Tillers m$^{-2}$ (no.) counted at 40 DAS | | | | Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| | EHS (08 Nov.) | OS (22 Nov.) | LHS (13 Dec.) | EXLHS (27 Dec.) | | EHS (08 Nov.) | OS (22 Nov.) | LHS (13 Dec.) | EXLHS (27 Dec.) | |
| Sourav | 556.0 j-n | 676.3 c-f | 636.0 fgh | 586.0 h-l | 613.58 | 561.7 k-n | 688.7 b-g | 646.0 e-j | 605.0 h-l | 625.35 |
| Gourab | 547.3 j-n | 720.7 bc | 628.0 f-i | 644.7 efg | 635.18 | 541.3 lmn | 734.7 abc | 636.0 g-k | 656.0 d-i | 642.00 |
| Shatabdi | 671.7 c-f | 729.3 ab | 652.0 def | 571.3 j-n | 656.08 | 696.3 b-g | 758.0 ab | 669.3 c-h | 583.3 i-m | 676.73 |
| Sufi | 696.0 b-e | 702.7 bcd | 747.0 ab | 711.3 bc | 714.25 | 640.7 f-j | 717.3 a-e | 762.7 ab | 724.7 a-d | 711.35 |
| Bijoy | 489.3 o | 563.3 j-m | 537.3 l-o | 375.3 p | 491.30 | 498.0 no | 580.0 j-m | 544.0 lmn | 398.0 p | 505.00 |
| Prodip | 412.7 p | 673.3 c-f | 539.3 k-o | 532.0 mno | 539.33 | 431.3 op | 664.7 c-h | 556.0 lmn | 548.0 lmn | 550.00 |
| BARI Gom-25 | 519.3 no | 578.0 i-m | 590.7 h-k | 632.0 fgh | 580.00 | 528.7 mn | 587.3 i-m | 604.0 h-l | 638.7 g-j | 589.68 |
| BARI Gom-26 | 592.7 g-j | 700.3 bcd | 705.0 bc | 776.7 a | 693.68 | 578.0 j-m | 715.3 a-f | 718.0 a-e | 784.7 a | 699.00 |
| CV (%) | 5.23 | | | | | 7.35 | | | | |
| LSD $^{(0.05)}$ | 52.66 | | | | | 75.09 | | | | |
| Genotypes | Tillers m$^{-2}$ (no.) at 45 DAS | | | | Mean | Tillers m$^{-2}$(no.) at 50 DAS | | | | Mean |
| | EHS (08 Nov.) | OS (22 Nov.) | LHS (13 Dec.) | EXLHS (27 Dec.) | | EHS (08 Nov.) | OS (22 Nov.) | LHS (13 Dec.) | EXLHS (27 Dec.) | |
| Sourav | 539.7 j-n | 642.0 c-h | 623.3 c-i | 606.0 d-l | 602.75 | 512.7 i-m | 598.0 b-h | 575.3 d-i | 560.7e-j | 561.68 |
| Gourab | 526.7 mn | 702.0 abc | 610.0 d-k | 644.0 c-g | 620.68 | 464.7 lmn | 663.0 abc | 592.0 b-i | 629.3 a-f | 587.25 |
| Shatabdi | 649.3 b-f | 736.3 a | 662.7 a-e | 578.7 f-n | 656.75 | 584.0 c-i | 702.7 a | 637.3 a-e | 535.3 h-l | 614.83 |
| Sufi | 608.7 d-k | 682.7 a-d | 732.0 a | 701.3 abc | 681.18 | 553.3 f-k | 636.7 a-e | 700.7 a | 640.0 a-e | 632.68 |
| Bijoy | 446.0 op | 564.0 h-n | 538.0 k-n | 370.7 p | 479.68 | 431.7 mno | 520.7 h-l | 516.0 i-l | 357.3 o | 456.43 |
| Prodip | 419.3 p | 676.7 a-d | 544.7 i-n | 528 lmn | 542.18 | 399.3 no | 618.0 b-g | 522.0 h-l | 481.3 j-m | 505.15 |
| BARI Gom-25 | 507.3 no | 568.7 g-n | 592.7 e-m | 617.3 d-j | 571.50 | 476.0 k-n | 514.0 i-l | 544.7 g-l | 540.0 g-l | 518.68 |
| BARI Gom-26 | 557.3 i-n | 683.3 a-d | 727.3 ab | 740.7 a | 677.15 | 537.3 g-l | 666.0 ab | 670.0 ab | 651.3 a-d | 619.53 |
| CV (%) | 8.00 | | | | | 8.87 | | | | |
| LSD $^{(0.05)}$ | 78.99 | | | | | 81.72 | | | | |

Mean followed by the same letter(s) within a parameter do not differ significantly at 5% level of LSD. EHS-early heat stress, OS-optimum sowing, LHS-late heat stress; EXLHS-extremely late heat stress.

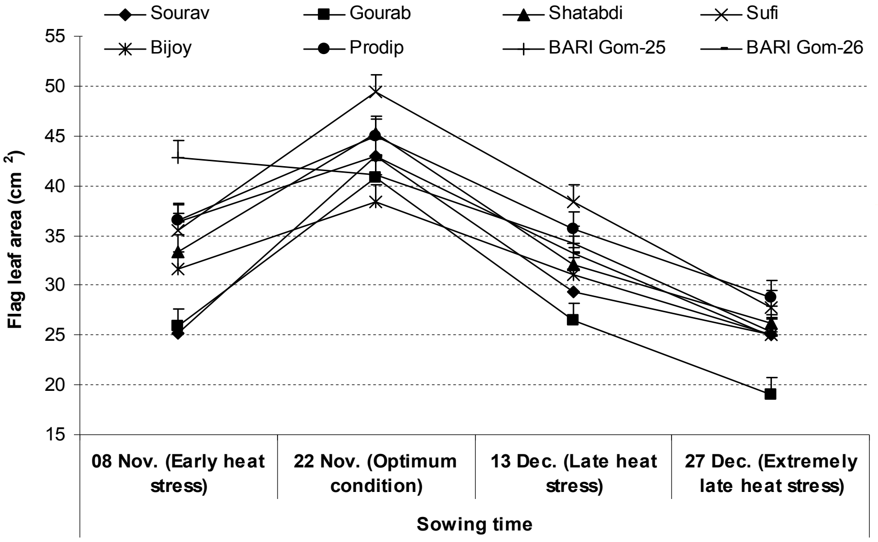

Figure 2. Flag leaf area of different wheat genotypes as affected by temperature. Bars indicate the mean standard deviations (±SD), which are significantly different at P≤0.01 (LSD test).

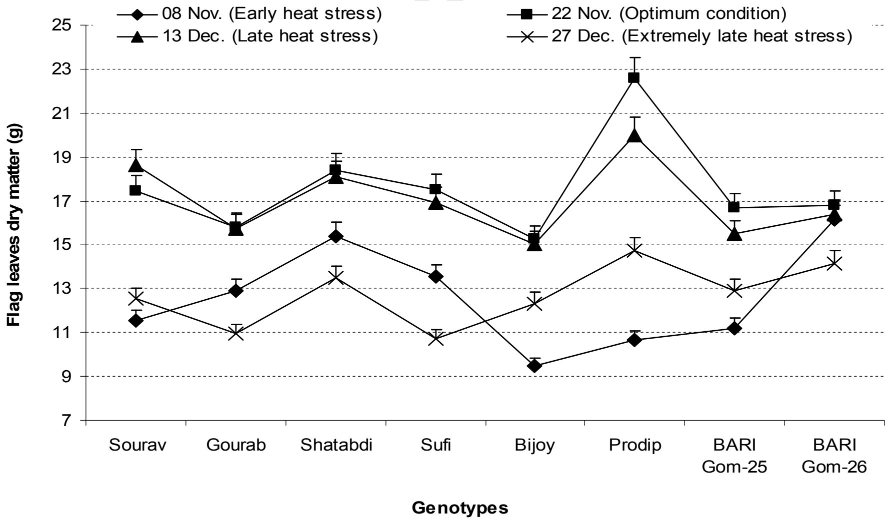

Figure 3. Flag leaf dry matter of different wheat genotypes as affected by temperature. Bars indicate the mean standard deviations (±SD), which are significantly different at P≤0.01 (LSD test).

### *Dry matter partitioning of above-ground parts*

In this study, wheat sown under EHS was highly affected by heat stress followed by EXLHS and LHS (Figure 4). In EHS, the crop faced high temperature from germination to the vegetative stage, resulting in poor germination, lower plant population, loss of viable leaf area and a decrease in green leaf duration, ultimately hampering photosynthesis (Figures 1, 4). 'Shatabdi' sown in OS produced maximum DMPAGP followed by 'Shatabdi' sown in LHS (Figure 4). On the other hand, 'Gourab' sown in EHS produced the lowest DMPAGP, followed by 'Sourav' and 'Sufi', also in EHS. Compared to OS, the dry matter reduction of EHS, LHS and EXLHS was 32.59, 11.43 and 25.04% in 'Sourav', 40.56, 8.07 and 17.29% in 'Gourab', 26.59, 17.58 and 24.78% in 'Shatabdi', 15.82, 6.72 and 7.25% in 'Sufi', 17.12, 7.46 and 19.99% in 'Bijoy', 26.09, 2.85 and 22.44% in 'Prodip', 16.34, 4.09 and 14.88% in 'BARI Gom-25' and 27.97, 1.55 and 4.12% in 'BARI Gom-26', respectively. In LHS and EXLHS, 'BARI Gom-26' was less affected by heat stress (1.55 and 4.12%), but at EHS, 'Sufi' (15.82%) was less affected than other varieties. Considering DMPAGP, 'Gourab' in EHS and 'Sourav' in EXLHS were highly heat sensitive (Figure 4). As observed in Figure 1, in EHS, the crop faced an unfavorable (high temperature) environment from germination to the vegetative stage, and in LHS and EXLHS, it faced unfavorable conditions at the reproductive stage, ultimately affecting DMPAGP and yield (data not presented).

### *Grain yield*

In our study (Figure 5), all varieties in OS produced higher GY than all stress conditions (EHS, LHS and EXLHS). 'Sourav', 'Gourab', 'Prodip' and 'BARI Gom-26' in OS produced statistically higher and similar GY (Figure 5). Comparing all varieties and sowing conditions, 'BARI Gom-26' produced higher GY in all stress conditions, followed by 'Shatabdi' in EHS, 'Prodip' in LHS and 'Sufi' in EXLHS, which might be due to the stress tolerance of these varieties. Considering yield reduction in heat stress condition (EHS, LHS and EXLHS), compared to OS, 'BARI Gom-26' was the lowest (2, 7 and 20%), followed by 'Sufi' (9, 12 and 11%) and 'Shatabdi' (4, 20 and 19%) and 'Gourab' was the highest (40, 27 and 45%) (Figure 5).

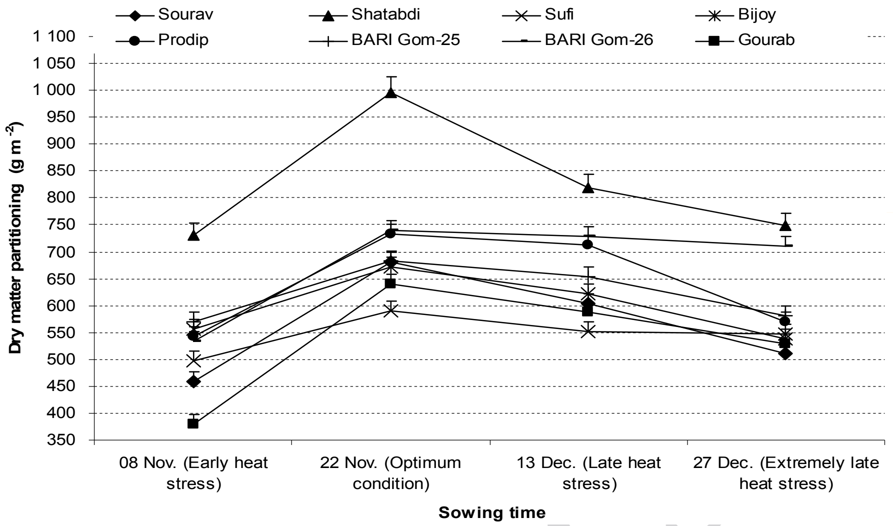

Figure 4. Dry matter partitioning of different wheat genotypes as affected by temperature. Bars indicate the mean standard deviations (±SD), which are significantly different at P≤0.01 (LSD test).

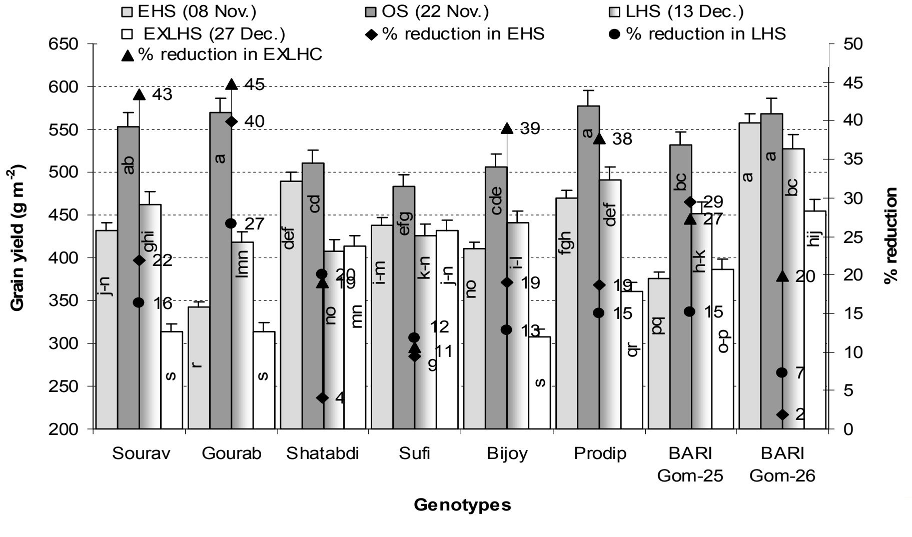

Figure 5. Grain yield (g m$^{-2}$) of different wheat genotypes as affected by temperature. Bars with different letter(s) and error bars (±SD), indicated significantly different at P≤0.01 (LSD test). EHS-early heat stress, OS-optimum sowing, LHS-late heat stress; EXLHS-extremely late heat stress.

### *Relative performance*

To compare the yield performance of a genotype under normal conditions and heat stress, relative performance (RP%) for yield is the parameter that can identify tolerance to heat stress. 'BARI Gom-26' (98 and 93%) was heat tolerant in EHS and LHS followed by 'Shatabdi' (96 and 88%) and 'Sufi' (91 and 87%) in EHS and LHS while 'Gourab' (60, 73 and 55%) was heat sensitive in EHS, LHS and EXLHS conditions, based on RP% values (Figure 6). On the other hand, in EXLHS, 'Sufi' (89%) was heat stress tolerant, followed by 'BARI Gom-26' (80%) and 'Shatabdi' (81%).

### *Heat susceptibility index*

HSI may be calculated separately in different stress environments to assess their stress potential. In this study, the HSI of 'Sourav', 'Gourab', 'Bijoy', 'Prodip' and 'BARI Gom-25' was higher than 1.0, indicating that these genotypes had no tolerance to heat stress in EHS and EXLHS (Figure 7). The HSI values of the remaining three wheat genotypes indicate their various levels of tolerance to high temperature. Among them, 'BARI Gom-26' (HSI=0.10, 0.65) and 'Shatabdi' (HSI=0.22, 0.62) were highly tolerant and moderately tolerant to heat stress in EHS and EXLHS, respectively. On the other hand, 'Sufi' was highly tolerant (HSI=0.35) and moderately tolerant (HSI=0.51) to heat stress in EXLHS and EHS, respectively (Figure 7). 'Sufi', 'BARI Gom-26' and 'Shatabdi' also showed high RP% under heat stress (Figure 6). Thus, it can be considered that these varieties are tolerant to heat stress.

## Discussion

In our research, fluctuations in weather conditions (Figure 1) were reflected in crop growth and development (Tables 1, 2; Figures 2-4) and ultimately by yield (Figure 5), which is common among several crops (Martiniello and Teixeira da Silva, 2011; Hakim et al., 2012; Hossain and Teixeira da Silva, 2012a; Hossain et al., 2012a; Hossain et al., 2012b; Hossain et al., 2012c; Hossain et al., 2012d).

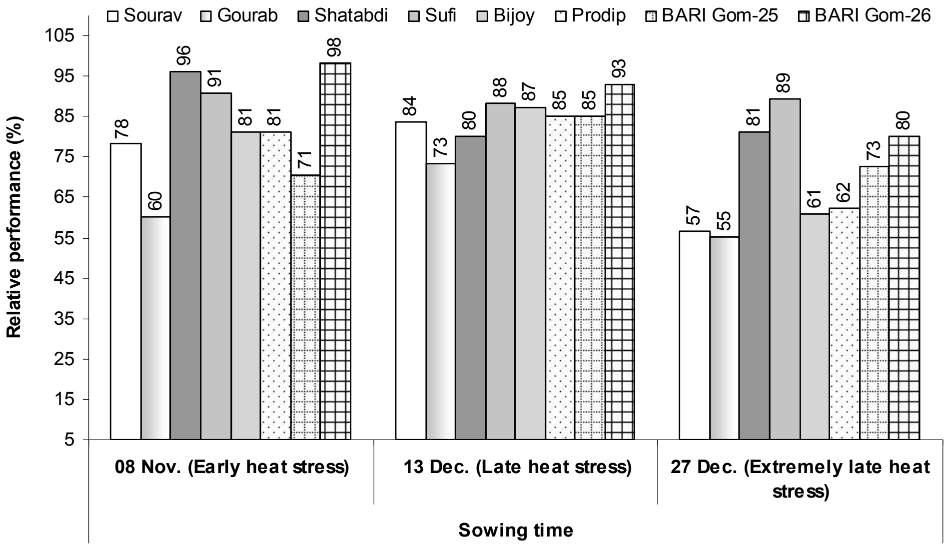

Figure 6. Relative performance (%) of grain yield in different wheat genotypes under heat stress conditions.

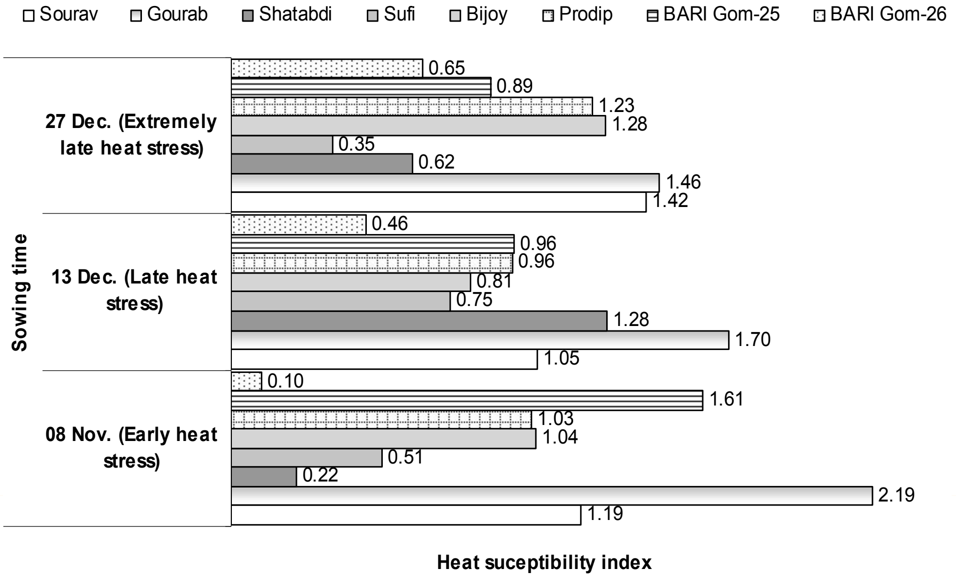

Figure 7. Heat susceptibility index of different genotypes under heat stress conditions.

### *Number of seedling emergence m$^{-2}$*

Seed germination is one of the most important phases effecting yield and quality in crop production (Almansouri et al., 2001). Further, the interaction between seedbed environment and seed quality plays an important role in the establishment of a crop (Khajeh-Hosseini et al., 2003). Hakim et al. (2012); Hossain and Teixeira da Silva (2012a); Hossain et al. (2012a); Hossain et al. (2012b); Hossain et al. (2012c) and Hossain et al. (2012d) reported favorable temperature for germination to be between 12 and 25 °C, and if maximum soil temperature reached 30 to 45 °C, seriously affecting seedling emergence, this would affect the initial plant population, and ultimately a loss in crop yield. Those authors also reported that when soil moisture and air temperature were low (<12 °C), germination was delayed, adversely affecting crop establishment, similar to our findings in which germination of all genotypes at EXLHS took longer than at OS, possibly because of low temperature (Table 1; Figure 1). When all varieties were compared, numerical differences were recorded in all four sowing conditions which might be due to varietal differences of seed size and seed rate. This notion is supported by Sarker et al. (2009), who stated that the plant population of wheat varieties is dependent on seed size i.e., number of plants/unit area was higher in a variety that had smaller seed.

### *Number of tillers*

The results of our study, with respect to number of tillers plant$^{-1}$ (Table 2), show a parallel resemblance to the following findings in wheat: In the late planting season, soil temperature can be expected to be below 10 °C, which affects seed germination and stand establishment, ultimately producing few tillers and finally decreasing grain yield (Farooq et al., 2008; Hakim et al., 2012; Hossain and Teixeira da Silva, 2012a; Hossain et al., 2012a; Hossain et al., 2012b; Hossain et al., 2012c; Hossain et al., 2012d). Kumer et al. (1994) and Fischer (1985) found, in EHS (1st and 2nd week of November), that wheat is exposed to an unfavorable environment (high temperature) at the vegetative stage in sub-tropical countries like Bangladesh, India and Pakistan. As a result, the crop becomes thin and produces less tillers, ultimately reducing the yield of early seeded crops.

## *Flag leaf area*

Flag leaf is most important organ (43% contribution to grain yield) of wheat regarding its contribution to grain yield (GRDC, 2003). Therefore, FLA is a very important determinant of grain yield in wheat. Post-anthesis high temperature stress in wheat is a major cause of yield reduction (Herbek and Lee, 2009). Our data on FLA shows parallels to earlier findings: Al-Khatib and Pallsen (1984) reported that high temperature adversely affected source and sink activities and accelerated the decline in viable leaf blade area and photosynthetic activity per unit leaf area, resulting in reduced dry weight of wheat. Volkova and Koshin (1984) stated that temperature above 41 °C decreases the potential photosynthetic rate of leaves in both heat-resistant and-susceptible wheat varieties. High temperatures can cause considerable pre-and post-anthesis damage, including scorching of leaves and twigs, sunburn on leaves, branches and stems, leaf senescence and abscission, shoot and root growth inhibition, discoloration and damage, and reduced yield (Vollenweider and Gunthardt, 2005).

## *Dry matter yield of flag leaf*

During the vegetative stage, high day temperature can damage leaf gas exchange properties. Vijayalakshmi et al. (2007) stated that post-anthesis high temperature stress in wheat is a major cause reducing yield due to the loss of viable LA and a decrease in the duration of green leaves, ultimately causing yield loss, similar to our present findings. They also found that increased duration of green leaves had a positive effect on GY under high temperature. LA of wheat largely depends on the diversity of the genotype, plant growth stage and air temperature. Genotypic difference in duration of green leaves and LA in response to heat stress was also reported by Stone and Nicolas (1998) and Fisher et al. (1998). Guttieri et al. (2001) reported that dry matter accumulation decreased due to a decrease in leaf number, leaf area index and accelerated leaf senescence.

## *Dry matter partitioning of above-ground parts*

Heat stress is one of the most important causes of reduced yield and dry matter production in many crops, including maize and wheat (Giaveno and Ferrero, 2003). The major impact of high temperatures on shoot growth is a severe reduction in the length of the first internode, resulting in the premature death of plants (Hall, 1992). Hossain and Teixeira da Silva (2012a); Hossain et al. (2012a); Hossain et al. (2012b); Hossain et al. (2012c) and Hossain et al. (2012d) noticed that when wheat was grown from sowing to maturity at high temperatures, phenological development was rapid, leading to poor biomass production and sterility, and consequently poor yield. Guttieri et al. (2001) reported that dry matter accumulation decreased due to a decrease in kernel number, leaf number, kernel weight and acceleration of leaf senescence. Our findings related to dry matter reduction in stress conditions are in agreement with observations made by Hossain et al. (2011a) and Hakim et al. (2012).

### *Grain yield*

In sub-tropical climates like Bangladesh, excess radiation and high temperatures are often the most limiting factors affecting plant growth and final GY (Wahid et al., 2007; Hossain et al., 2009; Hossain et al., 2011a; Hakim et al., 2012). 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 extended the duration of grain filling with a reduction in kernel growth leading to losses in kernel density and weight by up to 7% in spring wheat (Guilioni et al., 2003). Nahar et al. (2010) also observed yield reduction of five genotypes ('Sourav', 'Shatabdi', 'Sufi', 'Bijoy' and 'Prodip') under late heat stress condition. Carvalho et al. (1983) stated that the ideal wheat genotype should be high yielding under any environmental conditions. However, since genetic effects are not independent of environmental effects, most genotypes do not perform satisfactorily in all environments. When an interaction between a genotype and the environment occurs, the relative ranking of cultivars for yield often differs when genotypes are compared over a series of environments and/or years (Al-Otayk, 2010). These results indicate that the genotypes studied responded differently to different environmental conditions suggesting the importance of assessing genotypes under different environments in order to identify the best genetic make up for a particular environment. Similar results were obtained by El-Morshidy et al. (2001); Abd-El-Majeed et al. (2005) and Tawfelis (2006). Buriro et al. (2011) evaluated five wheat genotypes ('TJ-83', 'Imdad-2005', 'Abadgar-93', 'Moomal-2000', 'Mehran-89') under heat stress. Among these genotypes, 'Moomal-2000' and 'Mehran-89' performed better under heat stress

(20-30 °C air temperature) while the remaining three cultivars were found to be heat-sensitive.

### *Relative performance*

Asana and Williams (1965) reported that performance of different genotypes under stress may be observed by calculating RP%. They also reported that a higher value of RP% of a variety indicates that that variety is highly stress tolerant while a lower value of RP% indicates its susceptibility to heat stress. Sikder et al. (2001); Hossain and Teixeira da Silva (2012a) and Hossain et al. (2012d) stated that RP% of a variety can be used to determine heat tolerance under late seeded and warmer conditions. They also reported that GY of tolerant and moderately tolerant varieties showed higher RP% than sensitive varieties. There is a similarity between those findings and the present study (Figure 6).

### *Heat susceptibility index*

The importance of HSI in agriculture has been abridged by several researchers. It sometimes represents a measure of genotypic yield potential under heat stress (Bruckner and Frohberg, 1987) but does not account for differences in yield potential among genotypes (Clarke et al., 1992). Ahmad et al. (2003); Hossain and Teixeira da Silva (2012a) and Hossain et al. (2012d) claimed HSI to be a measure of yield stability. HSI actually provides a measure of yield stability based on minimization of yield loss under stressed compared to non-stressed conditions rather than on yield level under dry conditions *per se* (Clarke et al., 1984). Therefore, a stress-tolerant genotype as defined by HSI needs not necessarily to have a high yield potential. The ideal wheat genotype should be high yielding under any environmental conditions. However, since genetic effects are not independent of environmental effects, most genotypes do not perform satisfactorily in all environments (Carvalho et al., 1983).

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