

Phenology, Growth, and Yield of Three Wheat Varieties Under Late-Sown Terminal Heat Stress Conditions in Bangladesh and Implications for Variety Selection

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Abstract

Terminal heat stress imposed by late sowing is one of the most critical yield-limiting constraints for wheat (*Triticum aestivum* L.) cultivation in South Asia, including Bangladesh, where delayed rice harvest forces wheat sowing beyond the optimal window. This study evaluated three elite wheat varieties—BARI Gom 21, BARI Gom 26, and BARI Gom 27—under optimum sowing (25 November, S¹) and late-sowing heat stress (5 January, S²) conditions at the Bangladesh Wheat and Maize Research Institute (BWMRI), Dinajpur, during 2024–2025. A split-plot randomized complete block design with three replications was employed. Heat stress at S² compressed the entire crop life cycle by 28–35 days, reducing days to physiological maturity from 112–115 to 80–83 days across all three varieties. All growth parameters—plant population, leaf area index, dry biomass, and plant height—were significantly impaired under late sowing, with dry biomass at 45 DAS declining by 57–66% (Fig. 2). All yield components were significantly reduced; grain yield declined by 66% in BARI Gom 21, 62% in BARI Gom 26, and 66% in BARI Gom 27. Critically, BARI Gom 21 maintained the highest absolute grain yield under heat stress (1,742 kg ha⁻¹), while BARI Gom 26 recorded the highest relative performance (RP% = 37.65%) and the lowest heat susceptibility index (HSI = 0.92), indicating superior grain-filling stability under thermal stress. BARI Gom 27 was the most heat-susceptible variety, showing the greatest thousand-grain weight collapse (47% reduction). These findings identify BARI Gom 21 as the recommended variety for both optimum and heat-stressed late-sowing conditions, with BARI Gom 26 as the preferred option where grain-weight stability is the primary selection criterion.

1. Introduction

Wheat (*Triticum aestivum* L.) is the world's most widely grown cereal crop and the primary source of protein and calories for approximately 2.5 billion people in developing countries (Braun et al., 2010). Global wheat demand is projected to increase by 60% from current levels by 2050 (Shiferaw et al., 2013). Concurrently, climate change threatens to erode yield gains, with global wheat yield estimated to decline by approximately 6% per 1°C increase in temperature (Asseng et al., 2015; Lamba et al., 2023).

In Bangladesh, wheat is the second most important cereal after rice, with national production reaching 1.75 million tonnes from 0.47 million hectares in 2019–2020 (BBS, 2021). The national average farm yield of approximately 3.49 t ha⁻¹ falls far short of the climatic yield potential of > 6.0 t ha⁻¹, a persistent gap is attributed primarily to terminal heat stress arising from late sowing (Hossain et al., 2021; Hossain & Teixeira da Silva, 2012).

Terminal heat stress in wheat occurs when mean temperatures during grain filling exceed 31°C (Asseng et al., 2015; Prasad et al., 2011). In Bangladesh, approximately 80–85% of wheat is cultivated after transplanted *Aman* rice, of which 60% of the area is planted late due to delays in rice harvest (Badaruddin et al., 1994). This structural delay exposes wheat to two overlapping stresses: low-temperature stress (< 10°C) during germination in January-sown crops and high-temperature stress (> 25°C, escalating to > 31°C) during reproductive and grain-filling stages. The result is a compressed crop life cycle, reduced dry

matter accumulation, impaired grain filling, and significantly diminished grain yield (Fei et al., 2022; Sattar et al., 2023).

The Bangladesh Agricultural Research Institute (BARI) and Bangladesh Wheat and Maize Research Institute (BWMRI) have released over 30 wheat varieties, including BARI Gom 26 and BARI Gom 27 (both released 2010–2012), which carry claims of moderate heat tolerance (BARI, 2016). Yet, rigorous comparative field evaluation of these newer varieties—alongside the well-established BARI Gom 21—under well-characterized late-sowing heat stress has not been reported. Earlier benchmark studies (Hossain & Teixeira da Silva, 2012; Hossain et al., 2013) evaluated varieties that predate these releases, and did not include all three varieties in a single factorial design under a January late-sowing protocol—the most extreme scenario actually faced by Bangladeshi farmers, delayed by the rice harvest.

Against this backdrop, the present study was designed to: (i) characterize the phenological responses of three elite wheat varieties to optimum versus late-sowing heat stress; (ii) quantify the effects of heat stress on growth parameters, yield components, and grain yield of each variety; (iii) calculate heat tolerance indices (RP% and HSI) to identify the most heat-tolerant and heat-susceptible varieties; and (iv) provide evidence-based variety recommendations for Bangladesh's late-sown wheat cropping system.

2. Materials and Methods

2.1. Experimental Site and Period

The field experiment was conducted during the wheat growing season (November 2024 to April 2025) at the research farm of BWMRI, Dinajpur, Bangladesh (25° 44.574' N, 88° 40.344' E; 40 m above sea level; Agro-Ecological Zone 1, Old Himalayan Piedmont Plain). Soil was sandy-loam with pH 5.4, organic matter 1.2%, total N 0.08%, and low to adequate levels of K, S, Zn, B, and P. This zone supports the largest wheat-growing area in Bangladesh (FAO/UNDP, 1988).

2.2. Climate Conditions During the Experiment

Weekly average temperature, humidity, and rainfall were recorded at the BWMRI meteorological station. Under optimum sowing (OS; 25 November), maximum temperatures remained 23–26°C throughout the vegetative stage, peaking at 30–32°C during late grain filling. Under late sowing (LS; 5 January), germination coincided with minimum temperatures of 8–10°C; the grain-filling stage (February–March) was exposed to maximum temperatures of 31–34°C—the recognized threshold for terminal heat stress (Asseng et al., 2015; Prasad et al., 2011). The temperature contrast between OS and LS during grain filling exceeded 8°C on average.

2.3. Experimental Design and Treatments

A split-plot randomized complete block design (RCBD) with three replications was used. Sowing date constituted the main plot: S¹ = optimum sowing (25 November 2020); S² = late sowing under heat stress (5 January 2024). Three elite wheat varieties constituted the subplots: BARI Gom 21 (V¹), BARI Gom 26

(V²), and BARI Gom 27 (V³). This yielded six treatment combinations (S¹V¹ through S²V³) with 18 unit plots. Each unit plot measured 3 × 2 m² (10 rows, 3 m long; row spacing 20 cm).

2.4. Varieties and Crop Management

Table 1
Characteristics of the three wheat varieties evaluated.

Source: BARI (2016).

Variety	Duration (days)	Yield (t ha ⁻¹)	Adaptation	Year Released	Sowing Time	Stress Notes
BARI Gom 21 (Shatabdi)	105–110	3.6–5.0	All country except saline areas	2000	Nov 15–30	Tolerant to Bipolaris; resistant to leaf rust
BARI Gom 26	104–110	3.5–5.0	All country except salinity > 6 dS m ⁻¹	2010	Nov 15–30	Moderately tolerant to terminal heat stress; Ug99 APR
BARI Gom 27	105–110	3.5–5.4	All country except southern salinity > 8 dS m ⁻¹	2012	Nov 15–30	Moderately tolerant to terminal heat stress; Ug99 APR

APR = adult plant resistance; Ug99 = stem rust race.

Seeds were treated with Provax-200 WP fungicide (carboxin + thiram) and sown at 120 kg ha⁻¹ at 4–5 cm depth. Basal fertilizer was applied at the BWMRI-recommended rate (100-27-40-20-1 kg ha⁻¹ of N, P, K, S, and B), with the remaining one-third N applied 20 DAS. Three irrigations were applied at crown root initiation (20 DAS), booting (50 DAS), and grain filling (75 DAS). Standard weeding and pest management were maintained uniformly.

2.5. Data Collection

2.5.1. Phenological Parameters

Days to booting (DB), days to heading (DH), days to anthesis (DA), and days to physiological maturity (DPM) were recorded using the Zadoks decimal scale (Zadoks et al., 1974) from sowing to the date when approximately 80% of plants in each plot reached the respective stage. DPM was determined by complete yellowing of the peduncle.

2.5.2. Growth Parameters

Plant population (plants m⁻²) was counted at 12 DAS from five 1-m rows per plot. Total tillers (m⁻²) were counted at 37 DAS. Leaf area index (LAI) was measured at 45 DAS by the method of Yoshida

(1981). Total dry biomass (g m^{-2}) at 45 DAS was determined after oven-drying at 70°C for 72 hours. Plant height (cm) was measured from ground level to the tip of the highest spikelet on 10 randomly selected plants at harvest.

2.5.3. Yield and Yield Components

Spikes m^{-2} were counted at physiological maturity. Spike length (cm) and spikelets spike $^{-1}$ were measured from 10 randomly selected spikes per plot. Grains spike $^{-1}$ were counted from 10 spikes. Thousand-grain weight (TGW, g) was measured from 1000 grains adjusted to 12% moisture (Hellevang, 1995). Grain yield (kg ha^{-1}) was obtained from a 1 m^2 harvest area and adjusted to 12% moisture. Biological yield = grain yield + straw yield. Harvest index (HI, %) = (grain yield / biological yield) $\times$ 100.

2.6. Heat Tolerance Indices

Relative performance (RP%) = (Stress performance / Optimum performance) $\times$ 100 (Asana & Williams, 1965). Heat susceptibility index (HSI) = $(1 - Y/Y_p) / (1 - X/X_p)$, where Y = mean grain yield under stress, Y_p = mean yield under non-stress, X = mean yield of all genotypes under stress, and X_p = mean yield of all genotypes under non-stress (Fischer & Maurer, 1978). HSI < 0.5: highly tolerant; 0.5–1.0: moderately tolerant; >1.0: susceptible.

2.7. Statistical Analysis

Data were analyzed by ANOVA using MSTAT-C (Michigan State University). Treatment means were compared using Duncan's New Multiple Range Test (DNMRT) at the 5% probability level (Steel & Torrie, 1984). Pearson correlation analysis was performed between grain yield and all yield components under both sowing conditions.

3. Results

3.1. Climatic Conditions and Heat Stress Characterization

The temperature differential between sowing dates was pronounced. Under OS, maximum temperatures remained $23\text{--}26^{\circ}\text{C}$ through the vegetative stage, peaking at $30\text{--}32^{\circ}\text{C}$ during late grain filling—within the tolerable range. Under LS, germination coincided with minimum temperatures of $8\text{--}10^{\circ}\text{C}$, while the grain-filling stage (February–March) was exposed to maximum temperatures of $31\text{--}34^{\circ}\text{C}$ with mean temperatures consistently exceeding 25°C —the threshold above which wheat yield is significantly impaired (Asseng et al., 2015). The mean temperature excess during grain filling exceeded 8°C , constituting severe terminal heat stress.

3.2. Phenological Parameters

Late sowing dramatically compressed the phenological development of all three varieties across all four stages (Fig. 1; $p \leq 0.01$). Under OS, DB ranged from 58 days (BARI Gom 26) to 63 days (BARI Gom 27); under LS, DB was shortened to 42–52 days. The most pronounced booting compression occurred in

BARI Gom 21 (30% reduction: OS 60 days → LS 42 days), while BARI Gom 27 showed the smallest reduction (17%: OS 63 → LS 52 days).

Heading was similarly curtailed: OS DH ranged 65–72 days, reduced to 47–55 days under LS. Anthesis under LS was compressed by 19–24% (OS: 71–77 days; LS: 57–62 days). Most critically, DPM—the integrative measure of grain-filling opportunity—declined from 112–115 days under OS to 80–83 days under LS (27–32 days reduction), shown in Fig. 1. BARI Gom 21 retained the longest DPM under LS (83 days), while BARI Gom 26 and BARI Gom 27 both matured at 80 days. A longer DPM under heat stress is directly associated with greater grain-filling duration and higher TGW (Sattar et al., 2023; Lamba et al., 2023), conferring a relative advantage to BARI Gom 21. The temporal compression of each phenological interval is shown graphically in Fig. 1.

3.3. Growth Parameters

All four growth parameters assessed were significantly impaired by late sowing, as shown in Fig. 2 and Table 2.

3.3.1. Plant Population, Tillers, and Leaf Area Index

Plant population at 12 DAS declined from 304 (OS mean) to 237 plants m^{-2} under LS ($p \leq 0.01$; Fig. 2a). Under OS, BARI Gom 27 and BARI Gom 21 produced the highest stand counts (304 and 295 plants m^{-2} , respectively). LAI at 45 DAS declined sharply from a mean of 4.80 under OS to 2.77 under LS (Fig. 2b), with all varieties converging to similarly low LAI values under heat stress, indicating that inherent varietal differences in leaf area development were overridden by the common thermal constraint. High temperature impairs photosynthetic capacity by damaging chloroplast ultrastructure and reducing chlorophyll content (Fei et al., 2022; Prasad et al., 2008).

3.3.2. Dry Biomass and Plant Height

Dry biomass at 45 DAS was drastically reduced under LS (Fig. 2c; Table 2). S¹V¹ produced the highest biomass (170.07 g m^{-2}), while S²V³ produced the lowest (58.00 g m^{-2})—a 66% reduction. This profound early-season source limitation directly constrains the photosynthate pool available for grain filling. Plant height at harvest was reduced from a mean of 98 cm under OS to 77 cm under LS across varieties (Fig. 2d; Table 2). BARI Gom 21 retained the tallest stature under both sowing conditions (OS: 101 cm; LS: 80 cm), while BARI Gom 27 was shortest under LS (74 cm).

Table 2

Interaction effect of sowing date and variety on plants m^{-2} , tillers m^{-2} , LAI, dry biomass m^{-2} , and plant height at harvest.

Treatment	Plants m^{-2} (12 DAS)	Tillers m^{-2} (37 DAS)	LAI (45 DAS)	Biomass m^{-2} (g)	Height (cm)
S ¹ ×V ¹ (OS×BG21)	295.33	530.00	4.73	170.07	101.33
S ¹ ×V ² (OS×BG26)	237.33	500.00	3.30	145.50	96.00
S ¹ ×V ³ (OS×BG27)	304.33	608.67	4.87	118.17	96.00
S ² ×V ¹ (LS×BG21)	244.33	487.00	2.90	72.50	79.67
S ² ×V ² (LS×BG26)	249.33	655.67	2.93	65.77	78.33
S ² ×V ³ (LS×BG27)	249.67	558.00	2.70	58.00	73.67
LSD (0.05)	20.03	71.77	0.35	9.09	—
CV (%)	4.04	6.95	6.29	4.99	2.04

OS = Optimum sowing; LS = Late sowing; BG21 = BARI Gom 21; BG26 = BARI Gom 26; BG27 = BARI Gom 27. All effects significant at $p \leq 0.01$ (**). Plant height significance per Table 3.

3.4. Yield Components

All yield components were significantly reduced under late sowing, but the magnitude of reduction differed among components and varieties, as shown in Fig. 3 and Table 3.

3.4.1. Spikes, Spikelets, and Grains

Productive spikes m^{-2} declined from a mean of 338 under OS to 261 under LS (23–34% reduction; $p \leq 0.01$), reflecting conversion of vegetative tillers to non-productive sterile stems—a well-established mechanism of heat-induced yield loss (Prasad et al., 2011). The highest spikes m^{-2} under OS was recorded in BARI Gom 27 (381), and the lowest under LS in BARI Gom 26 (251). Spikelets spike^{-1} declined from 16 (OS) to 14 (LS), and grains spike^{-1} from 41.67 (S¹V², highest) to 28 (S²V³, lowest)—a 33% reduction driven primarily by pollen sterility and ovule abortion at anthesis temperatures exceeding 30°C (Prasad et al., 2008, 2011; Yang et al., 2002).

3.4.2. Thousand-Grain Weight (TGW)

TGW was the yield component suffering the greatest proportional decline under terminal heat stress, as illustrated in Fig. 3a ($p \leq 0.01$; Table 4). Under OS, TGW ranged from 36.00 g (BARI Gom 27; S¹V³) to 44.67 g (BARI Gom 26; S¹V²). Under LS, TGW collapsed to 19.00–29.67 g—representing reductions of 33–47%. BARI Gom 27 showed the most extreme TGW collapse (OS: 36.00 g → LS: 19.00 g; 47% reduction), despite its formal breeding designation as moderately heat-tolerant (BARI, 2016). BARI Gom 26 showed the smallest TGW decline (OS: 44.67 g → LS: 27.33 g; 39% reduction), consistent with its superior grain-filling stability under stress. High temperature reduces TGW by accelerating starch synthase denaturation, shortening grain-filling duration, and reducing assimilate supply from impaired photosynthesis (Prasad et al., 2006; Gibson & Paulsen, 1999; Khan et al., 2023).

Table 3

Interaction effect of sowing date and variety on plant height, spikes m⁻², spike length, spikelets spike⁻¹, and grains spike⁻¹.

Treatment	Plant Height (cm)	Spikes m ⁻²	Spike Length (cm)	Spikelets spike ⁻¹	Grains spike ⁻¹
S ¹ ×V ¹	101.33	335.33	8.67	15.00	37.67
S ¹ ×V ²	96.00	299.33	9.33	14.33	41.67
S ¹ ×V ³	96.00	381.33	8.33	16.33	39.00
S ² ×V ¹	79.67	256.67	8.00	15.00	29.67
S ² ×V ²	78.33	251.00	7.67	15.33	32.33
S ² ×V ³	73.67	273.33	8.33	15.00	28.00
LSD (0.05)	—	—	NS	—	—
CV (%)	2.04	4.25	6.59	3.96	2.72

NS = Non-significant for spike length. All other effects significant at $p \leq 0.01$ (**). S¹ = Optimum sowing; S² = Late sowing; V¹ = BARI Gom 21; V² = BARI Gom 26; V³ = BARI Gom 27.

3.5. Grain Yield, Biological Yield, and Harvest Index

3.5.1. Grain Yield

Grain yield was the most integrative measure of heat stress impact, showing significant main effects of sowing date, variety, and their interaction ($p \leq 0.01$; Table 4; Fig. 4). Under OS, BARI Gom 21 produced the highest grain yield (5,096 kg ha⁻¹), followed by BARI Gom 26 (4,529 kg ha⁻¹) and BARI Gom 27 (3,955 kg ha⁻¹).

Under LS, BARI Gom 21 again produced the highest grain yield (1,742 kg ha⁻¹), followed by BARI Gom 26 (1,705 kg ha⁻¹) and BARI Gom 27 (1,353 kg ha⁻¹), as shown in Fig. 4. The percentage yield reductions

under LS were: BARI Gom 21: 66%; BARI Gom 26: 62%; BARI Gom 27: 66%. Despite the similar absolute yield reductions in BARI Gom 21 and BARI Gom 27, BARI Gom 26's lower percentage loss (62%) and superior TGW retention under stress (Fig. 3a) indicate grain-filling stability that supports its breeding designation as moderately heat-tolerant. Every 1°C rise in temperature above the optimum (15°C) reduces wheat yield by 3–4% per spike (Wardlaw et al., 1989); the $\approx 8^{\circ}\text{C}$ mean temperature excess during grain filling under LS is consistent with the observed 62–66% yield losses.

3.5.2. Biological Yield and Harvest Index

Biological yield paralleled grain yield in response to heat stress (Table 4). The highest biological yield under OS was from BARI Gom 21 (13,587 kg ha⁻¹), and under LS also from BARI Gom 21 (6,952 kg ha⁻¹), confirming its superiority in total biomass production across sowing environments. Harvest index declined from 35.87–37.53% under OS to 25.00–28.07% under LS, reflecting impaired assimilate partitioning to grain under heat stress. The highest HI under OS was BARI Gom 21 (37.53%); under LS it was BARI Gom 26 (28.07%), reinforcing the grain-filling stability advantage of BARI Gom 26 under heat stress.

Table 4
Interaction effect of sowing date and variety on thousand-grain weight, grain yield, biological yield, and harvest index.

Treatment	TGW (g)	Grain Yield (kg ha ⁻¹)	Biological Yield (kg ha ⁻¹)	Harvest Index (%)
S ¹ ×V ¹	43.33	5,096 a	13,587 a	37.53 a
S ¹ ×V ²	44.67	4,529 b	12,627 b	35.87 b
S ¹ ×V ³	36.00	3,955 c	10,805 c	36.60 ab
S ² ×V ¹	29.67	1,742 d	6,952 d	25.00 e
S ² ×V ²	27.33	1,705 d	6,076 e	28.07 d
S ² ×V ³	19.00	1,353 e	5,113 f	26.47 de
LSD (0.05)	1.43	200.35	225.75	2.37
CV (%)	2.29	3.47	1.30	3.99

Different letters within columns indicate significant differences at $p \leq 0.05$ (DNMRT). TGW = thousand-grain weight. All effects significant at $p \leq 0.01$ (**). S¹ = Optimum sowing; S² = Late sowing; V¹ = BARI Gom 21; V² = BARI Gom 26; V³ = BARI Gom 27.

3.6. Heat Tolerance Indices

Heat tolerance indices are presented in Table 5 and Fig. 5. BARI Gom 26 exhibited the highest relative performance (RP% = 37.65%), indicating that it retained the greatest proportion of its optimum grain yield under heat stress, followed by BARI Gom 27 (34.21%) and BARI Gom 21 (34.18%). HSI values were:

BARI Gom 26: 0.92 (moderately tolerant); BARI Gom 21: 1.04 (susceptible); BARI Gom 27: 1.08 (susceptible). The dual-axis representation in Fig. 5 illustrates the complementary nature of RP% and HSI: while BARI Gom 26 is the most heat-tolerant variety on the basis of proportional yield retention and HSI, BARI Gom 21 delivers the highest absolute grain yield to the farmer under both sowing conditions. This distinction—between stress tolerance and stress-environment productivity—is of direct relevance to variety recommendation.

BARI Gom 27, despite its breeding designation as moderately heat-tolerant (BARI, 2016), showed the highest HSI (1.08) and the most extreme TGW collapse (47%). The convergence of these findings suggests that BARI Gom 27’s heat tolerance label is conditional on the stress severity: under the January 5 sowing protocol used here—the most extreme late-sowing date evaluated in any published study for Bangladeshi wheat varieties—its tolerance threshold is exceeded. Future variety evaluation programs should include January late-sowing protocols alongside the more commonly used December 27 treatment to fully characterize variety performance across the stress severity spectrum encountered by real farmers.

Table 5
Relative performance (RP%) and heat susceptibility index (HSI) for grain yield under late-sowing heat stress (5 January).

Variety	OS Yield (kg ha ⁻¹)	LS Yield (kg ha ⁻¹)	RP (%)	HSI
BARI Gom 21	5,096	1,742	34.18	1.04
BARI Gom 26	4,529	1,705	37.65	0.92
BARI Gom 27	3,955	1,353	34.21	1.08
Mean	4,527	1,600	35.35	—

RP% = (Stress performance / Optimum performance) × 100. HSI classification: <0.5 = highly tolerant; 0.5–1.0 = moderately tolerant; >1.0 = susceptible (Fischer & Maurer, 1978). OS = Optimum sowing; LS = Late sowing.

4. Discussion

4.1. Thermal Compression of Crop Phenology

The most immediate and unambiguous effect of late sowing was the dramatic shortening of all phenological stages, consistent with the accelerating effect of high temperature on developmental rate in wheat (Sattar et al., 2023; Fei et al., 2022; Hossain & Teixeira da Silva, 2012). As shown in Fig. 1, the total life cycle was compressed by 27–32 days across varieties—equivalent to a loss of nearly one month of potential photosynthate accumulation and grain filling. DPM declined from 112–115 days under OS to 80–83 days under LS, confirming that the crop under January sowing was forced into premature maturation by the high temperature (> 31°C) encountered during February–March.

BARI Gom 21 retained the longest DPM under LS (83 days), providing the most grain-filling opportunity among the three varieties. BARI Gom 26 and BARI Gom 27 both reached maturity at 80 days under LS, despite different formal tolerance designations. This equivalence in DPM under severe stress suggests that phenological duration under January sowing is constrained more by the thermal environment than by genetic background—a finding with implications for breeding programs that use DPM as a selection criterion for heat tolerance. Compared to earlier studies (Hossain & Teixeira da Silva, 2012: 19–25% DPM reduction at December 27 sowing), our study found 27–30% reductions, reflecting the more extreme January 5 sowing date.

4.2. Growth Penalties and Their Mechanistic Basis

The 57–66% reduction in dry biomass at 45 DAS under late sowing (Fig. 2c) represents a fundamental impairment of the photosynthetic source capacity early in the season. January-sown wheat faces a double-stress sequence: cold-stress-induced germination inhibition ($< 10^{\circ}\text{C}$) reduces plant establishment, and the shortened vegetative phase is then overtaken by terminal heat stress, collapsing LAI (Fig. 2b; mean $4.80 \rightarrow 2.77$). This cascade explains why varietal differences in growth parameters, which are pronounced under OS, converged to uniformly low values under LS—indicating that severe heat stress overrides genetic variation in vegetative growth capacity. The reduction in plant height (Fig. 2d; mean -22%) reflects reduced internode elongation due to heat-accelerated stem development and reduced assimilate availability.

4.3. Yield Components: Grain Filling as the Primary Stress Target

All yield components declined significantly under late sowing, but the analysis presented in Fig. 3 and Table 4 reveals that TGW suffered the greatest proportional decline (33–47%), identifying grain filling as the most thermally sensitive yield-determining process. This is mechanistically consistent with the known thermolability of key grain-filling enzymes: ADP-glucose pyrophosphorylase and starch synthase both lose activity at temperatures above 30°C , directly reducing starch deposition rate and shortening effective grain-filling duration (Prasad et al., 2006; Gibson & Paulsen, 1999).

The especially severe TGW collapse of BARI Gom 27 under LS (47%; OS: $36.00\text{ g} \rightarrow \text{LS: } 19.00\text{ g}$, Fig. 3a) directly contradicts its “moderately heat-tolerant” designation (BARI, 2016), at least under the January sowing protocol. BARI Gom 26’s smaller TGW decline (39%) and highest RP% (37.65%, Fig. 5) support its relative grain-filling stability and suggest that its heat tolerance mechanisms—which may include higher membrane thermostability or more efficient carbon remobilization under stress—are more effective than those of BARI Gom 27. This finding has immediate breeding implications: grain-filling stability, as measured by TGW retention under heat stress, should be explicitly incorporated into the BARI/BWMRI variety evaluation scoring matrix.

4.4. The Tolerance-Productivity Tradeoff and Variety Recommendation

The juxtaposition of RP%/HSI (Fig. 5) with absolute grain yield (Fig. 4) reveals a fundamental tradeoff: BARI Gom 26 is the most heat-tolerant variety (HSI = 0.92; RP% = 37.65%) but delivers lower absolute grain yield to the farmer under both sowing conditions. BARI Gom 21, despite an HSI of 1.04 (technically susceptible), delivers the highest absolute grain yield—both optimally ($5,096 \text{ kg ha}^{-1}$) and under heat stress ($1,742 \text{ kg ha}^{-1}$). This distinction—absolute productivity versus relative stress tolerance—is critical for practical variety recommendation. For food-insecure smallholder farmers, absolute yield under stress is the primary concern, not proportional retention of potential yield. For breeding programs targeting heat tolerance, RP% and HSI are the appropriate metrics.

These findings suggest a differentiated recommendation: BARI Gom 21 for farmers prioritizing maximum grain delivery under both sowing conditions; BARI Gom 26 for seed production systems and breeding programs targeting heat-tolerant germplasm; and BARI Gom 27 not recommended for very late-sown (January) systems pending re-evaluation under this stress severity. The identification of BARI Gom 21 as the preferred variety for late-sown systems aligns with its performance history across a range of Bangladeshi environments (BBS, 2021) and provides a contemporary, quantitative basis for extension advice previously lacking for this variety trio.

4.5. Broader Implications for Bangladeshi Wheat Production

The > 62% yield loss observed in all three varieties under January sowing—regardless of heat tolerance designation—underscores the urgency of systemic interventions that reduce the structural causes of late sowing. These include adoption of early-maturing rice varieties, direct-seeded rice, and mechanical harvesting technologies that can advance the rice harvest by 2–3 weeks and thus allow wheat to be sown within the November 15–December 15 optimum window (Hossain et al., 2021; Sattar et al., 2023). Variety selection and heat stress management are complementary rather than alternative strategies: even the most heat-tolerant variety available cannot fully compensate for a January sowing date under current climate conditions in northern Bangladesh.

5. Conclusions

Terminal heat stress imposed by late sowing (5 January) caused a 27–32-day compression of the wheat crop life cycle (Fig. 1), a 57–66% reduction in early-season dry biomass (Fig. 2), a 23–47% reduction in individual yield components (Fig. 3), and a 62–66% reduction in grain yield (Fig. 4) across all three elite varieties evaluated. Five principal conclusions are drawn:

- (1) **November 25 is confirmed as the suitable sowing date for maximizing wheat yield in northern Bangladesh.** All three varieties performed markedly and significantly better under optimum sowing.
- (2) **BARI Gom 21 is recommended for both optimum and late-sown heat-stressed conditions** due to its highest absolute grain yield ($5,096 \text{ kg ha}^{-1}$)

(3) **BARI Gom 26 is the most heat-tolerant variety by RP% and HSI** (Fig. 5) and shows the smallest TGW reduction under heat stress (39%), making it the preferred choice for breeding programs targeting grain-filling stability and for seed production systems under late-sowing conditions.

(4) **BARI Gom 27 should not be recommended for very late-sown (January) systems.** Despite its formal designation as moderately heat-tolerant, it showed the highest HSI (1.08) and the largest TGW collapse under January sowing (47%), warranting re-evaluation of its tolerance designation at this stress severity.

(5) **Three phenotypic traits emerge as priority targets for heat tolerance breeding in Bangladeshi wheat:** grain-filling duration (DPM retention under stress), TGW stability, and early dry matter accumulation capacity at 45 DAS. Future breeding should explicitly score these traits under a January late-sowing screening protocol.

The > 62% yield loss observed in all varieties regardless of tolerance designation highlights that varietal improvement must be complemented by systemic agronomic interventions—early-maturing rice varieties, direct-seeded rice, mechanical harvesting—that enable wheat sowing within the November 15–December 15 optimal window. These findings provide the first contemporary, head-to-head comparative performance baseline for BARI Gom 21, BARI Gom 26, and BARI Gom 27 under severe terminal heat stress, against which future heat-tolerant variety releases can be benchmarked.

Declarations

Competing interests:

The authors declare no competing interests.

Consent to publish

Not applicable.

Ethics and consent to participate

The cultivation and use of cultivated wheat (*Triticum aestivum*) in this study complied with all relevant local and national agricultural guidelines. Seeds for BARI Gom 21, BARI Gom 26, and BARI Gom 27 were sourced legitimately from the Bangladesh Wheat and Maize Research Institute (BWMRI). Human or animal consent to participate is not applicable.

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Author Contribution

ARAM - Conceptualization, Writing the Manuscript, Visualization.RM - Conducted the Literature ReviewAT
- Supervision, Data Analysis

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Asana, R.D., & Williams, R.F. (1965). The effect of temperature stress on grain development in wheat. *Australian Journal of Agricultural Research*, 16, 1–3.
2. Asseng, S., Ewert, F., Martre, P., Rötter, R.P., Lobell, D.B., Cammarano, D., ... & Zhu, Y. (2015). Rising temperatures reduce global wheat production. *Nature Climate Change*, 5(2), 143–151.
3. Badaruddin, M., Saunders, D.A., Siddique, A.B., Hossain, M.A., Ahmed, M.O., Rahman, M.M., & Parveen, S. (1994). Determining yield constraints for wheat production in Bangladesh. In D.A. Saunders & G.P. Hettel (Eds.), *Wheat in Heat Stressed Environments* (pp. 265–271). CIMMYT.
4. Bangladesh Agricultural Research Institute (BARI). (2016). Annual Report 2015–16. BARI, Joydebpur, Gazipur, Bangladesh.
5. Bangladesh Bureau of Statistics (BBS). (2021). Statistical Yearbook Bangladesh 2020–21. Ministry of Planning, Government of Bangladesh.
6. Braun, H.J., Atlin, G., & Payne, T. (2010). Multi-location testing as a tool to identify plant response to global climate change. In C.R.P. Reynolds (Ed.), *Climate Change and Crop Production*. CABI.
7. FAO/UNDP. (1988). Land resources appraisals of Bangladesh for agricultural development (Report No. 2). Food and Agriculture Organization of the United Nations.
8. Fei, L., Chu, J., Zhang, X., Dong, S., Dai, X., & He, M. (2022). Physiological and proteomic analyses indicate delayed sowing improves photosynthetic capacity in wheat flag leaves under heat stress. *Frontiers in Plant Science*, 13, 848464.
9. Fischer, R.A., & Maurer, R. (1978). Drought resistance in spring wheat cultivars. I. Grain yield responses. *Australian Journal of Agricultural Research*, 29, 897–912.
10. Gibson, L.R., & Paulsen, G.M. (1999). Yield components of wheat grown under high temperature stress during reproductive growth. *Crop Science*, 39(6), 1841–1846.
11. Hellevang, K.J. (1995). Grain moisture content effects and management. North Dakota State University Extension.
12. Hossain, A., Kizilgeci, F., Milon, M.S.H., Teixeira da Silva, J.A., & Gaydon, D.S. (2021). Evaluation of six elite irrigated spring bread wheat varieties tolerant to heat stress during late sowing. *Thai Journal of*

Agricultural Science, 54(1), 22–46.

13. Hossain, A., Sarker, M.A.Z., Saifuzzaman, M., Teixeira da Silva, J.A., Lozovskaya, M.V., & Akhter, M.M. (2013). Evaluation of growth, yield, relative performance and heat susceptibility of eight wheat genotypes grown under heat stress. *International Journal of Plant Production*, 7(3), 615–636.
14. Hossain, A., & Teixeira da Silva, J.A. (2012). Phenology, growth and yield of three wheat varieties as affected by high temperature stress. *Notulae Scientia Biologicae*, 4(3), 97–109.
15. Khan, H., Mamrutha, H.M., Krishnappa, G., Mishra, C.N., Parkash, O., Singh, G., ... & Singh, G.P. (2023). Harnessing high yield potential in wheat under climate change scenario. *Plants*, 12(6), 1271.
16. Lamba, K., Singh, G.P., Manoj, K., Nain, A.S., Kumar, U., & Sharma, I. (2023). Heat stress tolerance indices for identification of the heat tolerant wheat genotypes. *Scientific Reports*, 13, 10842.
17. Nahar, K., Ahamed, K.U., & Fujita, M. (2010). Phenological variation and its relation with yield in several wheat cultivars under normal and late sowing mediated heat stress condition. *Notulae Scientia Biologicae*, 2(3), 51–56.
18. Prasad, P.V.V., Pisipati, S.R., Ristic, Z., Bukovnik, U., & Fritz, A.K. (2008). Impact of nighttime temperature on physiology and growth of spring wheat. *Crop Science*, 48(6), 2372–2380.
19. Prasad, P.V.V., Boote, K.J., & Allen, L.H. Jr. (2006). Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum. *Agricultural and Forest Meteorology*, 139(3–4), 237–251.
20. Prasad, P.V.V., Djanaguiraman, M., & Shroyer, J.P. (2011). Impact of high temperature stress on wheat and barley production in the Great Plains. In *Crop Adaptation to Climate Change* (pp. 175–188). Wiley-Blackwell.
21. Redhu, M., Bishnoi, S.K., Singh, G.P., & Singh, A. (2024). Assessing alpha lattice design for heat stress indices and yield stability in wheat genotypes. *Scientific Reports*, 15, 2781.
22. Sattar, A., Nanda, S., Singh, K., Jha, R.K., & Bal, S.K. (2023). Responses of phenology, yield attributes, and yield of wheat varieties under different sowing times in Indo-Gangetic Plains. *Frontiers in Plant Science*, 14, 1224334.
23. Shiferaw, B., Smale, M., Braun, H.J., Duveiller, E., Reynolds, M., & Muricho, G. (2013). Crops that feed the world 10. *Food Security*, 5(3), 291–317.
24. Sial, M.A., Arain, M.A., Khanzada, S., Naqvi, M.H., Dahot, M.U., & Nizamani, N.A. (2005). Yield and quality parameters of wheat genotypes as affected by sowing dates and high temperature stress. *Pakistan Journal of Botany*, 37(3), 575–584.
25. Steel, R.G.D., & Torrie, J.H. (1984). *Principles and Procedures of Statistics: A Biometrical Approach* (2nd ed.). McGraw-Hill.
26. Timsina, J., Humphreys, E., & Dhungana, S.K. (2016). Increasing wheat yield in the rice-wheat system of South Asia. *Field Crops Research*, 199, 48–60.
27. Wahid, A., Gelani, S., Ashraf, M., & Foolad, M.R. (2007). Heat tolerance in plants: An overview. *Environmental and Experimental Botany*, 61(3), 199–223.

28. Wardlaw, I.F., Dawson, I.A., & Munibi, P. (1989). The tolerance of wheat to high temperature during reproductive growth. I. Australian Journal of Agricultural Research, 40, 1–13.

29. Yang, J., Shen, Q., Gu, X., & Peng, S. (2002). Potentials and strategies for improving nitrogen use efficiency in rice-wheat cropping systems. In Agricultural Nitrogen Pollution and its Control (pp. 255–259). CSIC.

30. Yoshida, S. (1981). Fundamentals of Rice Crop Science. International Rice Research Institute.

31. Zadoks, J.C., Chang, T.T., & Konzak, C.F. (1974). A decimal code for the growth stages of cereals. Weed Research, 14(6), 415–421.

32. Zia-Ul-Hassan, Shah, A.N., Jamil, M., Saud, S., Ahmad, I., Arif, M., & Ahmad, S. (2014). Effect of sowing dates and phosphorus application on wheat grain quality. American Journal of Plant Sciences, 5, 3038–3047.

Figures

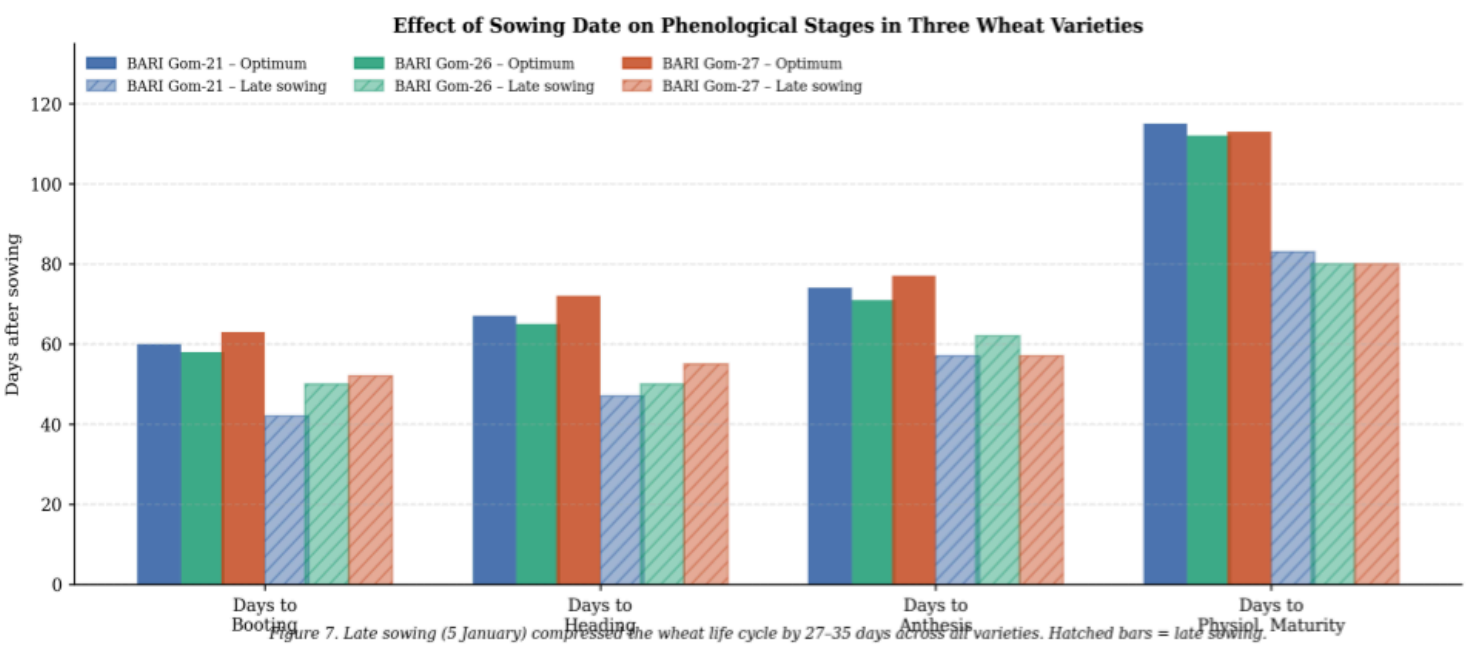


Figure 7. Late sowing (5 January) compressed the wheat life cycle by 27–35 days across all varieties. Hatched bars = late sowing.

Figure 1

Effect of sowing date on phenological stages—days to booting (DB), heading (DH), anthesis (DA), and physiological maturity (DPM)—in three wheat varieties under optimum sowing (25 November, solid bars) and late-sowing heat stress (5 January, hatched bars). Late sowing compressed the total life cycle by 27–35 days across all varieties. BARI Gom 21 retained the longest DPM under late sowing (83 days), conferring greater grain-filling opportunity. BG-21 = BARI Gom 21; BG-26 = BARI Gom 26; BG-27 = BARI Gom 27. Stages recorded using the Zadoks decimal scale. Error bars = $\pm$ SE (n = 3). Sowing date effect significant at $p \leq 0.01$ for all stages.

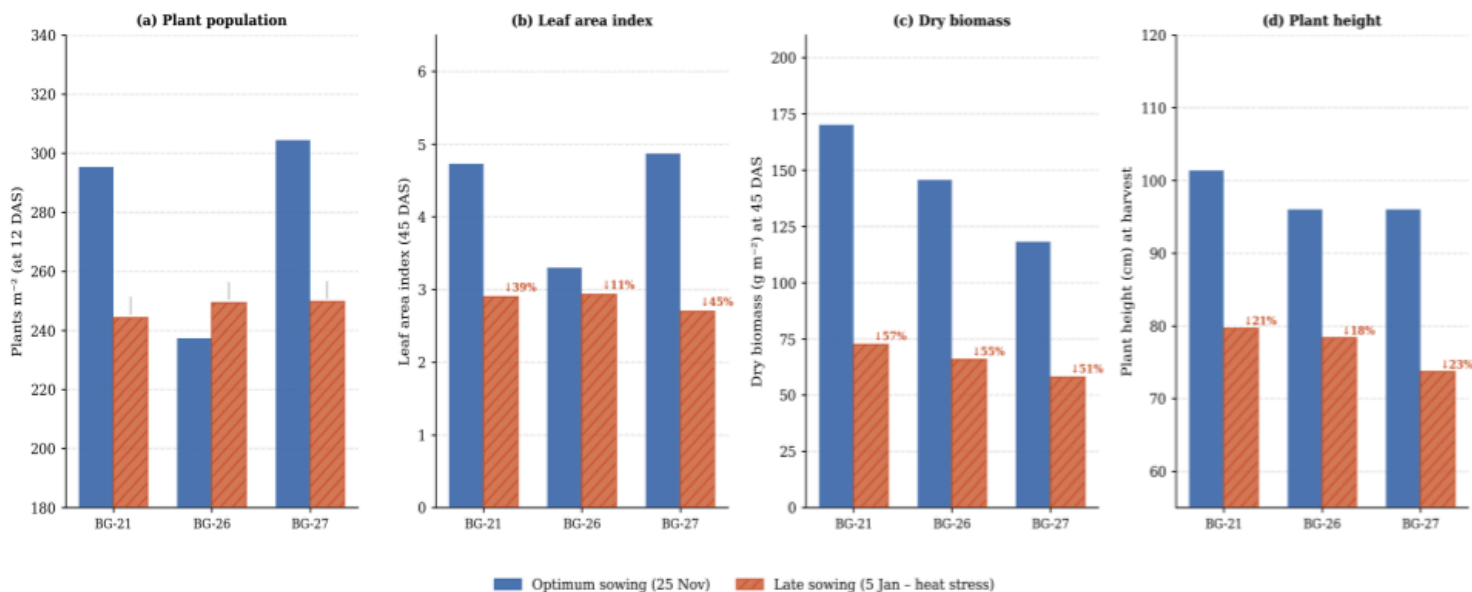


Figure 2. Effect of sowing date (optimum: 25 November; late: 5 January) and wheat variety on key growth parameters. Percentage values above late-sowing bars indicate reduction relative to optimum sowing of the same variety. BG = BARI Gom; error bars = $\pm$ SE (n=3).

Figure 2

Effect of sowing date (optimum: 25 November; late: 5 January) and wheat variety on key vegetative growth parameters: (a) plant population at 12 DAS (plants m⁻²); (b) leaf area index (LAI) at 45 DAS; (c) dry biomass (g m⁻²) at 45 DAS; and (d) plant height (cm) at harvest. Percentage values above late-sowing bars indicate reduction relative to optimum sowing of the same variety. All parameters significantly reduced under late sowing ($p \leq 0.01$). Hatched bars = late sowing (5 January). BG-21 = BARI Gom 21; BG-26 = BARI Gom 26; BG-27 = BARI Gom 27. Error bars = $\pm$ SE (n = 3).

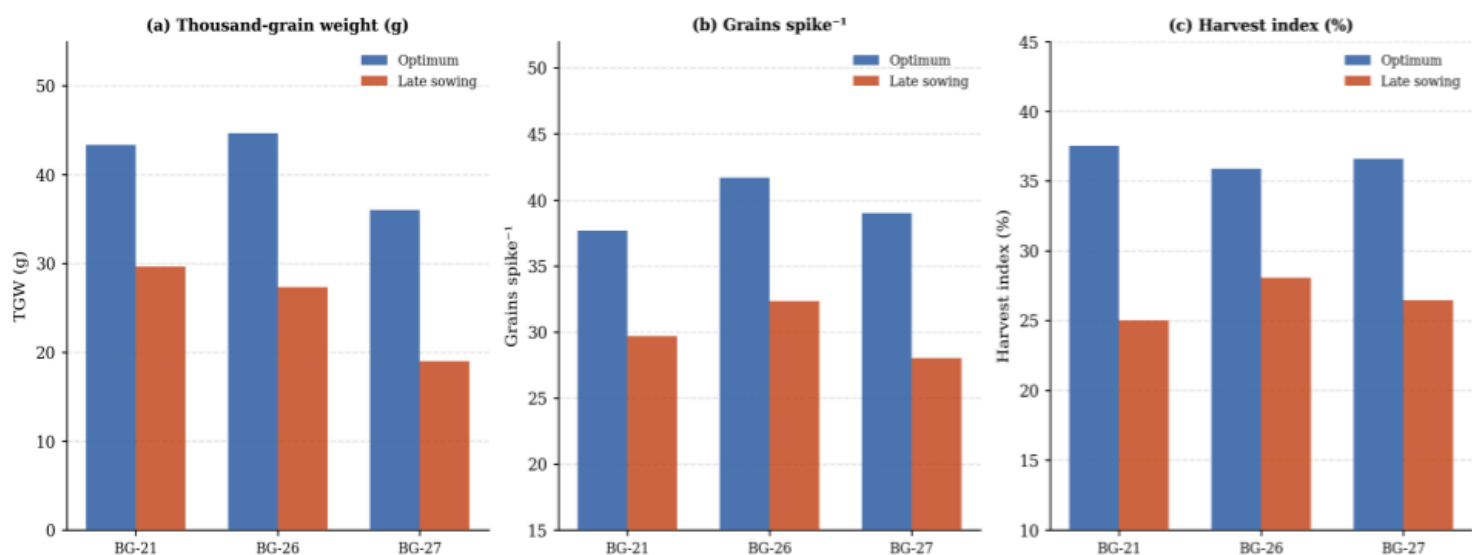


Figure 9. Thousand-grain weight showed the greatest proportional decline (33–47%) under heat stress, indicating grain filling as the primary thermally sensitive process.

Figure 3

Effect of sowing date and wheat variety on yield components: (a) thousand-grain weight (TGW, g); (b) grains spike⁻¹; and (c) harvest index (%). Thousand-grain weight showed the greatest proportional decline under late-sowing heat stress (33–47%), identifying grain filling as the most thermally sensitive yield-determining process. BARI Gom 26 showed the smallest TGW decline (39%), supporting its characterization as relatively heat-stable in grain-filling. BARI Gom 27 showed the largest TGW collapse (47%), warranting re-evaluation of its “moderately heat-tolerant” breeding label. BG-21 = BARI Gom 21; BG-26 = BARI Gom 26; BG-27 = BARI Gom 27. Error bars = ±SE (n = 3). All effects significant at $p \leq 0.01$.

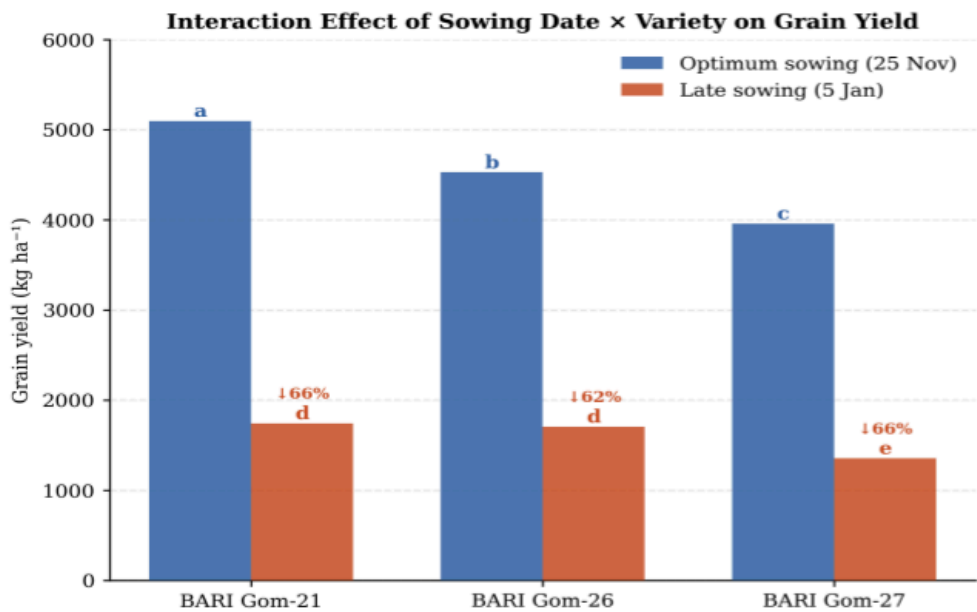


Figure 8. BARI Gom-21 produced the highest absolute grain yield under both sowing conditions. Arrows indicate % yield reduction from optimum sowing.

Figure 4

Interaction effect of sowing date and wheat variety on grain yield (kg ha⁻¹). BARI Gom 21 produced the highest absolute grain yield under both optimum (5,096 kg ha⁻¹) and late-sowing heat stress (1,742 kg ha⁻¹) conditions. Downward arrows above the late-sowing bars indicate the percentage yield reduction relative to the same variety under optimum sowing. BARI Gom 26 showed the smallest percentage yield loss (62%), while BARI Gom 21 and BARI Gom 27 both showed 66% yield reduction. Different letters above the bars indicate significant differences among all treatment–variety interactions at $p \leq 0.05$ (DNMRT). Grain yield is adjusted to 12% moisture content.

Heat Tolerance Indices: Relative Performance (RP%) and Heat Susceptibility Index (HSI)

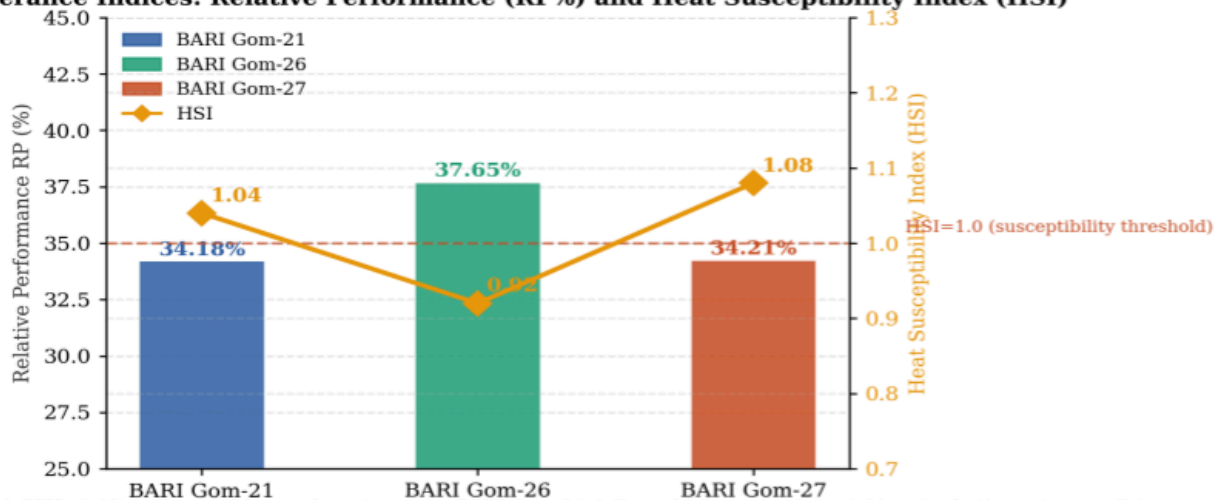


Figure 10. BARI Gom-26 (HSI=0.92) is the most heat-tolerant variety; BARI Gom-21 delivers highest absolute yield under both sowing conditions.

HSI=0.5 (high tolerance threshold)

Figure 5

Heat tolerance indices for three wheat varieties under late-sowing terminal heat stress: relative performance (RP%, bars, left axis) and heat susceptibility index (HSI, diamond markers and line, right axis). Dashed horizontal lines indicate HSI thresholds: red = HSI 1.0 (susceptibility boundary); amber = HSI 0.5 (highly tolerant boundary) per Fischer and Maurer (1978). BARI Gom 26 (HSI = 0.92; RP% = 37.65%) is the most heat-tolerant variety by both indices. BARI Gom 21 (HSI = 1.04) delivers the highest absolute grain yield under both sowing conditions (5,096 kg ha⁻¹ under optimum; 1,742 kg ha⁻¹ under heat stress), illustrating the tolerance-productivity tradeoff relevant to variety recommendation.