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Research Article
Evaluation of Tolerance of Six Irrigated Spring Wheat (*Triticum aestivum* L.) Genotypes to Heat Stress using Stress Tolerance Indices and Correlation Analysis

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Abstract
Background and Objective: Climate models indicate that temperatures across the globe will increase impacting on food security. Therefore, it is important to develop wheat cultivars that are heat-tolerant and are suitable for cultivation under a changing climate. The objectives of this study were to examine the accuracy of different Stress Tolerance Indices (STIs) in a bid to identify wheat genotypes that are suitable to grow under heat-stressed environments and can also be used for future breeding programs developing heat-tolerant genotypes. **Materials and Methods:** An experiment was conducted over two years with six wheat genotypes ('BARI Gom 26', 'BARI Gom 27', 'BARI Gom 28', 'BAW 1130', 'BAW 1138', 'BAW 1140') under six environmental conditions, namely Early Sowing (ES) (10 November), Optimum Sowing (OS) (20 November), Slightly Late Sowing (SLS) (30 November), Late Sowing (LS) (10 December), Very Late Sowing (VLS) (20 December) and Extremely Late Sowing (ELS) (30 December)) in four Agro-Ecological Zones (AEZs) of Bangladesh. To identify wheat genotypes suitable for a heat-stressed environment, seven STIs were calculated based on wheat Grain Yield (GY), i.e., Stress Susceptibility Index (SSI), Mean Productivity Index (MPI), Tolerance Index (TOL), Geometric Mean Productivity Index (GMPI), Yield Index (YI), Yield Stability Index (YSI) and relative performance (RP%). **Results:** Based on STIs, two genotypes, 'BARI Gom 28' and 'BARI Gom 26', were found to be tolerant to ES, LS, SLS, VLS and ELS whereas 'BARI Gom 27' was susceptible to all five heat-stress conditions (ES, LS, SLS, VLS and ELS). Similarly, when considering the correlations between GY and STIs, 'BAW 1140', 'BARI Gom 28' and 'BARI Gom 26' performed best while 'BARI Gom 27' and 'BAW 1130' performed poorest under heat stress in all four locations and for all six sowing dates in both years. **Conclusion:** Therefore, genotypes 'BAW 1140', 'BARI Gom 28' and 'BARI Gom 26' are recommended for early and late heat-stress conditions experienced when sown during early or late in the season.

Key words: Correlation analysis, heat stress, stability, stress tolerance indices, wheat genotypes

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The rise in ambient temperature that has taken place over the last 30 years in the Northern Hemisphere is believed to be the greatest period of warming in over a millennium[1]. Climate models indicate that mean temperatures across the globe will continue to increase by 1-4°C by 2099 with more frequent heat waves[2-4]. Temperatures are expected to increase in zones that are typically in extremely cold latitudes across all continents, making them more suitable for crop production[5]. However, as we tend towards the equator where crops become more sensitive to heat stress, there will be significant losses in yield of crops that are sensitive to high temperatures[6]. Crop yields may also be reduced by 15-35% in Asia and the Middle East if average temperatures increase by 3-4°C[6].

In South Asia, it is expected that temperature will increase by 1.09-1.18°C from 2010 -2039, by 1.89-3.07°C from 2040-2069 and by 2.82-5.33°C by 2070-2099 [3]. Blame is also expected to be placed on climate change for as much as a 30% decrease in wheat, maize and rice yield in South Asia by 2099 versus 20% in East and South East Asia[3].

Bangladesh, a deltaic country in South Asia that has a small land area (147,570 km^2) but the 8th largest world population (ca.161 million) and the 13th highest world population density[7], is prone to great variation in climate, including extreme events, given its heterogeneous geophysics[8-9]. In terms of importance as a food grain, wheat ranks second after rice[7,10]. Wheat production is most threatened by heat[2,11]. There is already some evidence that wheat production in Bangladesh might drop by 32% by 2050 due to an increase in temperature[3,11,12] and to meet food security, Bangladesh will have to import more wheat[7].

Heat stress in plant may be mitigated either by developing and using heat-tolerant cultivars and practicing improved heat management practices. Developing cultivars that are tolerant to heat stress is, however, a big challenge for wheat breeders[13-15]. Modern wheat varieties around the globe are not sufficiently heat-tolerant and also not tolerant to extreme abiotic stresses[16-17]. Therefore an effective breeding program or alternative effective methods are necessary to either develop or detect the heat-tolerant cultivars[17]. Several Stress Tolerance Indices (STIs)[18], including stress tolerance (TOL)[19], Mean Productivity (MP)[20], Geometric Mean Productivity (GMP)[21] and Stress Susceptibility Index (SSI)[22], etc., can be used to identify high-yielding wheat varieties with improved tolerance to stress. Therefore, this study examined the accuracy of different STIs to identify genotypes that are suitable to grow in a heat-stressed environment and discover robust genetic materials for future breeding programs for development of stress-tolerant genotypes.

MATERIALS AND METHODS

Locations of the experiment: The research was carried out over two consecutive years (November-March, 2012-13 (Y1) and 2013-14 (Y2)) in four agricultural research centres/stations of the Bangladesh Agricultural Research Institute (BARI):

- The Regional Wheat Research Centre, BARI, Gazipur-Joydebpur (AEZ-28; Madhupur Tract)
- The Regional Agricultural Research Station (RARS), BARI, Jamalpur (AEZ-9; Old Brahmaputra Floodplain)
- The RARS, BARI, Khaertala, Jessore (AEZ-11; High Ganges River Floodplain)
- The Wheat Research Centre, BARI, Dinajpur (AEZ-1; Old Himalayan Piedmont Plain)[23]

Soil properties and meteorological information: Soils of the experimental sites were analyzed before sowing wheat. Soil pH was measured in soil/water (1:2, w/v) using a glass electrode pH meter. Organic carbon was determined by the Walkley and Black oxidation method[24], total N (nitrogen) by the micro-Kjeldhal method[25], phosphorus (P), potassium (K), sulphur (S) and zinc (Zn) by a modified Hunter's method[26] and boron (B) was determined colorimetrically by the Azomethine-H method[27,28].

Daily maximum and minimum temperatures as well as rainfall were measured at the meteorological stations of RARS, Jamalpur and Jessore; the RWRC at Rajshahi and Gazipur and the WRC, at Dinajpur. Rainfall was monitored by rain gauge (Fig. 1).

Experimental design and treatments: A split plot design was used for this experiment and included three replications. Treatments were six sowing dates (in the main plots) and six genotypes (in the subplots). The genotypes in all four locations were evaluated with six sowing dates: Early Sowing (ES) (sown on 10 November), Optimum Sowing (OS) (sown on 20 November), Slightly Late Sowing (SLS) (sown on 30 November), Late Sowing (LS) (sown on 10 December), Very Late Sowing (VLS) (sown on 20 December) and Extremely Late Sowing (ELS) (sown on 30 December). Six wheat genotypes from the WRC, including three existing elite varieties ('BARI Gom 26', 'BARI Gom 27', 'BARI Gom 28') and three advanced lines ('BAW 1130', 'BAW 1138', 'BAW 1140'), were used (Table 1). Individual plot size was 1.6×4 m, i.e., eight 4 m long rows and a 20 cm row-to-row distance with 9.6 g of seeds row^{-1}.

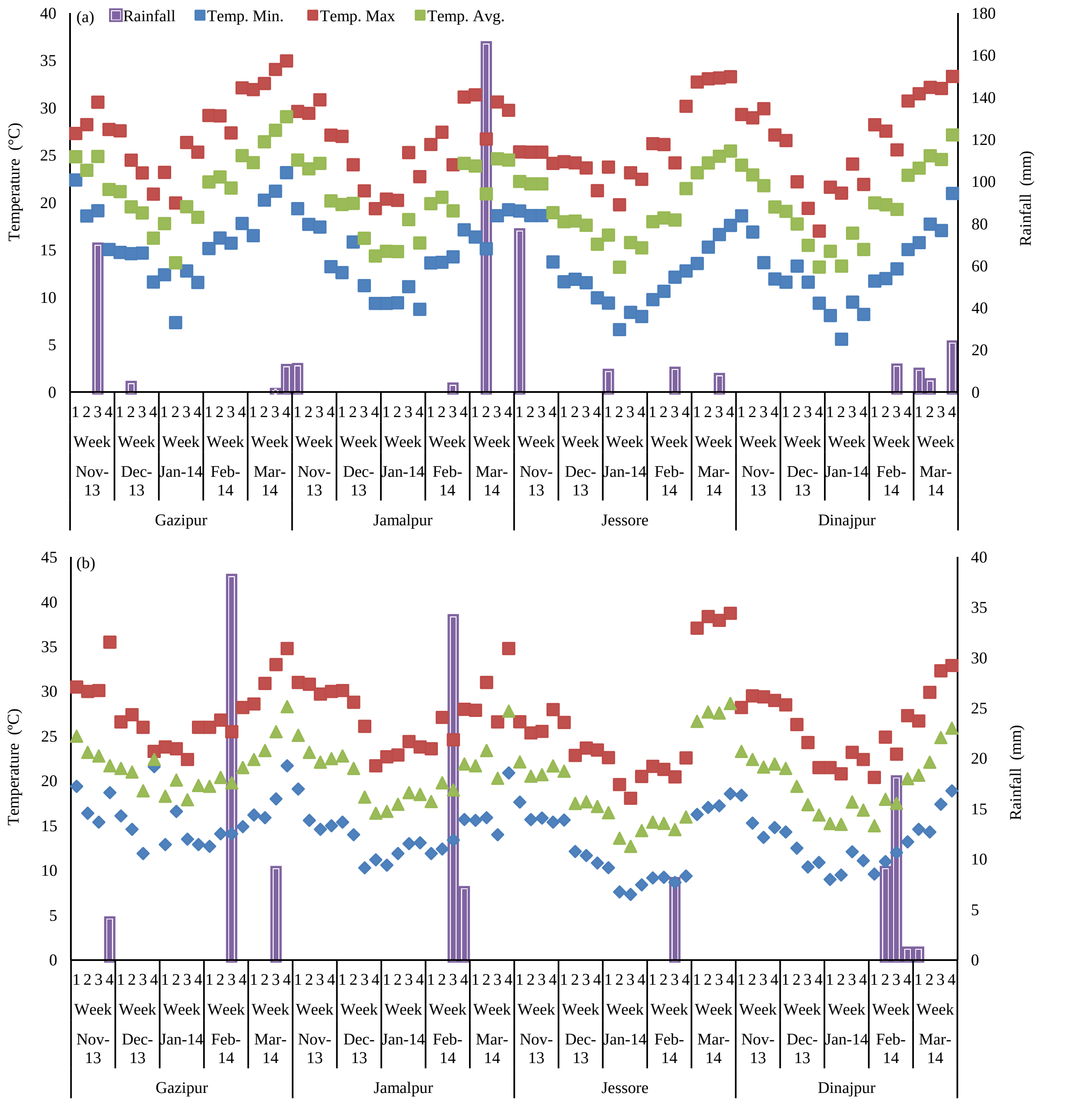

Fig. 1(a-b): Weekly average meteorological information during the (a) 2012-13 and (b) 2013-14 wheat seasons in three locations

Experimental procedure and crop management: Before sowing wheat at 120 kg ha^{-1}, seeds were treated with a fungicide Provax-200 WP (manufactured by Chemtura Corp., USA) to achieve excellent (about 85-95%) seed germination. Except for Jessore, dolomite limestone (30% CaO, 22% MgO, 48% CO_2)[29] sat 2 t ha^{-1} was applied 7-10 days prior to sowing seed in all other locations[30]. Dolomite lime was spread 15-20 days before planting on the soil surface and then mixed into soil 25 cm deep and irrigated immediately after application[31]. Other fertilizers "were applied at recommended rates by the WRC: 100, 27, 40, 20 of N, P, K and Sand 1 kg ha^{-1} of B. A full amount of other fertilizers and two-thirds of N were applied as basal during final land preparation. The remaining one-third N fertilizer was applied immediately after the first irrigation (at crown root initiation stage). Second and third irrigations were applied at the booting stage and grain-filling stage.

Data collection and processing: The crop was harvested plot-wise at full maturity. The harvested samples from each

Table 1: Pedigree and general characteristics of wheat genotypes tested in the present research

Genotype	Pedigree	Stress tolerance capacity	Life span (days)	Yield (kg ha^{-1})	Suitable area for cultivation	Year of release	Major diseases and pests
BARI Gom 26	ICTAL 123/3/RAWAL87//VEE/HD2285	Tolerant to terminal heat stress in late seeding	104-108	3500-5000	Possible to grow throughout the country except in areas with salinity level >6 ds m^{-1}	2010	Tolerant to *Bipolaris* leaf blight and resistant to leaf rust (stem rust) race Ug 99
BARI Gom 27	FRANCOLIN #1	Moderate level of tolerance to heat stress	105-110	3800-5400	All over the country except saline areas	2012	Resistant to leaf rust and tolerant to *Bipolaris* leaf blight and possesses good level of APR to the Ug 99 race of stem rust and its variants
BARI Gom 28	CHIL/2*STAR/4/BOW/CROW//BUC/ PVN/3/2*VEE#10	Tolerant to terminal heat stress in late seeding	100-105	4000-5500	All over the country except saline areas	2012	Resistant to leaf rust and tolerant to *Bipolaris* leaf blight
BAW 1130	GOURAB/PAVON 76 NCD99-04-0DI-1DI-0DI-0DI-0DI-0DI-22DI-DIRC4	Tolerant to terminal heat stress in late seeding	105-109	3500-5400	All over the country except saline areas	Advance line	Resistant to leaf rust and tolerant to *Bipolaris* leaf blight
BAW 1138	CHEN/AE.SQ(TAUS)//BCN/3/2*PASTOR CMSS98Y00844S-040Y-0B-0MXI-3DI-010DI-010DI-1DI-DIRC6	Tolerant to terminal heat stress in late seeding	106-110	3600-5500	All over the country except saline areas	Advance line	Resistant to leaf rust and tolerant to *Bipolaris* leaf blight
BAW 1140	SOURAV/GOURAB BD(JE)959S-0DI-5DI-010DI-010DI-010DI-1DI-DIRC8	Tolerant to terminal heat stress in late seeding	105-110	3500-5500	All over the country except saline areas	Advance line	Resistant to leaf rust and tolerant to *Bipolaris* leaf blight

plot were bundled separately and tagged. Bundles were thoroughly dried under bright sunshine until fully dried and threshed and then yield was recorded at 12% Moisture Content (MC) according to Hellevang[32]. Grain yield under different stress conditions were used to calculated stress tolerance indices as well as correlation between STIs and GY.

Calculation of resistance indices

Stress susceptibility index: The SSI is used to measure stress tolerance in terms of minimizing the reduction in yield caused by unfavorable versus favorable environments and was calculated using the following equation[22]:

$$\text{SSI} = \frac{1 - \text{Ys/Yp}}{1 - \text{Ys/Yp}}$$

where, Ys is the yield of genotypes under heat stress, Yp is the yield of genotypes under OS, $\overline{\text{Y}}$s is the mean yield of all genotypes under heat stress and $\overline{\text{Y}}$p is their mean yield under OS and 1-($\overline{\text{Y}}$s-$\overline{\text{Y}}$p) is the stress intensity. The OS treatment was maintained undernon-stress condition to have a better estimate of optimum environment.

Genotypes tolerant to stress are negatively correlated with SSI, i.e., genotypes with a low SSI are more stable in variable stress conditions. A genotype is considered to be highly stress tolerant when SSI<0.5; moderately tolerant when 0.5>SSI<1.0 and intolerant when SSI>1.0.

Mean productivity index: The MPI measures stress tolerance in terms of mean GY under stressed and OS environments and was calculated for each genotype with the following equation[19]:

$$\text{MPI} = \frac{\text{Yp} + \text{Ys}}{2}$$

where, Ys and Yp are as defined above for SSI. A genotype tolerantto stress hasa positive correlation between GY and MPI.

Tolerance index: The TOL measures stress tolerance in terms of reducing the GY reduction caused by stressed compared to OS environments and was calculated for each genotype with the following equation[19]:

$$\text{TOL} = \text{Yp-Ys}$$

where, Ys and Yp are defined as above for SSI. Stress-tolerant genotypes are negatively correlated with TOL.

Geometric mean productivity index: The GMPI is used to measure stresstolerance in genotypes by comparing GY under stressed and OS environments and was calculated using the following equation[18]:

$$\text{GMPI} = \sqrt{\text{Yp} \times \text{Ys}}$$

where, Ys and Yp are defined as above for SSI. Normally, stress-tolerant genotypes have a positive correlation between GY and GMPI, i.e., genotypes with a high GMPI will be more tolerant to stress.

Yield index: The YI is used to measure the stress tolerance of genotypes by comparing GY under stressedcondition and OS and was calculated for each genotype with the following equation[33]:

$$\text{YI} = \frac{\text{Ys}}{\bar{\text{Y}}\text{s}}$$

where, Ys and Yp are defined as above for SSI. A stress-tolerant genotype shows a positive correlation between GY and YI, i.e., genotypes with a high YI value will be tolerant to stress.

Yield stability index: The YSI is used to identify genotypes that are suitable to grow under heat stress and was calculated by using the following equation[34]:

$$\text{YSI} = \frac{\text{Ys}}{\text{Yp}}$$

where, Ys and Yp are as defined above. The YSI is positively correlated with GY under stress, i.e., a genotype which is tolerant to stress has a higher YSI.

Relative performance: The RP% measures stress tolerance and was calculated with the following equation[35]:

$$\text{RP (\%)} = \frac{\text{Ys}}{\text{Yp}} \times 100$$

where, Ys and Yp are as defined above. Another measure, relative yield performance[35], was also used and expressed as %. A higher RP% means the genotype is stress tolerant while a lower RP% means it is stress susceptible.

Data analysis: Before calculating resistance indices and GY data for each wheat genotype across locations and sowing dates for each year were subjected to statistical analysis (Table 2) using R package 'stats' (version 2.15.3), with "R" at 5% significance level[36]. The correlation coefficients between GY and each of the STIs (SSI, MP, TOL, GMP, YI, YSI and RP%) were calculated to determine the most desirable stress-tolerant genotypes (Table 3) by STAR Software[37].

Table 2: ANOVA of the two years yield of 6 wheat genotypes under six environmental conditions in 4 locations

			Probability	
			GY (t ha^{-1})	
K-value	Source	DF	Y1	Y2
1	Location	3	0.0000**	0.0000**
3	R(L)	8	0.0821^{ns}	0.0781^{ns}
4	Factor A	5	0.0000**	0.0000**
5	LA	15	0.0000**	0.0000**
-7	Error	40	-	-
8	Factor B	5	0.0000**	0.0000**
9	LB	15	0.0000**	0.0000**
12	AB	25	0.0014**	0.0006**
13	LAB	75	0.0000**	0.0053**
-15	Error	240	-	-
	Total	431	-	-

Factor A: 6 sowing times, Factor B: 6 wheat genotypes, LA: Performance of 6 sowing times in 4 locations, LB: Performance of 6 wheat genotypes in 4 locations, AB: Performance of 6 wheat genotypes under 6 sowing times, LAB: Performance of 6 wheat genotypes in 6 sowing dates in 4 locations, DF: Degree of freedom, GY: Grain yield, Y1: In 2012-13, Y2: In 2013-14, *,**Significant at 1 and 5 % level, ns: Non-significant

RESULTS

Initial soil status: Soil in AEZ-28 (Gazipur) was weakly acidic (pH 6.5), AEZ-9 (Jamalpur) was strongly acidic (pH 5.5), AEZ-11 (Jessore) was neutral (pH 7.02) and AEZ-1 (Dinajpur) was very strongly acidic (pH<5). Organic matter content in all AEZs was low (range: 1.0-1.21%) and total N very low (range: 0.05-0.07%). Except for B in AEZ-11, K, S, B and Zn content were below critical levels. P in AEZ-28 and AEZ-11 was very low (3.76, 6.56, respectively) but in AEZ-9 and AEZ-1 it was high (14.5 and 15, respectively). Overall, all nutrients except P were deficient in Dinajpur (AEZ-1) and Jamalpur (AEZ-9).

Stress tolerance indices and genotypic stability

Stress susceptibility index: Considering SSI, 'BARI Gom 27' and 'BAW 1140' were stress tolerant in ES, 'BAW 1138' in SLS, 'BARI Gom 27', 'BARI Gom 28' and 'BAW 1130' in LS, 'BARI Gom 28', 'BAW 1130', 'BAW 1138', 'BAW 1140' in VLS and 'BARI Gom 28' and 'BAW 1140' in ELS. Among them, 'BARI Gom 28' and 'BAW 1140' were suitable under LS, VLS and ELS, whereas 'BARI Gom 26' was susceptible under all sowingdates in Gazipur (Fig. 2). In Jamalpur, 'BAW 1130' was suitable for ES while 'BARI Gom 27' was suitable for SLS, LS, VLS and ELS. However,

Table 3: Correlation matrix between grain yield and different stress tolerance indices in both years

Indices	GY Y1	GY Y2	SSI Y1	SSI Y2	MPI Y1	MPI Y2	TOI Y1	TOI Y2	GMPI Y1	GMPI Y2	YI Y1	YI Y2	YSI Y1	YSI Y2	RP (%) Y1	RP (%) Y2
GY	1.0	1.0	-0.19*	-0.27*	0.95**	0.91**	-0.90**	-0.69**	0.97**	0.93**	0.31*	0.50**	0.89**	0.79**	0.94**	0.82**
SSI			1.0	1.0	-0.50^{ns}	-0.07^{ns}	0.33**	0.42**	-0.07^{ns}	-0.09^{ns}	-0.04**	-0.46**	-0.32**	-0.45**	-0.30**	-0.47**
MP					1.0	1.0	-0.69**	-0.34**	0.99**	0.99**	0.36**	0.49**	0.72**	0.50**	0.78**	0.52**
TOI							1.0	1.0	-0.76**	-0.40**	-0.20*	-0.26**	-0.95**	-0.93**	-0.99**	-0.95**
GMP									1.0	1.0	0.35**	0.51**	0.77**	0.54**	0.84**	0.57**
YI											1.0	1.0	0.21*	0.29**	0.22*	0.34**
YSI													1.0	1.0	0.95**	0.97**
RP (%)															1.0	1.0

Y1: 2012-13, Y2: 2013-14, GY: Grain yield, SSI: Stress tolerance index, MPI: Mean productivity index, TOI: Tolerance index, GMPI: Geometric mean productivity index, YI: Yield index, YSI: Yield stability index, RP (%): Relative performance, *,**Significant at 1 and 5 % level, ns: Non-significant

'BAW 1138' and 'BAW 1140' were not suitable for all sowing dates in Jamalpurin both years (Fig. 2). In Jessore, 'BARI Gom 27' and 'BARI Gom 28' performed best in ES, 'BARI Gom 26', 'BAW 1138' and 'BAW 1140' in SLS and 'BARI Gom 27' and 'BAW 1130' in VLS. No genotypes were suitable in LS and ELS (Fig. 2). In Dinajpur, 'BAW 1138' was suitable in ES and SLS, 'BAW 1140' in ES, LS and ELS and 'BARI Gom 28' in LS and ELS but 'BAW 1130 was susceptible to heat stress in LS (Fig. 2).

Mean productivity index: Considering MPI values, 'BARI Gom 28' and 'BARI Gom 26' were stress tolerant in ES, SLS, LS, VLS and ELS but 'BAW 1130' was susceptible in all stressed sowing conditions in Gazipur (Fig. 3). In Jamalpur, 'BARI Gom 28' and 'BAW 1140' were suitablein ES, SLS, LS, VLS and ELS but 'BARI Gom 27' was not suitable in Jamalpur in both years (Fig. 3). In Jessore, 'BARI Gom 28' performed best in ES, SLS, LS and ELS, followed by 'BAW 1140' but 'BARI Gom 27' was unsuitable for all conditions in Jessore (Fig. 3). In Dinajpur, 'BARI Gom 26' was suitable in ES, SLS and LS, followed by 'BAW 1140' and 'BAW 1138', 'BARI Gom 28' was suitable in ELS but 'BAW 1130' and 'BARI Gom 27' were not suitable under ES and LS (Fig. 3).

Tolerance index: Considering the two-year TOL index, all tested genotypes were suitable in ES, SLS and LS in all four locations but no genotypes were suitable in VLS and ELS in these locations (Fig. 4).

Geometric mean productivity index: Considering GMPI, 'BARI Gom 28' and 'BARI Gom 26' were tolerant in all stressful sowing conditions but 'BAW 1130' was susceptible in ES, SLS and LS and 'BARI Gom 27' was susceptible in VLS and ELS in Gazipur in both years (Fig. 5). In Jamalpur, 'BARI Gom 28' and 'BAW 1140' were suitable in ES, SLS, LS, VLS and ELS, 'BARI Gom 27' was susceptible in ES, SLS and LS and 'BAW 1138' was susceptible in VLS and ELS in Jamalpur in both years (Fig. 5). Similar to Jamalpur and Gazipur, 'BARI Gom 28' and 'BAW 1140' performed best under ES and LS in Jessore in both years, whereas 'BARI Gom 27' was not suitable for ES and LS (Fig. 5). In Dinajpur, 'BARI Gom 26' was suitable in ES, SLS and LS, followed by 'BAW 1140', 'BAW 1138 and 'BARI Gom 28' suitable in ELS, whereas 'BARI Gom 27' was unsuitable for ES and LS (Fig. 5).

Yield index: With few exceptions, 'BARI Gom 28', 'BAW 1140' and 'BARI Gom 26' performed best under all stressful sowing conditions in the four tested locations while 'BARI Gom 27' and 'BAW 1130' performed poorest in all sowing conditions (Fig. 6).

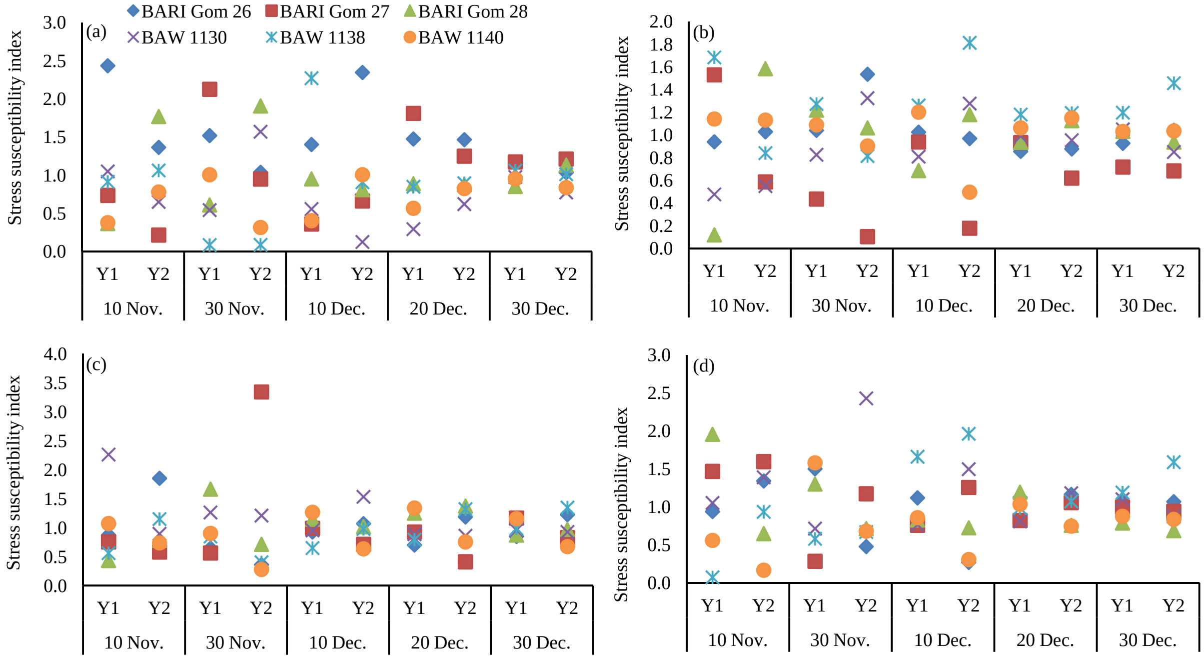

Fig. 2(a-d): Stress susceptibility index of six wheat genotypes, experienced as early and late heat stress, when grown under six sowing dates in 2012-13 (Y1) and 2013-14 (Y2) in four locations of Bangladesh, (a) Gazipur, (b) Jamalpur, (c) Jessore and (d) Dinajpur

Treatments details are in Table 3

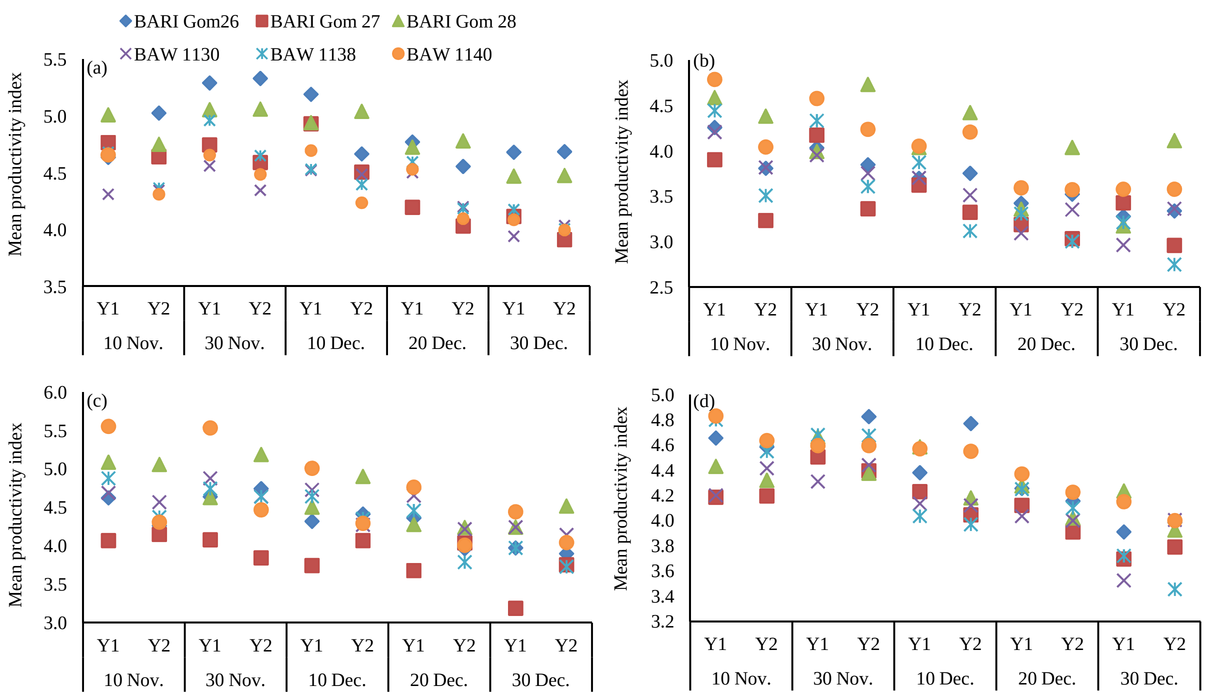

Fig. 3(a-d): Mean productivity index of six wheat genotypes, experienced as early and late heat stress, when grown under six sowing dates in 2012-13 (Y1) and 2013-14 (Y2) in four locations of Bangladesh, (a) Gazipur, (b) Jamalpur, (c) Jessore and (d) Dinajpur

Treatments details are in Table 3

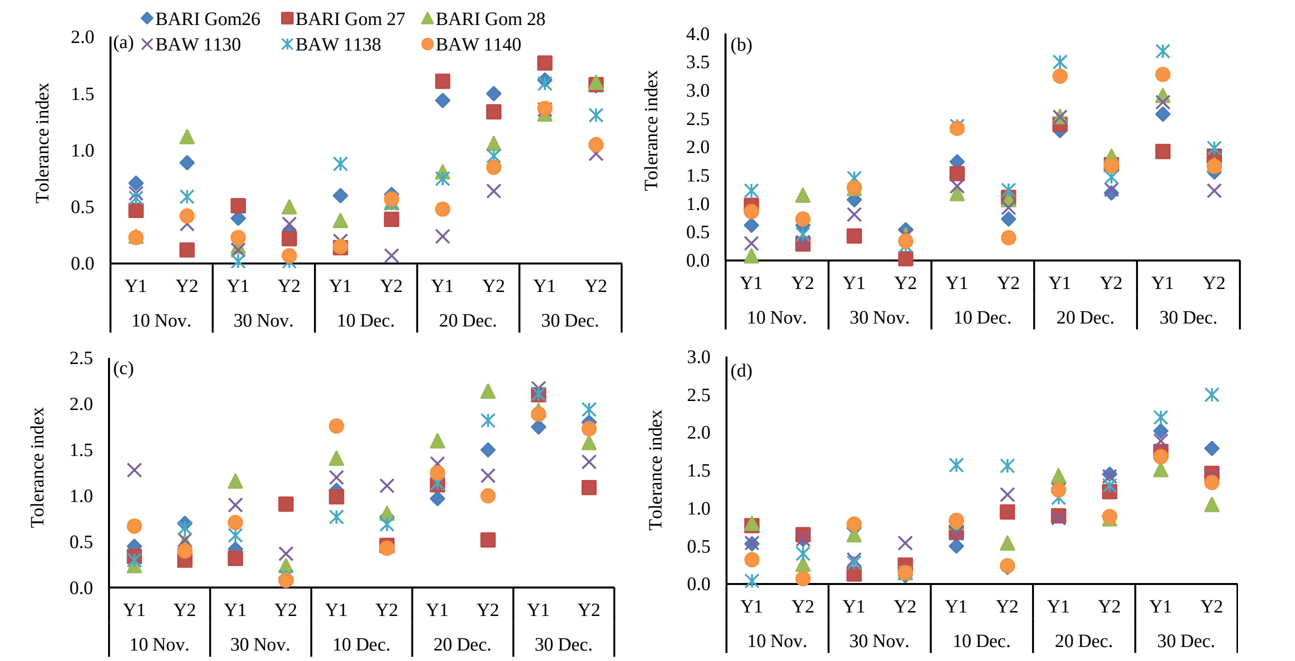

Fig. 4(a-d): Tolerance index of six wheat genotypes, experienced as early and late heat stress, when grown under six sowing dates in 2012-13 (Y1) and 2013-14 (Y2) in four locations of Bangladesh, (a) Gazipur, (b) Jamalpur, (c) Jessore and (d) Dinajpur

Treatments details are in Table 3

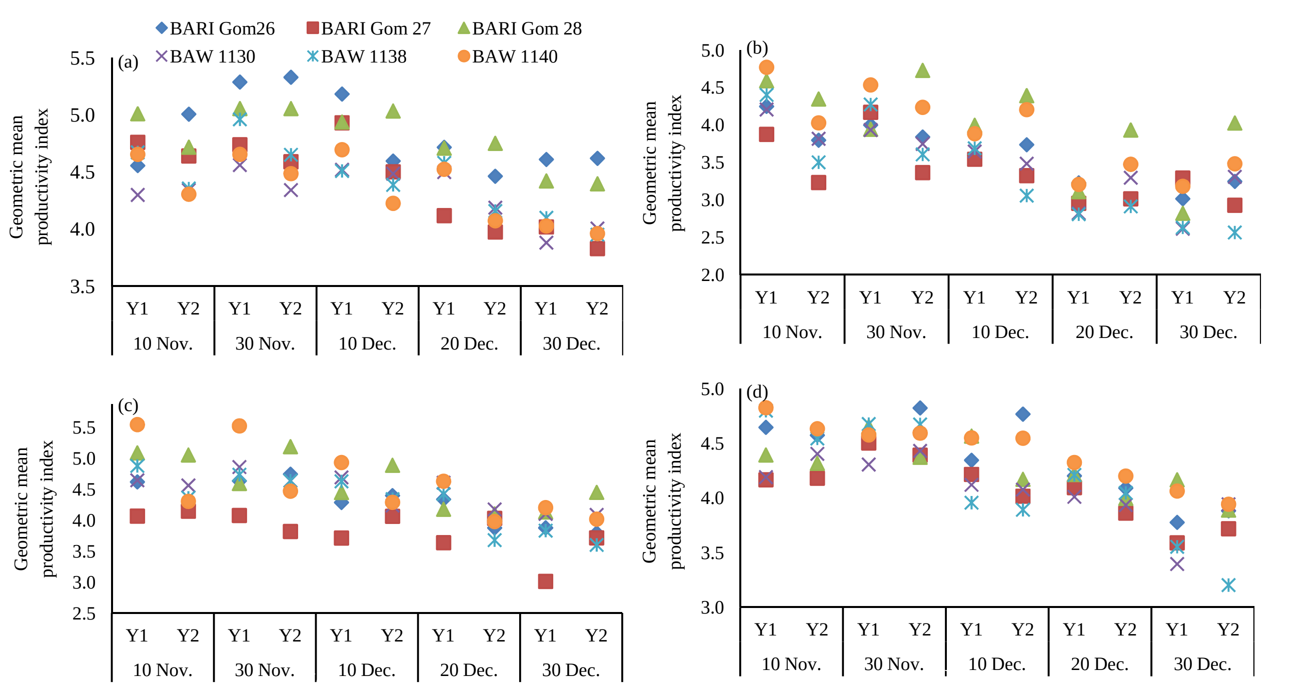

Fig. 5(a-d): Geometric mean productivity index of six wheat genotypes, experienced as early and late heat stress, when grown under six sowing dates in 2012-13 (Y1) and 2013-14 (Y2) in four locations of Bangladesh, (a) Gazipur, (b) Jamalpur, (c) Jessore and (d) Dinajpur

Treatments details are in Table 3

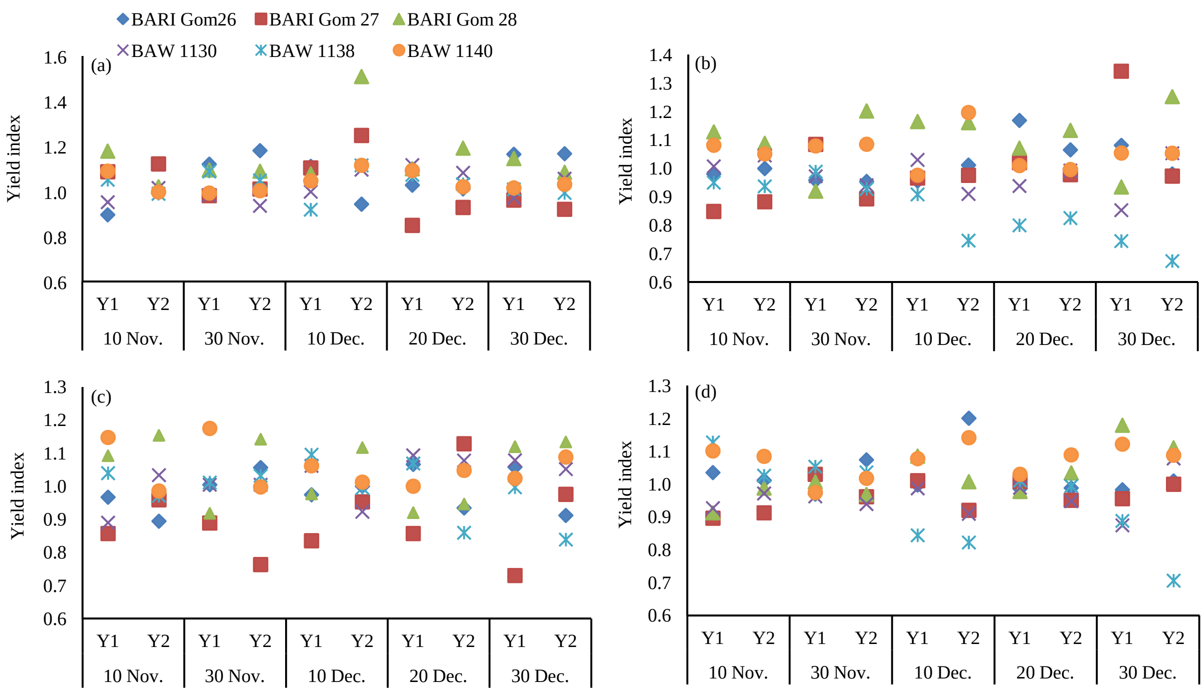

Fig. 6(a-d): Yield index of six wheat genotypes, experienced as early and late heat stress, when grown under six sowing dates in 2012-13 (Y1) and 2013-14 (Y2) in four locations of Bangladesh, (a) Gazipur, (b) Jamalpur, (c) Jessore and (d) Dinajpur
Treatments details are in Table 3

Yield stability index: Higher and similar values of YSI for all genotypes in both years were recorded in ES, SLS and LS, indicating that all the tested genotypes were suitable for these sowing data in all four locations (Fig. 7). However, lower but similar YSI values for all genotypes were observed in VLS and ELS, indicating that all tested genotypes were susceptible to heat stress under LS condition (Fig. 7). Among all genotypes, 'BARI Gom 28', 'BAW 1140' and 'BARI Gom 26' performed better under all stressful sowing conditions.

Relative performance: Similar to YSI, higher but similar RP% for all genotypes in both years were recorded under ES, SLS and LS, indicating that all the tested genotypes were suitable for these sowing conditions in all four locations (Fig. 8) and lower but similar RP% for all genotypes were found under VLS and ELS, indicating that all tested genotypes were susceptible to heat stress under LS (Fig. 8).

Correlation analysis: A significantly positive correlation was observed between GY and each of the stress indices such as MP, GMP, YI, YSI and RP% in Y1 (r = 0.94**, 0.97**, 0.31**, 0.89** and RP% 0.94**, respectively) and Y2 (0.91**, 0.93**, 0.50**, 0.79** and 0.82**, respectively), indicating that genotypes with higher values of the indices are tolerant to heat stress with higher GY under heat-stressed conditions. In contrast, significantly negative correlations between GY and SSI (r = -0.18* and -27**, respectively, in Y1 and Y2 and between GY and TOL (r = -0.90** and -0.69**, respectively in Y1 and Y2), indicate that genotypes with higher indices give lower yields and those with lower indices give higher yields under heat stress conditions (Table 3). Furthermore, even though MP, GMP, YI, YSI and RP% were significantly positively correlated with each other, they were negatively correlated with SSI and TOL in both years (Table 3).

DISCUSSION

Temperature and rainfall variations across seasons and locations: In the sub-tropical environment, late sown wheat faces low temperature stress from germination to the seedling establishment period, while high temperature stress at reproductive phase reduces the number of days to physiological maturity as well as the grain-filling duration, ultimately reducing the GY of wheat[38,39]. For late planting, the wheat variety should be of short duration that may escape from high temperature at the grain filling stage[40]. Hossain *et al.*[41] reported that the early-sown crop encountered unfavourable environment (high temperature) at vegetative stage, as a result the wheat crop produced less tillers, despite the heading and the grain formation stages being quite

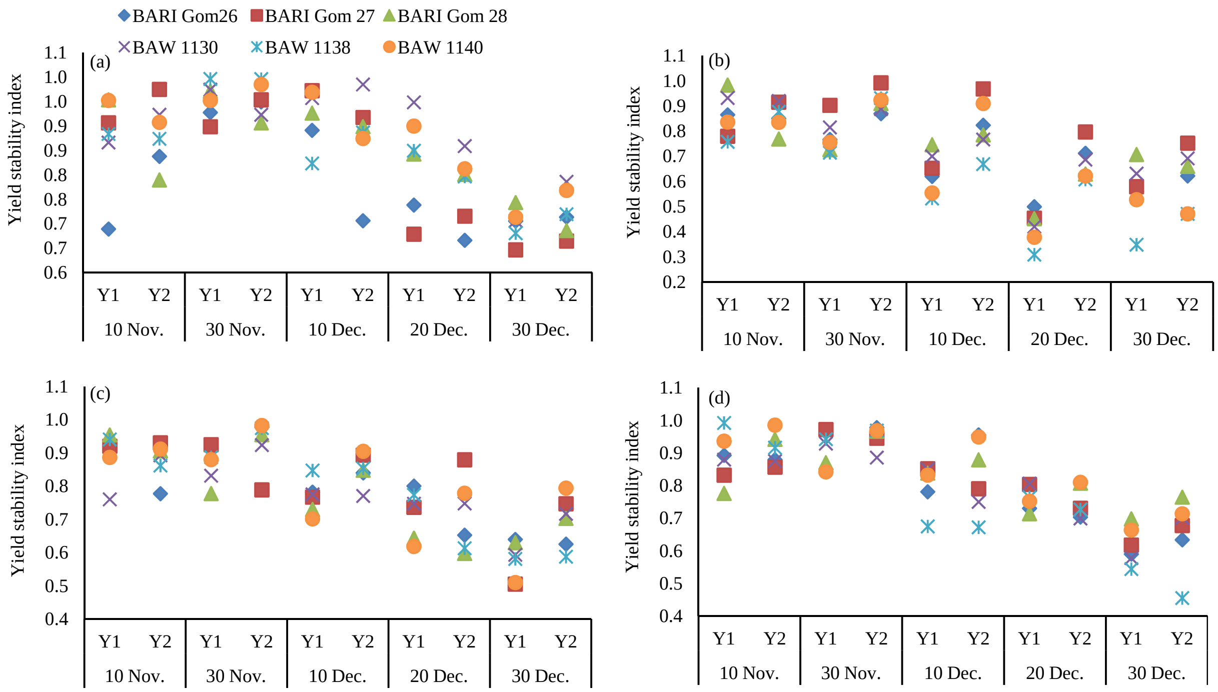

Fig. 7(a-d): Yield stability index of six wheat genotypes, experienced as early and late heat stress, when grown under six sowing dates in 2012-13 (Y1) and 2013-14 (Y2) in four locations of Bangladesh, (a) Gazipur, (b) Jamalpur, (c) Jessore and (d) Dinajpur

Treatments details are in Table 3

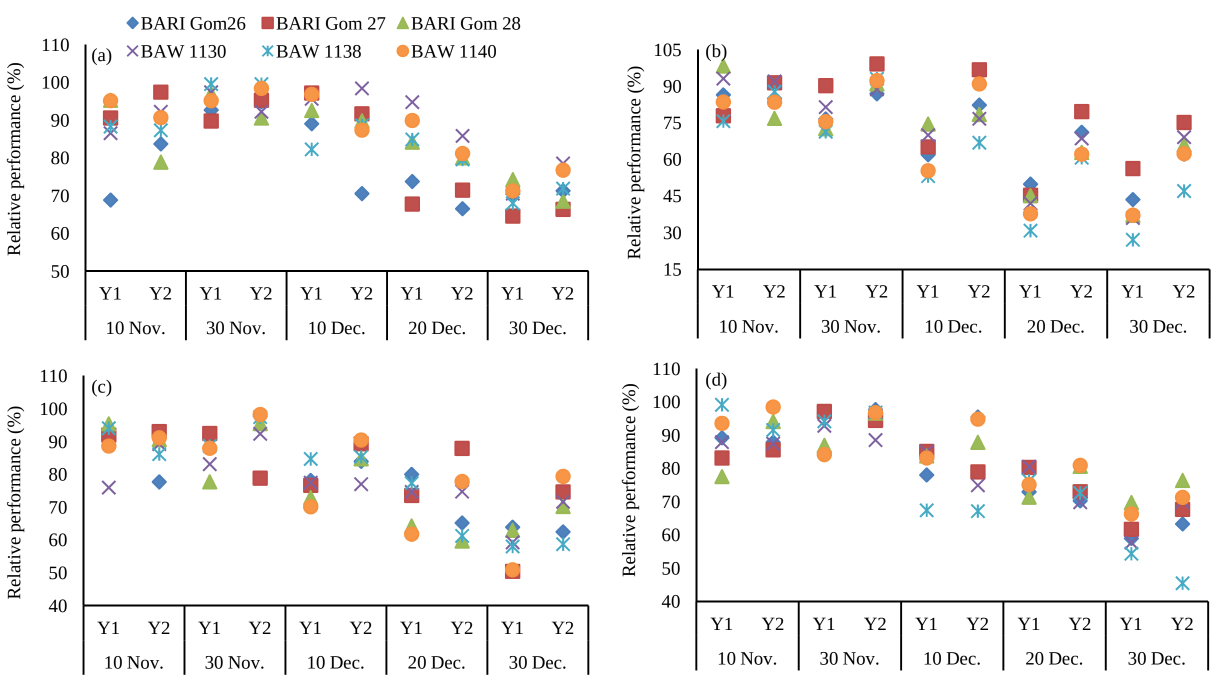

Fig. 8(a-d): Relative performance (%) of six wheat genotypes, experienced as early and late heat stress, when grown under six sowing dates in 2012-13 (Y1) and 2013-14 (Y2) in four locations of Bangladesh, (a) Gazipur, (b) Jamalpur, (c) Jessore and (d) Dinajpur

Treatments details are in Table 3

favourable but the crop did not recover the stress from the vegetative stage. They also reported that delayed sowing suppressed the yield, caused by reduction in the yield contributing traits like number of tillers, number of grains spike^{-1} and grain yield. Delayed wheat sowing also shortened the duration of all developmental phases due to increased air temperatures in Bangladesh[42,43]. In these studies, the differences for number of days to heading for optimum and late planting were up to 23 days. In the present research, temperature at the germination stage under ES was higher than OS and at the grain-filling stage was lower than OS which ultimately reduced GY. However, under OS, the mean minimum temperature ranged from 10-12°C while the mean maximum temperature ranged from 20-25°C (Fig. 1), which were suitable for the growth and development of wheat. Under SLS, LS, VLS and ELS, temperatures at the germination stage were very low and at the grain-filling stage were high, which ultimately shortened the life cycle and thus reduced yield (Fig. 1).

Stress tolerance indices: A higher SSI value indicates relatively greater sensitivity to a given stress. Thus, for wheat grown under stress condition, a lower SSI is desired. Selection based on SSI guides for the selection of genotypes with low GY under non-stress and high GY under stress conditions[44,45]. Similar to SSI, genotypes with low TOL are relatively more stable under stress-prone environments[15,41]. In the present study, 'BARI Gom 27' and 'BAW 1140' were stress tolerant in ES, 'BAW 1138' in SLS, 'BARI Gom 27', 'BARI Gom 28' and 'BAW 1130' in LS, 'BARI Gom 28', 'BAW 1130', 'BAW 1138', 'BAW 1140' in VLS and 'BARI Gom 28' and 'BAW 1140' in ELS (Fig. 2). Considering the TOL index, all wheat genotypes were found suitable in ES, SLS and LS in all locations, whereas no genotypes performed better in VLS and ELS in these locations, due to higher TOL values (Fig. 4). Ankit *et al.*[46] and Singh *et al.*[47] also found that wheat genotypes with higher SSI and TOL values were susceptible to stress and with lower value of SSI and TOL were tolerant to stress.

However, genotypes with higher values for each of MP[48,49], GMP reported by Fischer and Maurer[22] and Schneider *et al.*[50], YI (noticed by Gavuzzi *et al.*[33], YSI noticed by Bouslama and Schapaugh[34] and Abdi *et al.*[48] and RP% (noticed Hossain and da Silva[15] and Hossain *et al.*[41] suggest higher stress tolerance compared to lower tolerance for lower values of these indices. In contrast with earlier study for MPI (Fig. 3), GMPI (Fig. 5), YI (Fig. 6), YSI (Fig. 7) and RP% (Fig. 8), genotypes 'BARI Gom 28' and 'BARI Gom 26' were tolerant to ES, LS, SLS, VLS and ELS conditions, whereas 'BARI Gom 27' was susceptible to all stressful conditions (ES, LS, SLS, VLS and ELS conditions).

Correlation analysis: Correlations between heat tolerance indices and GY can be used to screen the wheat genotypes under stress conditions. Mitra[51] suggested that a significant correlation between GY and STIs shows a good genotype under stress. In this research, there were significantly positive correlations between GY and each of MP, GMP, YI, YSI and RP% under stress conditions in both years and significantly negative correlations between GY and SSI and between GY and TOL (Table 3). These results are similar to many earlier findings. For example, Toorchi *et al.*[52] showed that the correlations between GY and each of MP, GMP and GY were positive. Dehghani *et al.*[53] and Khalili *et al.*[54] also reported that GY was significantly and positively correlated with each of GMP, MP, YI and YSI under heat stress conditions. Such correlations also hold true for other stresses such as water stress. For example, significantly higher correlations between GY and each of SSI (r = - 0.48*), STI (r = 0.95**), GMP (r = 0.94**), MP (r = 0.91), HM (r = 0.96**), YSI (r = 0.50**), YI (r = 0.97**), DI (r = 0.93**) and SNPI (r = 0.95**) were observed under water stress conditions in Turkey[55].

CONCLUSION AND RECOMMENDATIONS

When considering the correlations between GY and STIs, 'BAW 1140', 'BARI Gom 28' and 'BARI Gom26' performed best while 'BARI Gom 27' and 'BAW 1130' performed poorest under heat stress in all four locations and for all six sowing dates in both years. Therefore, genotypes 'BAW 1140', 'BARI Gom 28' and 'BARI Gom 26' are recommended for early and late heat stress conditions when sown early and late.

SIGNIFICANCE STATEMENT

This study discovered that all tested genotypes resulted in the greatest Grain Yield (GY) under optimum sowing, followed by slightly late (SLS), Early Sowing (ES) and Late Sowing (LS), while worst GY was observed in Very Late Sowing (VLS) and Extremely Late Sowing (ELS). When GY and the correlations between GY and STIs were considered, 'BAW 1140', 'BARI Gom 28' and 'BARI Gom26' performed best under heat stress in all locations and sowing dates in both years. Therefore, 'BAW 1140', 'BARI Gom 28' and 'BARI Gom 26' are recommended wheat genotypes for early or late sowing in heat stress environments of Bangladesh.

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