



Evaluation of wheat varieties from Bangladesh for grain yield and heat tolerance

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Abstract

Background and Objective: High-temperature stress is a key ecological element that restricts growth and yields in wheat crops. Keeping this important aspect in mind, eleven wheat varieties from Bangladesh were assessed for yielding ability and heat tolerance behavior.

Methodology: The research was conducted at the Agrotechnology Discipline Farm, Khulna University. The genotypes were evaluated in a randomized complete block design (RCBD) and replicated thrice. Eleven high-yielding wheat varieties from Bangladesh (BARI gom20 (Gourab), BARI gom21 (Shatabdi), BARI gom22 (Sufi), BARI gom23 (Bijoy), BARI gom24 (Prodip), BARI gom25, BARI gom26, BARI gom27, BARI gom29, BARI gom30, and Sourov) were used in the study. Data were gathered on different growth and yield parameters. Membrane thermal stability (MTS) and relative injury (RI) levels were considered to estimate the tolerance level of cultivars to temperature stress. Analysis of variance and principal component analysis were performed on different physiological and yield parameters. In addition, bivariate analyses (correlation and regression) were carried out to establish relationships among different characters.

Main Results: Significant variation ($P < 0.05$) was found among the eleven wheat varieties regarding all the growth and yield contributing characters as well as MSI and RI. Varieties BARI gom20 (Gourab), BARI gom21 (Shatabdi), BARI gom24 (Prodip), and BARI gom26 showed superior performance regarding yield (2.39, 2.81, 3.01, and 2.38 t ha⁻¹, respectively) and MTS (65.72, 77.66, 84.64, and 56.12%, respectively). Grain yield was positively related to MTS but negatively related to RI, as revealed by regression analysis.

Conclusions: Wheat varieties BARI gom20 (Gourab), BARI gom21 (Shatabdi), BARI gom24 (Prodip), and BARI gom26 are recommended for cultivation in Khulna region of Bangladesh as these varieties exhibited better yielding ability and greater MTS.

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INTRODUCTION

Wheat (*Triticum aestivum* L.) is the second most important grain crop next to rice in Bangladesh and plays a significant part in achieving food security. It covers 4.45% of the total cropped area and provides 7% of the total production of grain cereals in the country (Banglapedia, 2021). During 2022–2023 in Bangladesh, wheat is grown in 317,000 ha of land with a total production of 1,170,000 t, thus giving a yield of 3.69 t ha⁻¹ only (BBS, 2024), which is much lower than other wheat-producing countries of the world. Temperature stress is one of the key factors limiting wheat yield in the country. Hence, breeding for high-temperature tolerance in wheat is one of the key objectives of wheat improvement programs in Bangladesh (Hossain and Teixeira da Silva, 2013). Keeping the above scenario in mind, the objectives of the study were framed to identify the heat tolerance behavior existing among the eleven wheat genotypes of Bangladesh.

Heat stress is described as the increase in temperature away from a threshold level for a period enough to create irreversible injury to plant progress and development. It may cause a partial or total collapse of the morphology, anatomy, physiology, and biochemistry of wheat crops. At the molecular level, temperature stress lessens the actions of the enzyme, e.g. rubisco activase and soluble starch synthase, which contribute to the photosynthesis and starch biosynthetic mechanisms (Mathur *et al.*, 2014), alters membrane protein structural configuration, lipid structure, the scheduling, and the richness of gene expression

that controls grain growth, stimulates the assembly of reactive oxygen species (ROS) and ethylene, and boosts the performances of enzymes, like chlorophyllase, which take part in chlorophyll destruction (Hays *et al.*, 2007). For wheat, the optimal temperature throughout anthesis and grain filling arrays is between 12 and 22°C (Islam *et al.*, 2017). Several studies indicated that the damaging threshold temperature for wheat is estimated to be about 32°C (Trnka *et al.*, 2014). The temperature exceeding 30°C during anthesis may result in a decrease in sink size or comprehensive grain bareness (Pradhan and Prasad, 2015). Pollen development is considered the greatest heat-subtle procedure in plant sexual reproduction, with both meiosis and gametogenesis being thermo-sensitive (Bokszczanin *et al.*, 2013).

Tolerance to temperature stress is a multifarious phenomenon governed by many genes directing several bio-physiological alterations, such as changes in membrane assemblies and activities, cell water content, conformation of proteins, lipids, and metabolites (Barnabas *et al.*, 2008). A substantial improvement of knowledge in the understanding level of the molecular base of wheat stress tolerance will permit plant breeders to handle the difficulty of built-in resistance against elevated temperature trauma. It is thus necessary to reveal the molecular and genetic origin of temperature tolerance in wheat, to detect valuable genes, and to employ these in wheat breeding programs aimed at developing premium wheat varieties in the upcoming days.

The ideal sowing period for wheat in Bangladesh occurs between November 15 and 30. However, a

substantial land area in Bangladesh where wheat is sown after the harvest of Aman rice or where land rests wet because of heavy showers, sowing is made up to January, and wheat crops encounter a relatively heated situation, causing poorer harvest (Hossain *et al.*, 2012). Accordingly, the creation of extra temperature-resistant varieties remains prominent in wheat development projects (Mohamed, 2013). There exist several key aspects of heat tolerance from the biochemical and molecular levels, the relationship to membrane thermo-stability, making heat shock proteins, and production potential under elevated temperature stress. Studies on the impact of prolonged supra-optimal temperature under field growing conditions on wheat grain yield are rare. Additional research is, therefore, essential for a complete understanding of the effects of thermal stress on the yield of wheat crops under diverse agro-climate settings.

Global wheat production is hampered due to global warming, the long-term absence of rainfall converting regions into drought, sometimes heat waves, etc. The IPCC forecasts global temperatures might increase by 1.5°C between 2030 and 2052, getting 2°C by 2100 (IPCC, 2018). Projections suggest further temperature rises: 1.0°C by 2030, 1.4°C by 2050, and 2.4°C by 2100, with winter warming would be more than summer warming. From 1949 to 2013, yearly temperatures increased by 0.13°C/decade, with periodic and extreme temperatures growing quicker (Zaman *et al.*, 2013). Rising temperatures are harmful to the morpho-physiological, biochemical, metabolic, and molecular processes of wheat (Alam *et al.*, 2023). Photosynthates can't transport from source to sink; an upsurge in respiration and scorching injury is observed in plant parts, causing dwarf plants. Plants also show premature leaf abscission. As a result, unfilled, shriveled, constricted, and choppy grains are developed, finally decreasing the grain yield in wheat. Cultivation of heat-tolerant wheat varieties might overcome the problems of global warming. In this context, the present investigation bears great

importance. The present investigation was, thus, commenced to appraise the performance of newly released modern wheat varieties under late sowing conditions and to identify genotypes with high yield potential for cultivation in coastal soils of Bangladesh based on membrane thermal stability (MTS) and principal component analysis (PCA).

MATERIALS AND METHODS

Experimental Site and Soil

The investigation was conducted at the Farm of Agrotechnology Discipline, Khulna University, Khulna, from December 2017 to March 2018. The study area is located between 22°48' N and 22°80' N latitudes and between 89°31' and 89°53' E longitudes, with an elevation of 9.0 m above sea level. The experimental site fits into the Agro-ecological Zone 13 of the Ganges Tidal Floodplain. The soil was well drained and dominated by clay particles with an electrical conductivity value of 6.5 dS m⁻¹. In the southern part of Bangladesh, farmers are seldom encouraged to wheat cultivation because of the low yield of wheat due to short winter, high temperatures and late sowing dates. We have chosen the experimental location considering the above-mentioned three criteria prevail here.

Climatic Conditions

The weather condition during the study period is described in Figure 1. The peak rainfall happened in the study area in December 2017 (51 mm), followed by March 2018 (1 mm). The other two months did not receive any rainfall. The maximum temperature was the highest in March 2018 (33.7°C), trailed by February 2018 (30.0°C), and the least was in January 2018 (24.0°C). The trend of minimum and mean monthly temperature follow a similar pattern as found for maximum temperature during the crop growth period (Figure 1)

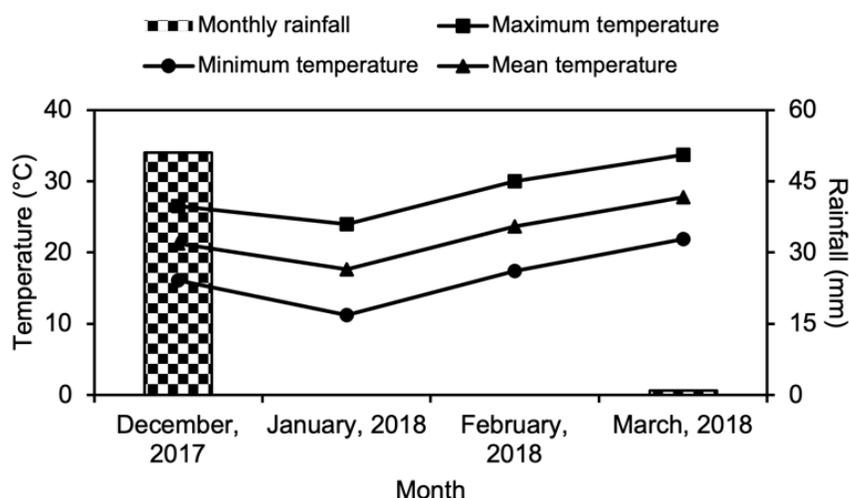


Figure 1 Monthly temperature (maximum, minimum, and mean) and rainfall status of Khulna University during the experimental period from December 2017 to March 2018. Data were collected from the Regional Inspection Centre (RIC), Bangladesh Meteorological Department, Gollamari, Khulna.

Environmental Conditions and Heat Stress

The soils of the experimental location are clay loam (i.e., loam with a major proportion of clay) in texture. Within a week after land opening by tillage, the soil becomes hard with frequent cracking. This phenomenon results in excessive percolation and, ultimately, rapid drying of soil. Moreover, the area is characterized by high rainfall in the monsoon season and scanty rainfall in winter. Both soil type and excess rainfall in the rainy season favor late drainage conditions, which ultimately creates unfavorable conditions for the timely sowing of wheat crops. Late sowing wheat crop generally faces heat stress during flowering and later stages of growth. The absence of rainfall in winter months creates temporary drought. The detrimental effects of the dry period on wheat yield may aggravate while happening with heat stress. Concurrent heat and drought stress cut the rate of photosynthesis together with abnormal respiration, closed stomata and increased leaf temperature. These effects may be synergistic, antagonistic or hypo-additive on the yield of wheat.

Experimental Material

The Bangladesh Wheat and Maize Research Institute (BWMRI) developed some improved wheat varieties for optimal as well as late sowing conditions. Of the eleven wheat genotypes selected for the present study as treatment materials, few were designated as heat tolerant, as found by various researchers (Hossain *et al.*, 2021). A brief description of the varieties is given in Table 1. The seeds of the varieties were collected from the Bangladesh Agricultural Research Institute (BARI), Gazipur, Bangladesh. The varieties were designated as different treatments according to the following way which included T₁-BARI gom20 (Gourab), T₂-BARI gom21 (Shatabdi), T₃-BARI gom22 (Sufi), T₄-BARI gom23 (Bijoy), T₅-BARI gom24 (Prodip), T₆-BARI gom25, T₇-BARI gom26, T₈-BARI gom27, T₉-BARI gom29, T₁₀-BARI gom30, and T₁₁-Sourov. Two varieties, BARI gom27 and BARI gom29, were used as a negative check.

Experimental Design

The field experiment was directed following a randomized complete block design (RCBD) with

three replications. The experimental area was separated into three blocks. Each block had 11 plots where 11 treatments (varieties) were allocated randomly. So, in the experiment, the total number of plots was 33. The size of each individual plot was $2 \times 2 \text{ m}^2$, keeping the plot-to-plot distance of 50 cm.

Table 1 A short description of the eleven wheat varieties used in the experiment

Variety	Life span (day)	Yield (t ha^{-1})	Important characteristics	Institution and year of release
BARI gom20 (Gourab)	100–108	3.6–4.8	Early maturing variety, moderately heat tolerant and suitable for late planting.	BARI, 1998
BARI gom21 (Shatabdi)	105–110	3.6–5.0	Semi dwarf with good tillering ability. Strong stem with non-lodging.	BARI, 2000
BARI gom22 (Sufi)	100–110	3.6–5.0	Semi dwarf high yielding variety. Tolerant to high temperature and spike sterility.	BARI, 2005
BARI gom23 (Bijoy)	103–112	4.3–5.0	Semi-dwarf early maturing high yielding variety. Tolerant to high temperature and gives 10-20% higher yield under late seeding. Moderately tolerant to terminal heat stress.	BARI, 2005
BARI gom24 (Prodip)	102–110	4.3–5.1	Semi-dwarf, early maturing, high yielding variety. Tolerant to terminal heat stress. Suitable for growing under both optimum and late sown conditions.	BARI, 2005
BARI gom25	102–110	3.6–5.0	Early maturing high yielding variety. Moderately tolerant to terminal heat stress and salinity up to 10 dS m^{-1} .	BARI, 2010
BARI gom26	104–110	3.6–5.0	Tolerant to terminal heat stress giving 10-12% higher yield under late seeding. Suitable for north and north-western blast affected areas.	BARI, 2010
BARI gom27	105–110	4.0–5.4	Resistant to stem rust and leaf rust diseases. Suitable for all over the country except southern saline areas.	BARI, 2012
BARI gom29	105–110	4.0–5.0	Dwarf variety with strong stem, non-lodging. Resistant to leaf rust disease.	BARI, 2014
BARI gom30	100–105	4.5–5.5	Short duration heat tolerant variety. Suitable for late planting.	BARI, 2014
Sourov	102–110	3.5–4.5	Resistant to lodging due to its strong stem. Tolerant to leaf blight and leaf rust diseases.	BARI, 1998

Note: BARI = Bangladesh Agricultural Research Institute, Gazipur, Bangladesh. Source: Hossain and Teixeira da Silva (2013)

Crop Management

The total experimental area was prepared with the help of a power tiller. Weeds, straw, and other crop residues were assembled and isolated from the experimental area. Recommended fertilizer doses,

100-27-40-20-1 kg ha^{-1} of N-P-K-S-B respectively (Hossain *et al.*, 2021), were applied during final preparation. Treatments were randomly distributed among the plots. Seeds of the wheat varieties were sown on December 6, 2017. Before sowing, seeds

were treated with Vitavax 200 @ 3 g kg⁻¹ seed. Supplementary water was provided thrice at crown root initiation, booting, and grain filling stages. All intercultivation practices were completed accurately and timely. The wheat crop was considered mature when 90% of the grains became golden yellow. The crop was harvested 110 days after sowing (DAS) when fully matured.

Data Collection

Sampling procedure

For collecting plant height data, 10 plants from the inner rows of each plot were selected and tagged properly, and plant height was taken from the previously selected plants up to 100 DAS. For recording dry matter data, destructive sampling of five randomly selected plants, excluding the boundary row of every plot, was followed. Moreover, yield attributes data (fertile tillers and grains spike⁻¹) were assembled from randomly selected 10 plants from each plot. Grain and straw yield were determined from the central 1 m² area of each plot and then converted to t ha⁻¹ basis.

Growth parameters

Plant height (cm)

For measuring plant height, 10 plants were sampled from each plot. The plant height was measured from the ground level to the tip of the flag leaf at a 10-day interval from 50 DAS to 100 DAS. The recorded values were then averaged to note the plant height of each variety and were expressed in cm.

Plant dry matter (g plant⁻¹)

For recording dry matter, five sample plants were harvested from each experimental unit 50 DAS and continued up to 100 DAS. The samples were dried in an oven at 70°C for 48 h, and the dry weights were taken using an electronic balance. The dry matter was expressed as g plant⁻¹, taking the total average weight.

Yield and yield parameters

Data on yield and yield attributes were gathered during and after harvest. Data on fertile tillers m⁻², filled grains spike⁻¹, test (1000-grain) weight (g), grain yield (t ha⁻¹), straw yield (t ha⁻¹), biological yield (t ha⁻¹), and harvest index (%) were collected.

Fertile tillers

A number of ear-bearing tillers were counted from 10 sample plants in each unit. Then, the average value was taken for fertile tillers plant⁻¹.

Filled grains spike⁻¹

Ten spikes were selected randomly from each plot; the filled grains were counted manually and then averaged to get filled grains spike⁻¹.

1,000 grain weight (g)

From each plot, one thousand grains were taken randomly from sun dried sample and weighed (g) using an electronic balance. Then, the test weight was converted to 14% moisture content.

Straw yield and grain yield

Samples were taken from 1 m² in the middle of individual plots by harvesting the crop near the soil level at full maturity. The harvests were sun-dried, beaten, and cleaned, and weights of straw and grain were noted. The straw and grain yield were articulated in t ha⁻¹. Grain yield was accustomed to a 14% moisture level.

Harvest index (%)

The harvest index is explained by the ratio of grain yield to biological yield and was calculated by using the following formula:

$$\text{Harvest index (\%)} = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

Membrane thermal stability (MTS)

Membrane thermal stability was determined to evaluate heat-tolerant genotypes of field-grown wheat following the method described by Yildirim *et al.* (2009). Membrane thermal stability tests of fully expanded leaves were analyzed at the milky stage. Eight completely developed leaves of each variety were collected randomly from a selection of plants in every repetition. Every leaf was separated into two parts for use as control and for warmth-action. The divided leaf parts were retained in two dissimilar test tubes with 10 mL ion-free water and then kept for 18 hours in a freezer at 10°C. Then, the leaf parts were carefully splashed away with ion-free water. Again, 15 mL of ion-free water was supplemented. Further, 50% of the two test tubes were set aside at 25°C and the remaining half at 45°C aimed at 1 hour in a water bath. Then, different heat-treated sections were preserved for 18 hours in a fridge at 10°C to stabilize the fluid composite after the action time. Conductivity values were recorded at 25°C using an EC meter for both tubes. Then, the two different combinations were given heat counting for an hour. At that point, both the test tubes were retained at room temperature. Likewise, the second conductivity measure of liquid segments (T_2 and C_2) was done while maintaining 25°C when the contents were chilled. The membrane thermostability and relative injury (RI) of the leaf samples were assessed by the equations given below:

$$MTS (\%) = [1 - (T_1/T_2)] \times 100$$

$$RI (\%) = 100 - \{[1 - (T_1/T_2)] / [1 - (C_1/C_2)] \times 100\}$$

where C and T indicate to electrical conductivity (EC) of control and heat-treated segments, the subscripts 1 and 2 denote EC values during pre- and post-boiling, respectively.

Statistical Analyses

The collected data were scrutinized using the Statistical Tool for Agricultural Research (STAR)

following the one-way analysis of variance (ANOVA) technique (R Core Team, 2018). Variety means were separated by Duncan's multiple range test (DMRT) at a 5% level of significance. The degree of association among plant growth characters, yield attributes, and grain yield was estimated by correlation studies. Regression analysis is one of the most extensively used statistical tools for estimating the relationship between a set of independent and dependent variables. It can be used to measure the strength of the relationship between variables. Therefore, functional relationships between wheat yield (dependent variable) and yield parameters (independent variable) were established through bivariate analysis. The association between grain yield and MTS, as well as between grain yield and RI, was inquired about using simple regression analysis. Multivariate analysis methods are needed to discover relations, categorize, and choose traits from a diverse data set. These tactics are highly illustrative, significant, and exact conclusions paralleled to other methods. The PCA enlightens the divergence among genotypes. A biplot was made by PCA to explore the diversity of traits related to the wheat genotypes.

RESULTS AND DISCUSSION

Yield and Yield Contributing Characters

Fertile tillers

The varietal effect on fertile tillers plant⁻¹ was found momentous ($P < 0.01$) for the eleven Bangladeshi wheat genotypes. Spike bearing tillers oscillated from 3.00–4.33 plant⁻¹. BARI gom21 (Shatabdi) and BARI gom24 (Prodip) displayed the maximum spikes plant⁻¹ (4.33), trailed by BARI gom20 (Gourab) and BARI gom22 (Sufi), i.e., 3.33 tillers plant⁻¹. The rest seven varieties bearded statistically identical but minimum (3.00) number of ear-bearing tillers (Table 2). This variation in tillers plant⁻¹ might be explained by the genetic character of the varieties as well as field-specific ecological features (Malik *et al.*, 2013).

Filled grains number per panicle

Filled grain number is a main component in wheat yield. The difference in grains spike⁻¹ among the eleven wheat varieties investigated is given in Table 2. It was found from the results that variety exerted a significant impact ($P < 0.01$) on grains spike⁻¹. The number of grains spike⁻¹ maintained the range from 35.67 to 54.67. The BARI gom24 (Prodip) produced the utmost grains spike⁻¹ (54.67), followed by Sourov (53.33) and BARI gom22 (Sufi) (51.67). In opposition, BARI gom30 possessed the least grains spike⁻¹ (35.67), preceded by BARI gom29 (36.00), BARI gom23 (Bijoy) (39.00), BARI gom27 (39.33), and BARI gom25 (40.67). Hossain *et al.* (2021) also reported variability in grain number in wheat varieties from Bangladesh. Farooq *et al.* (2014) stated that the drop in the number of grains might be attributed to the heat stress on the separation of floral parts, micro and macro sporogenesis, pollination, and reproduction.

Test weight (1000 grain weight)

The test weight of eleven wheat varieties was significantly influenced ($P < 0.01$) (Table 2). The weight of 1000 grains fluctuated between 36.33 and 54.00 g. The BARI gom24 (Prodip) yielded the heaviest grains (54.00 g), which was statistically at par with varieties BARI gom21 (Shatabdi) (45.33 g), BARI gom23 (Bijoy) (46.00 g), and BARI gom25 (48.67 g). On the contrary, BARI gom30 developed the lightest grain weight (36.33 g). High temperatures lessen the duration between anthesis and physiological maturity, which marks a decline in single-grain mass. The reduced grain weight under elevated temperature conditions might be attributed to the shriveled size of endosperm cells in grains and declined starch accumulation due to the reduced activity of the soluble starch synthase (SSS) enzyme. Significant genetic variation has also been recognized in wheat grain weight under increased temperature stress (Narayanan, 2018).

Grain yield

Grain yield among the eleven studied wheat varieties differed considerably ($P < 0.01$). The array of grain yield was 1.44–3.01 t ha⁻¹ (Table 2). BARI gom24 (Prodip) gave the highest harvestable product (3.01 t ha⁻¹), which was similar to BARI gom21 (Shatabdi) (2.81 t ha⁻¹). Consequently, BARI gom30 offered the lowest harvestable amount (1.44 t ha⁻¹). This variation might be due to the inherited characters, crop climate and tiny-edaphic features as recognized during crop growth. Comparable tendencies in diverse genotypes were detected by Hossain *et al.* (2013). The premium yield of BARI gom24 (Prodip) is described by its additional fertile tillers plant⁻¹, extra seeds spike⁻¹, superior test weight, plus higher value of harvest index. Wheat grain yield (t ha⁻¹), when plotted against straw yield (t ha⁻¹) yielded a straight line (Figure 2). It can be concluded from Figure 2 that there exists a positive relationship between these two parameters, and over 80% ($R^2 = 0.82$) of the variation in yield could be defined by the discrepancy in straw yield.

Straw yield

The straw yield of eleven wheat cultivars is presented in Table 2 where momentous disparity ($P < 0.01$) was identified among these varieties. Straw yield maintained an array of 3.14–5.02 t ha⁻¹. Seeing on cultivars, the peak straw yield in the unit area was noted from variety BARI gom21 (Shatabdi) (5.02 t ha⁻¹) trailed by BARI gom24 (Prodip) (4.21 t ha⁻¹). However, statistical similarity was noticed among all the genotypes except BARI gom21 (Shatabdi) and BARI gom24 (Prodip). Hossain *et al.* (2011) also found significant variation in straw yield in eight spring wheat varieties in Bangladesh. The difference in straw yield among the wheat varieties might be owing to the diverse pre-anthesis growth spells under increased temperature stress.

Harvest index

Harvest index (%) was considerably influenced ($P < 0.01$) due to variety (Table 2). In the present study harvest index differed from 30.97 to 42.03%. The uppermost harvest index was estimated in BARI gom24 (Prodip) (42.03%), which was closely followed by BARI gom20 (Gourab) (41.71%) and Sourov (41.40%). The lowest value recorded was in BARI gom30 (30.97%), which was statistically similar to BARI gom27 (34.27%) and BARI gom29 (31.27%) (Table 2). Hossain *et al.* (2021) obtained a variable

harvest index in eight elite spring wheat varieties from Bangladesh. It has been postulated that the capability to improve the speed of photosynthate translocation to grains is one of the processes that offer heat tolerance to wheat (Dias and Lidon, 2009). A simple linear regression using the harvest index as the independent variable and yield as the dependent variable exhibited a positive relationship (Figure 3). The value of R^2 (0.90) indicates that a 90% variation in wheat yield could be the variation in the harvest index of field-grown wheat.

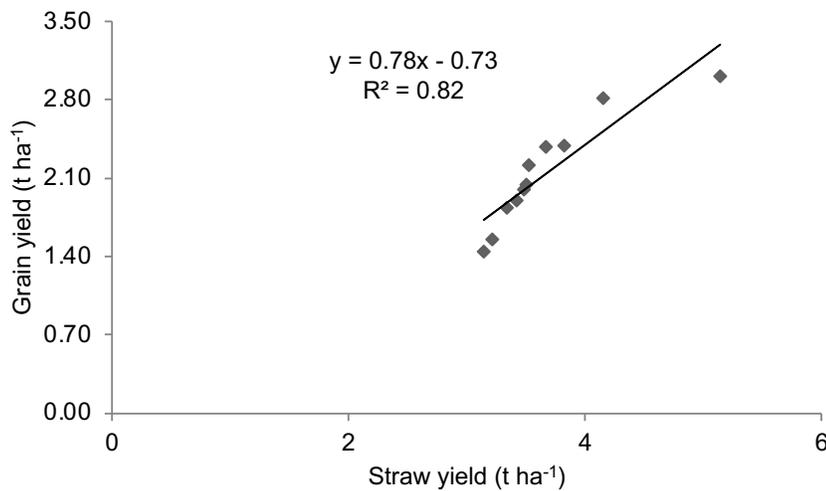


Figure 2 Relationship between grain yield (t ha⁻¹) and straw yield (t ha⁻¹) of wheat

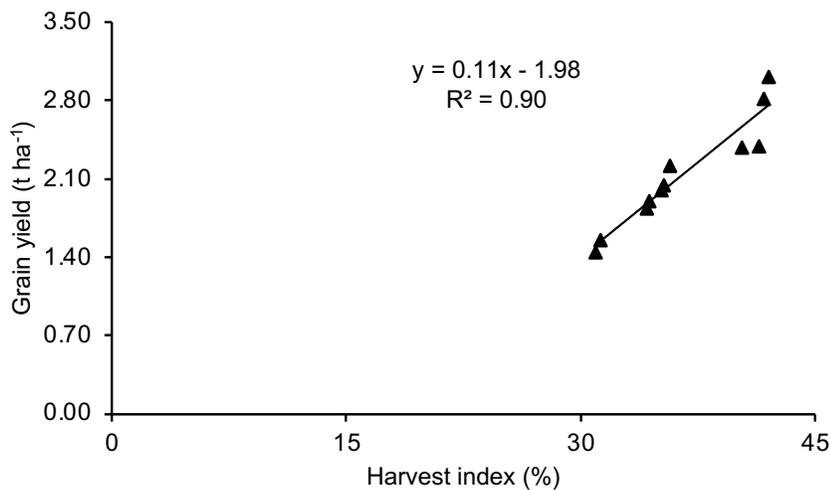


Figure 3 Relationship between grain yield (t ha⁻¹) and harvest index (%) of wheat

Table 2 Yield and yield attributes of eleven wheat varieties from Bangladesh

Variety	Fertile tillers plant ⁻¹	Filled grains spike ⁻¹	Test weight (g)	Grain yield (t ha ⁻¹)	Straw yield (t ha ⁻¹)	Harvest index (%)
BARI gom20 (Gourab)	3.33 ± 0.54 ^{ab}	45.00 ± 3.90 ^{cde}	42.00 ± 1.05 ^{bcd}	2.39 ± 0.40 ^{bc}	3.34 ± 0.51 ^b	41.71 ± 2.00 ^a
BARI gom21 (Shatabdi)	4.33 ± 1.02 ^a	46.67 ± 2.88 ^{bcd}	45.33 ± 0.80 ^{abc}	2.81 ± 0.39 ^{ab}	5.02 ± 0.41 ^a	35.33 ± 0.90 ^{cd}
BARI gom22 (Sufi)	3.33 ± 0.54 ^{ab}	51.67 ± 6.22 ^{abc}	39.33 ± 0.51 ^{cd}	2.00 ± 0.32 ^{cdef}	3.82 ± 0.40 ^b	34.37 ± 1.50 ^{de}
BARI gom23 (Bijoy)	3.00 ± 0.60 ^b	39.00 ± 1.70 ^{ef}	46.00 ± 1.50 ^{abc}	2.04 ± 0.35 ^{cde}	3.67 ± 0.44 ^b	35.70 ± 1.40 ^{cd}
BARI gom24 (Prodip)	4.33 ± 1.00 ^a	54.67 ± 3.20 ^a	54.00 ± 2.00 ^a	3.01 ± 0.20 ^a	4.21 ± 0.30 ^a	42.03 ± 2.20 ^a
BARI gom25	3.00 ± 0.54 ^b	40.67 ± 4.97 ^{def}	48.67 ± 0.82 ^{ab}	1.90 ± 0.30 ^{defg}	3.48 ± 0.55 ^b	35.17 ± 1.45 ^{cd}
BARI gom26	3.00 ± 0.54 ^b	46.67 ± 2.45 ^{bcd}	45.00 ± 0.89 ^{bcd}	2.38 ± 0.35 ^{bcd}	3.52 ± 0.54 ^b	40.30 ± 1.62 ^{ab}
BARI gom27	3.00 ± 0.54 ^b	39.33 ± 2.75 ^{def}	41.67 ± 0.51 ^{bcd}	1.83 ± 0.27 ^{efg}	3.50 ± 0.50 ^b	34.27 ± 1.50 ^{def}
BARI gom29	3.00 ± 0.56 ^b	36.00 ± 2.22 ^f	37.67 ± 0.50 ^{cd}	1.55 ± 0.20 ^g	3.42 ± 0.45 ^b	31.27 ± 1.08 ^{ef}
BARI gom30	3.00 ± 0.56 ^b	35.67 ± 1.92 ^f	36.33 ± 0.52 ^d	1.44 ± 0.22 ^g	3.21 ± 0.29 ^b	30.97 ± 1.02 ^f
Sourov	3.00 ± 0.50 ^b	53.33 ± 4.50 ^{ab}	42.00 ± 0.63 ^{bcd}	2.22 ± 0.30 ^{cde}	3.14 ± 0.25 ^b	41.40 ± 1.84 ^{ab}
P-value	0.0081	0.0067	0.0071	0.0056	0.0061	0.0073
CV (%)	10.93	5.75	4.86	7.64	9.54	4.14
LSD _(0.05)	1.10	7.50	8.70	0.48	0.94	3.36

Note: Means within the same column followed by different superscript letters (a, b, c, d, e, f) are significantly different ($P < 0.05$). Values are presented as mean ± standard deviation. CV = coefficient of variation, LSD = least significant difference.

Membrane Thermal Stability (MTS)

There was a significant difference in membrane thermal stability and membrane injury of leaf among the genotypes (Table 3). Results showed that the highest membrane thermal stability (84.64%) was detected in BARI gom24 (Prodip) which was trailed by BARI gom21 (Shatabdi) (77.66%), BARI gom20 (Gourab) (65.27%), and BARI gom26 (56.12%). While the lowest membrane thermal stability had been computed in BARI gom30 (16.02%). Bala and Sikder (2017) also reported variability in membrane thermal stability in eight wheat cultivars from Bangladesh. Varieties BARI gom24 (Prodip), BARI gom21 (Shatabdi), BARI gom20 (Gourab), and BARI gom26 are recognized as heat tolerant as they had membrane thermal stability values more than 55% (Bala and Sikder, 2017). BARI gom23 (Bijoy) and Sourov are designated as moderately tolerant to extreme temperatures with membrane thermal stability values more than 45%. The rest five varieties are named susceptible as their thermal stability values remain below 45%. Comparable results were observed by Yildirim *et al.* (2009), who established that membrane thermostability can act as a valuable choice benchmark for high-temperature stress resistance in wheat. It has been reported that increased membrane thermal stability, which is a sign of reduced membrane injury, is a selection criterion used to select heat-tolerant wheat genotypes in both managed and natural settings (Narayanan, 2018). Heat stress tolerance is a multifaceted phenomenon and is regulated by a combination of physiological and biochemical factors. The results of our study suggest that MTS can be considered as complementary tools in breeding projects for the selection of heat tolerance potential in wheat genotypes as well as assessing genetic variability in membrane thermal stability among varieties (Yildirim *et al.*, 2009). Moreover, breeders should also utilize MTS as selection indicators in the plant breeding programs for the development of heat-tolerant wheat varieties, as these

were revealed here to be firmly related to wheat yield. Again, the highest membrane injury is found in BARI gom30 (81.74%), which was trailed by BARI gom29 (77.96%), BARI gom27 (69.23%), and BARI gom25 (63.54%). The lowest membrane injury is calculated in BARI gom24 (Prodip) (2.73%), preceded by BARI gom21 (Shatabdi) (7.20%), BARI gom20 (Gourab) (17.03%), BARI gom26 (32.67%), and Sourov (40.03%). The findings of the current investigation are well supported by the results of Bala and Sikder (2017), who also reported variation in thermal injury in several wheat genotypes from Bangladesh. Genotypes differ in the magnitude of membrane injury under elevated temperature stress, as shown by Narayanan (2018). It is noteworthy here that varieties showing the superior MTS (%) exhibited the lower RI (%) (Table 3).

Bivariate analysis was employed to explore the association between membrane thermal stability to grain yield of wheat (Figure 4). The relationship between membrane thermal stability and yield was detected as positive ($R^2 = 0.97$), signifying that greater membrane thermostability offered yield advantages. The regression equation found was $y = 0.02x + 1.17$. The R^2 values for eleven varieties suggested that a 97% improvement in grain yield. Narayanan (2018) also stated that membrane thermostability is well associated with wheat grain yield under hot situations. The meaningfully positive association between grain yield and membrane thermal stability among wheat genotypes exposed that the assessments at the later developing phase would be more beneficial to identify inherent high-yielding varieties. Regression analysis was engaged to discover the relationship between membrane thermal injury and mean wheat yield (Figure 5). The analysis demonstrated a linear but negative association ($R^2 = 0.95$), signifying that higher membrane injury provided inferior yield. The regression equation determined was $y = -0.02x + 2.91$.

Table 3 Membrane thermal stability (%) and relative injury (%) of wheat varieties

Variety	Membrane thermal stability (%)	Relative injury (%)
BARI gom20 (Gourab)	65.72 ± 0.38 ^c	17.03 ± 0.15 ^g
BARI gom21 (Shatabdi)	77.66 ± 0.60 ^b	7.20 ± 0.14 ^h
BARI gom22 (Sufi)	38.00 ± 0.50 ^f	58.92 ± 0.77 ^c
BARI gom23 (Bijoy)	46.51 ± 0.46 ^e	44.59 ± 0.49 ^d
BARI gom24 (Prodip)	84.64 ± 0.84 ^a	2.73 ± 0.08 ^h
BARI gom25	32.38 ± 0.20 ^f	63.54 ± 0.62 ^b
BARI gom26	56.12 ± 0.88 ^d	32.67 ± 0.38 ^f
BARI gom27	25.98 ± 0.60 ^g	69.23 ± 0.68 ^b
BARI gom29	19.22 ± 0.23 ^h	77.96 ± 0.54 ^a
BARI gom30	16.02 ± 0.22 ^h	81.74 ± 1.11 ^a
Sourov	49.26 ± 1.14 ^e	40.03 ± 0.22 ^e
P-value	0.0065	0.0082
CV (%)	2.94	4.09
LSD _(0.05)	4.03	5.46

Note: Means within the same column followed by different superscript letters (a, b, c, d, e, f, g, h) are significantly different ($P < 0.05$). Values are presented as mean ± standard deviation. CV = coefficient of variation, LSD = least significant difference.

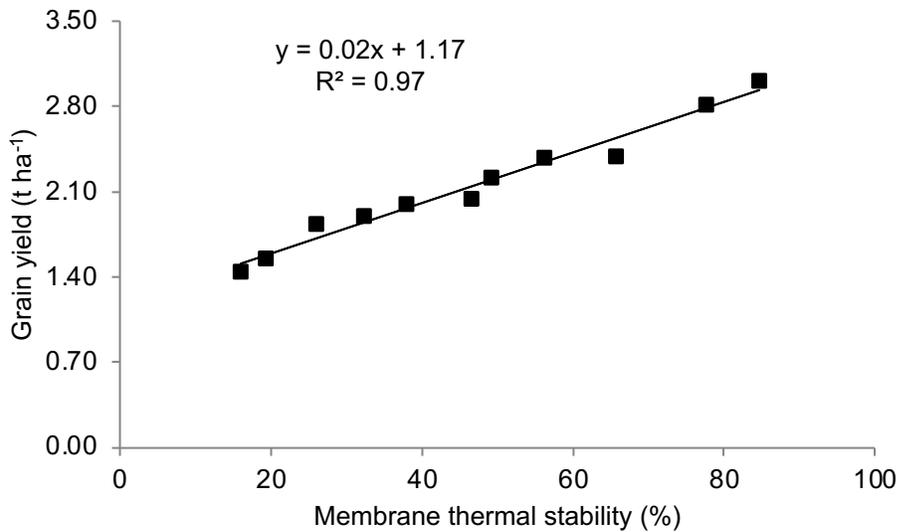


Figure 4 Relationship between grain yield (t ha⁻¹) and membrane thermal stability (%) of wheat

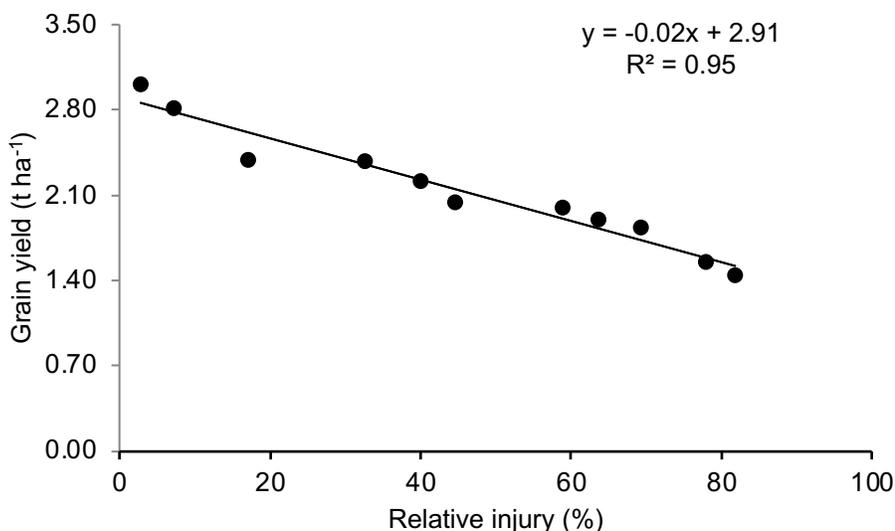


Figure 5 Relationship between grain yield (t ha⁻¹) and relative injury (%) of wheat

In the present investigation, the relationship between grain yield with other morphological and physiological characteristics was also explored (data not shown). Plant height at 100 DAS had a significant positive correlation with grain yield ($r = 0.96$; $P < 0.01$). Dry matter plant⁻¹ at 100 DAS also showed a significant positive association with grain yield ($r = 0.95$; $P < 0.01$). Our results are similar to the findings of Okechukwu *et al.* (2016). They reported a significant and positive relationship between plant height and grain yield, as well as between dry matter and grain yield for 189 wheat germplasms from Syria. Grain yield of wheat varieties also exhibited a significant ($P < 0.01$) and positive association with fertile tillers plant⁻¹, filled grains spike⁻¹, and 1000-grain weight. The corresponding values of the correlation coefficient (r) are estimated as 0.81, 0.75, and 0.74 ($P < 0.01$), respectively. The findings of the present study are well supported by the results of other scholars (Qin *et al.*, 2015; Tausz-Posch *et al.*, 2015; Gao *et al.*, 2017).

Principal Component Analysis (PCA)

In our investigation, the PCA was performed to heighten the inequitable influence for classifying

the measured characters depending on their relationships in heat stress circumstances (Figure 6). The results of PCA indicated that the first two principal components (PCs) explained about 88% of the total variance, and thus were used to create a PCA biplot (Figure 6). The biplot visibly indicates that the wheat varieties do not overlap, which symbolizes a high degree of variability in the results gained. Ahmed *et al.* (2024) reported similar trends in PCA among the five-yardlong bean varieties of Bangladesh. It is noteworthy that only RI acted differentially among the measured traits and the remaining other parameters collectively in determining the variations among the wheat genotypes. Interestingly, PCA biplot outstandingly divided high-yielding varieties BARI gom24 (Prodip), BARI gom21 (Shatabdi), BARI gom20 (Gourab), and BARI gom26 from the low-yielding genotypes BARI gom25, BARI gom27, BARI gom29, and BARI gom30 (Figure 6). The findings of the present study are in line with the results of Alam *et al.* (2025).

Canopy temperature depression, less damage to the photosynthetic apparatus, high chlorophyll content under heat stress, enhanced mobilization of stem reserves, and membrane thermostability are

some significant physiological mechanisms for heat tolerance which support plants to adapt in high temperatures (Sarkar *et al.*, 2021). Membrane systems which stay active during heat stress direct the adaptation of crop plants to elevated temperatures. Therefore, the tolerance to heat stress is explained by the efficacy of the plant in sustaining the integrity and activity of the membrane. If grain filling happens under stressful

situations, then the wheat genotypes with high MTS attain better yields than the genotypes with low MTS (Khatoun *et al.*, 2016). In wheat, cell MTS gives a rational index of genetic variability and exhibits a relationship to the performance of the crop under high-temperature stress and may reflect as an essential selection benchmark for heat stress tolerance.

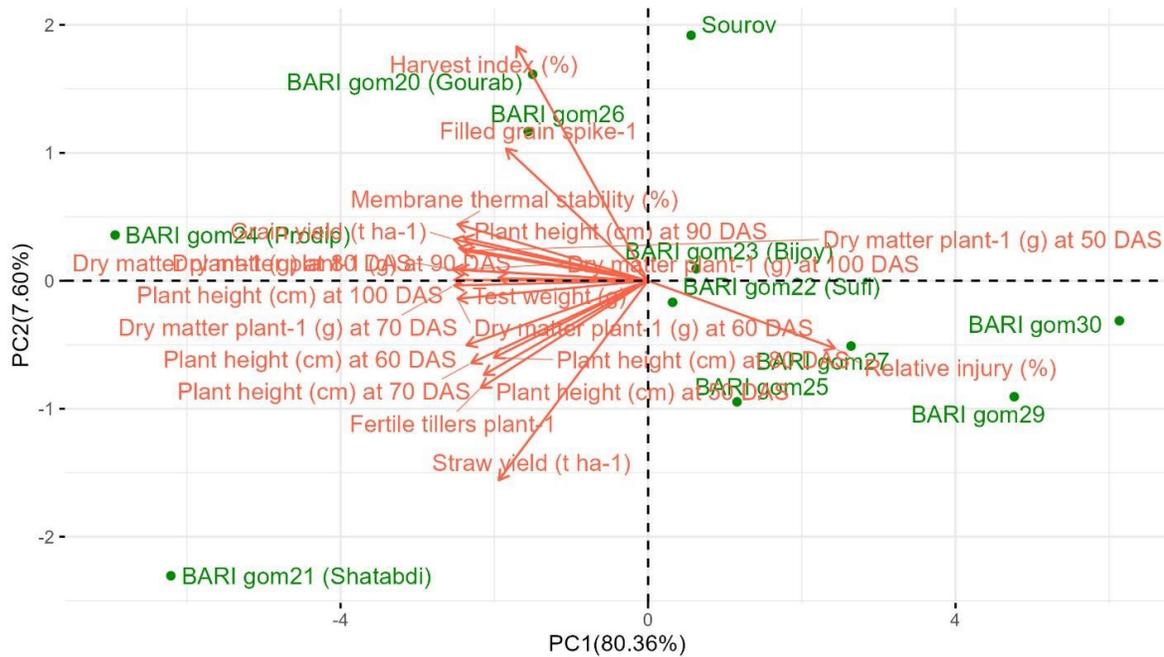


Figure 6 Principal component analysis (PCA) biplot displaying relations between wheat varieties and various selected traits

In the context of global warming scenario, the average global temperature is projected to rise by 3.3–5.7°C by the culmination of the 21st century (IPCC, 2021). The findings of this study have considerable implications for wheat breeding programs and agricultural practices, particularly in regions with high-temperature stress. The study identifies BARI gom24 (Prodip), BARI gom21 (Shatabdi), BARI gom20 (Gourab), and BARI gom26 as high-yielding and heat-tolerant wheat varieties. These varieties showed superior MTS, which is crucial for sustaining cellular integrity under heat stress (Narayanan, 2018). Breeding programs should

highlight these genotypes as parental lines for developing new heat-tolerant cultivars. Farmers can cultivate BARI gom24 (Prodip) and BARI gom21 (Shatabdi) to alleviate the adverse effects of elevated temperatures. Further studies should focus on the genetic mapping of heat tolerance traits to facilitate marker-assisted selection (MAS) in wheat breeding programs. Long-term field trials through varied climatic regions are required to authenticate the stability of heat tolerance characters in dissimilar agroecological regions. This research emphasizes the importance of MTS as a selection criterion in wheat breeding programs for heat-prone

areas. The practical application of these results can improve yield stability and food security by encouraging the cultivation of heat-tolerant wheat genotypes. Future research should carry on exploring physiological, genetic, and agronomic interferences to improve wheat resilience against increasing global temperatures.

CONCLUSIONS

Based on the outcomes of our study, BARI gom24 (Prodip), BARI gom21 (Shatabdi), BARI gom20 (Gourab), and BARI gom26 are considered superior in terms of yield and MTS. Policymakers should allocate more funds for breeding programs intended to enhance heat tolerance in wheat genotypes to ensure stable yields in climate change situations. They also need to develop policies that inspire the adoption of high-yielding and heat-tolerant wheat varieties identified in the study through subsidies and farmer training programs. Breeders may crossbreed heat-tolerant varieties with high-yielding lines through advanced screening techniques (molecular markers and physiological screening methods) to develop improved wheat cultivars with superior stress tolerance and productivity. Farmers of Khulna can cultivate BARI gom24 (Prodip), BARI gom21 (Shatabdi), BARI gom20 (Gourab), and BARI gom26, as they have confirmed

higher MTS and improved yield performance under heat stress conditions. The substantial influence of the high-temperature stress on the performance of the wheat variety's grain yield highlights the serious necessity for breeding for heat stress tolerance. The noteworthy genotypic effect found indicates the existence of enough genetic variation among the wheat genotypes that can be used in the heat tolerance breeding plans in the future. The current study offers the opportunity to investigate further the biochemical and genetic mechanisms that govern heat tolerance in wheat to enhance breeding tactics. However, assessment of the long-term effects of climate change on wheat yield and the development of forecasting models to monitor adaptive breeding programs are essential for further studies.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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