



RESEARCH ARTICLE

# Genotypic performance of wheat (*Triticum aestivum* L.) for terminal heat stress across different sowing dates

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Received: 08 August 2025; Accepted: 07 April 2026; Available online: Version 1.0: 15 September 2026

**Cite this article:** Kamla DJ, Rabiya P, Hitendra K, Sarvesh S, Rupinder K, Girish C, Shweta S. Genotypic performance of wheat (*Triticum aestivum* L.) for terminal heat stress across different sowing dates. Plant Science Today. 2026;13(sp5):01–08. <https://doi.org/10.14719/pst.11679>

## Abstract

One major issue that restricts wheat productivity in India that are susceptible to climate change is terminal heat stress. The present study evaluated the effect of different sowing dates on growth, physiological traits and yield performance of six wheat genotypes under terminal heat stress conditions. Field experiments were conducted during the rabi season of 2023–24 using three sowing dates: early (5<sup>th</sup> November), timely (25<sup>th</sup> November) and late (20<sup>th</sup> December), which progressively exposed the crop to increasing heat stress during reproductive stages. Growth parameters, yield attributes, chlorophyll content and grain yield were recorded and analysed using a two-way ANOVA. Results revealed that sowing date significantly influenced all major growth and yield traits. Early and timely sowing promoted greater plant height, biomass accumulation, spike length, grain weight per spike, test weight and ultimately higher and more stable grain yields. In contrast, late sowing imposed severe terminal heat stress, resulting in substantial reductions in growth, chlorophyll content and yield. Mean grain yield declined sharply from about 4.55–4.56 t ha<sup>-1</sup> under timely sowing to only 1.41 t ha<sup>-1</sup> under late sowing. Among the genotypes, UP2565 and UP2844 consistently performed better under stress, maintaining higher biomass, test weight and yield stability, indicating superior tolerance to elevated temperatures. Conversely, PBW343 was highly sensitive to terminal heat stress, exhibiting marked reductions in growth, photosynthetic capacity and yield. The study highlights the critical role of optimising sowing time to minimise heat-induced yield losses and underscores the importance of identifying heat-tolerant genotypes. Timely sowing combined with the use of resilient genotypes such as UP2565 and UP2844 can serve as effective strategies for sustaining wheat productivity under future climate variability.

**Keywords:** biomass accumulation; sowing dates; terminal heat stress; wheat varieties; yield stability

## Introduction

Wheat (*Triticum aestivum* L.) is one of the most vital and staple food crops globally, providing essential nutrition and livelihoods for millions of people. With rising global temperatures and the increasing frequency of extreme weather events, terminal heat stress has emerged as a significant challenge affecting wheat production (1, 2). This phenomenon, which occurs during the reproductive phase of wheat growth, can lead to reduced grain yield and quality, making it imperative to evaluate and develop heat-tolerant wheat genotypes. Understanding the interaction between sowing dates and heat stress is crucial for optimizing agricultural practices and ensuring food security in the face of climate change (3–5).

Research has indicated that the timing of sowing can significantly influence the susceptibility of wheat plants to terminal heat stress. Early sowing allows plants to establish during cooler temperatures, thereby enhancing growth and mitigating the adverse effects of heat during critical developmental stages (6). Conversely, late sowing can expose plants to elevated temperatures during flowering and grain filling, leading to detrimental effects on yield (7, 8). Consequently, evaluating wheat genotypes under varying sowing dates is essential for identifying varieties that can withstand heat stress while maximising yield potential.

In addition to genetic factors, agronomic practices also significantly influence the impact of terminal heat stress on wheat crops. Effective management strategies, such as optimising sowing dates, can help mitigate the adverse effects of heat stress (9, 10).

This highlights the importance of integrated approaches that consider both genetic and environmental factors in wheat production systems. By evaluating the performance of various wheat genotypes under different sowing dates, researchers can provide valuable insights into best practices for managing heat stress and improving overall yield stability.

Furthermore, as climate change continues to pose challenges to global agriculture, the need for resilient crop varieties becomes increasingly urgent. The development of heat-tolerant wheat genotypes is not only vital for enhancing food security but also for ensuring the sustainability of wheat production systems worldwide (11, 12).

By conducting comprehensive evaluations of wheat genotypes under terminal heat stress conditions, researchers can contribute to the identification of strategies that enhance crop resilience and adaptability in the face of changing climatic conditions.

## Materials and Methods

Field experiments were conducted during the rabi season of 2023–2024 at the Crop Research Centre, Department of Agronomy, School of Agricultural Sciences, Shri Guru Ram Rai University, Pathribagh, Dehradun, Uttarakhand. The study site is characterised by a temperate climate conducive to wheat cultivation. During the rabi season 2023–24 in Dehradun, weather was dry and cool with below-normal rainfall, especially in December, causing limited soil moisture for crops. Maximum temperatures ranged from 25 °C (November) to 27 °C (March), while minimum temperatures dropped from 10 °C (November) to 6–8 °C (January). Relative humidity was 70 % in peak winter, decreasing to 57% by March. Rainfall was minimal throughout, with most months receiving only trace amounts. These conditions affected wheat, gram and winter vegetable growth.

A total of 6 treatments (6 different wheat genotypes) and 3 sowing dates 5 November (D1), 25 November (D2) and 20 December as D3, were evaluated using a factorial randomised complete block design (FRCBD). Each treatment was replicated 3 times. Each plot size measured 10 m x 4 m. The experimental design resulted in a comprehensive assessment of genotypic performance under varying sowing dates with different temperature conditions. The experimental treatments included 6 wheat genotypes: UP2865 (V1), UP2565 (V2), PBW 373 (V3), UP2844 (V4), UP2855 (V5) and PBW 343 (V6). Data were collected on various growth and yield parameters at critical growth stages. Five plants were randomly selected for data collection and plant height was measured in centimetres (cm) at 60 and 120 days after sowing (DAS). Fresh weight was recorded at maturity. The days to anthesis were noted as the number of days from sowing to the emergence of the first flower spike, while spike length was measured in centimetres (cm) from the main spike. Grain weight was taken per spike and calculated using the standard formula. Dry matter content and the number of grains per spike were also assessed. In addition, test weight was calculated by dividing the weight of a sample by its volume in cubic centimetres (cm). Plant stand was determined by counting the total number of plants and dividing it by the area in square meters. Finally, yield per hectare was harvested from a defined area (e.g., 1 m<sup>2</sup>) and expressed in kilograms per hectare (kg/ha). It was calculated by taking the total yield (in kg) divided by the area harvested in hectares.

Chlorophyll content was assessed using a soil-plant analysis development (SPAD) chlorophyll meter (Minolta, Japan) at 30, 50, 70, 90, 110 days after sowing. This instrument gives the SPAD values, which are directly related with the greenness or chlorophyll content of the leaf. Soil-plant analysis development values were recorded from the middle of the most fully developed 30 leaves randomly selected from net area and key growth stages to evaluate the plants photosynthetic efficiency under heat stress conditions.

The experiment was conducted in a FRCBD to evaluate the effects of sowing date (D<sub>1</sub>, D<sub>2</sub> and D<sub>3</sub>), wheat genotype (V<sub>1</sub> to V<sub>6</sub>) and their interaction (D × V). Data were analysed using two-way analysis of variance (ANOVA) in R software. The significance of main and interaction effects was tested using F-tests at the 5 % probability level. Where *F*-values were significant, treatment means were separated using the critical difference (CD) test ( $p \leq 0.05$ ). Non-significant (ns) effects indicate that differences among treatments were not statistically meaningful.

## Results

This study examined the impact of terminal heat stress, induced by different sowing dates, on various agronomic parameters in six different wheat genotypes. The measured parameters include plant height at 60 and 120 days, fresh weight of the plant, dry matter, days to anthesis, spike length, grain weight per spike (g), number of grains per spike, test weight (g), plant stand, chlorophyll content and yield per hectare. The results are summarized in the tables.

### Plant height at 60 days after sowing

At 60 DAS, significant variation in plant height was observed among the different wheat genotypes and treatments (Table 1 & Fig. 1). The tallest plant height was recorded for UP2565 (V2) under treatment D2V2, reaching 22.91 cm. This height indicates this genotype is strongly adaptability to the early growth conditions provided by the second sowing date (25 November). In contrast, the shortest plant height was noted for PBW343 (V6) under D3V6, measuring only 12.26 cm.

### Plant height at 120 days after sowing

At 120 DAS, the differences in plant height were even more pronounced (Table 1 & Fig.1). UP2565 (V2) continued to lead with a remarkable height of 109.86 cm under treatment D1V2, reaffirming its strong performance throughout the growing season. This sustained growth suggests that this variety effectively utilised favourable conditions during the early to mid-growth phases. Conversely, PBW343 (V6) under D3V6 exhibited the shortest height at 67.86 cm, reflecting the adverse effects of heat stress that this variety experienced due to late sowing.

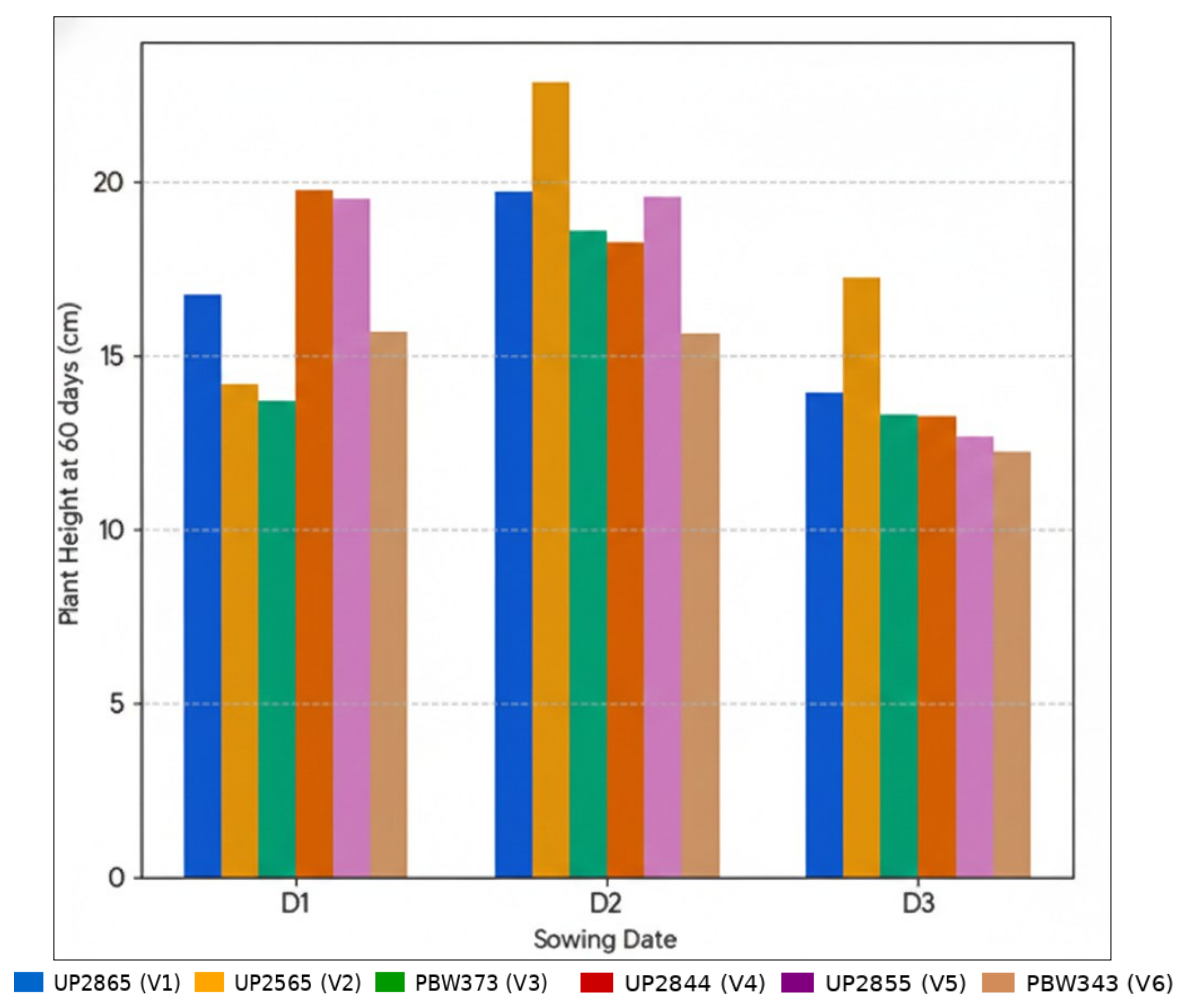
Overall, mean plant height was highest in D2 (19.13 cm at 60 DAS; 98.61 cm at 120 DAS) and lowest in D3 (13.77 cm at 60 DAS; 76.71 cm at 120 DAS), indicating that delayed sowing (D3) negatively affected plant growth. The differences were statistically significant as indicated by the CD values (4.74 cm at 60 DAS; 1.9 cm at 120 DAS). The observed differences were statistically significant ( $p \leq 0.05$ ), as indicated by the ANOVA and mean separation was performed using CD values (4.74 cm at 60 DAS and 1.90 cm at 120 DAS), confirming the adverse effect of delayed sowing (D3) on plant growth.

**Table 1.** Influence of different sowing date on agronomic parameters of different wheat genotypes

| Varieties   | Treatment | Plant height (cm) (60) | Plant height (cm) (120) | Fresh weight of plant (gm) | Dry matter   | Days to anthesis | Spike length (cm) |
|-------------|-----------|------------------------|-------------------------|----------------------------|--------------|------------------|-------------------|
| UP2865 (V1) | D1V1      | 16.77                  | 99.73                   | 13.6                       | 8.6          | 124              | 12.41             |
| UP2565 (V2) | D1V2      | 14.2                   | <b>109.86</b>           | 18.9                       | <b>16.36</b> | 102.67           | 9.67              |
| PBW373(V3)  | D1V3      | 13.69                  | 93.06                   | <b>21.26</b>               | 4.15         | <b>132.67</b>    | 10.63             |
| UP2844 (V4) | D1V4      | 19.78                  | 101.3                   | 9.65                       | 9.916        | 127.67           | 11.76             |
| UP2855 (V5) | D1V5      | 19.53                  | 103.66                  | 8.45                       | 3.07         | 103.33           | 11.7              |
| PBW343(V6)  | D1V6      | 15.69                  | 98.73                   | 20.53                      | 15.19        | 136              | 9.21              |
| UP2865 (V1) | D2V1      | 19.71                  | 95.23                   | 40.93                      | 7.3          | 104.67           | 10.93             |
| UP2565 (V2) | D2V2      | 22.91                  | 103.43                  | <b>72.67</b>               | 15.71        | 100.33           | 9.81              |
| PBW373(V3)  | D2V3      | 18.63                  | 100.06                  | 41.14                      | 9.53         | 121.67           | 10.16             |
| UP2844 (V4) | D2V4      | 18.27                  | 99.96                   | 42.216                     | 6.99         | 117              | 11.66             |
| UP2855 (V5) | D2V5      | 19.6                   | 100.56                  | 43.28                      | 7.29         | 102.33           | 11.74             |
| PBW343(V6)  | D2V6      | 15.66                  | 92.46                   | 42.4                       | 6.097        | 123.67           | 10                |
| UP2865 (V1) | D3V1      | 13.93                  | 78.57                   | 5.59                       | 1.196        | 101.33           | 10.59             |
| UP2565 (V2) | D3V2      | 17.26                  | 83.73                   | 6.38                       | 1.06         | 110.67           | 9.77              |
| PBW373(V3)  | D3V3      | 13.3                   | 71.66                   | 4.17                       | 1.296        | 124.67           | 10.21             |
| UP2844 (V4) | D3V4      | 13.26                  | 79.2                    | 7.25                       | 1.93         | 123              | 11.88             |
| UP2855 (V5) | D3V5      | 12.66                  | 79.26                   | 6.9                        | 1.55         | 126              | 10.40             |
| PBW343(V6)  | D3V6      | <b>12.26</b>           | 67.86                   | 5.89                       | 0.86         | 123              | 9.26              |
|             | S.Em      | 1.54                   | 7.9                     | 5.06                       | 2.12         | 11.86            | 9.4               |
|             | CD        | 4.74                   | 1.9                     | 15.22                      | 2.9          | 3.2              | 3.9               |
|             | D1        | 16.61                  | 101.05                  | 15.39                      | 9.54         | 121.05           | 10.89             |
|             | D2        | 19.13                  | 98.61                   | 47.10                      | 8.81         | 111.61           | 10.71             |
|             | D3        | 13.77                  | 76.71                   | 6.03                       | 1.31         | 118.11           | 10.35             |

1. Bold values indicate significant differences at  $P \leq 0.05$  (based on CD).

2. Rows represent interaction treatments (D  $\times$  V).

**Fig. 1.** Effect of three different sowing dates on plant height (at 60 days after sowing) in different wheat genotypes.

### Fresh weight of plant

Fresh weight measurements highlighted significant differences among wheat varieties and treatments (Table 1 & Fig. 2) The maximum fresh weight was observed in UP2565 (V2) under D2V2 (72.67 g), Conversely, D3 had the lowest mean fresh weight (6.03 g), with PBW373 (V3) exhibiting 4.17 g. This indicates that sowing under optimal conditions (D2) substantially enhanced biomass accumulation.

### Days to anthesis

This variation highlights how different sowing dates affect flowering time, which is crucial for reproductive success. Days to anthesis differed significantly among genotypes and sowing dates. The earliest anthesis was observed in UP2565 (V2) under D2 (100.33 days), whereas the latest was in PBW343 (V6) under D1 (136 days). Mean days to anthesis were shortest in D2 (111.61 days) and longest in D1 (121.05 days), suggesting that early sowing accelerates reproductive development under terminal heat stress conditions.

### Dry matter

The dry matter accumulation also varied significantly across treatments. UP2565 (V2) achieved the highest dry matter (15.71 g) under D2V2, while PBW343 (V6) recorded the lowest (0.86 g) under D3V6. This indicates that earlier sowing dates allow for better nutrient absorption and growth conditions, leading to higher dry matter content. Mean dry matter was significantly higher under D2 (8.81 g) compared to D3 (1.31 g), reflecting the adverse effect of late sowing on plant maturation and biomass production.

### Spike length

Finally, the spike length showed significant differences, with UP2865 (V1) achieving a spike length of 12.41 cm under D1V1, while PBW343 (V6) exhibited the shortest length of 9.21 cm under D1V6. Spike length varied among genotypes and sowing dates, with the highest mean recorded in D1 (10.89 cm) and the lowest in D3 (10.35 cm) (Table 1 & 2, Fig. 3). Statistical analysis indicated significant differences among treatments (CD=3.9 cm).

### Grain weight per spike

The grain weight per spike varied significantly among different treatments. The highest grain weight was recorded in UP2565 (V2) under treatment D1V2 at 3.33 g, indicating that this variety performs well under optimal conditions. In contrast, the lowest grain weight was noted in PBW343 (V6) under D3V6 at 0.26 g. Across sowing dates, the mean grain weight was highest in D1 (2.75 g), followed by D2 (2.58 g) and lowest in D3 (0.92 g), indicating a significant reduction under terminal heat stress induced by late sowing (Table 3 & 4). The tolerant genotype will be stable under the stress condition and The maximum yield stability index indicates the more stable genotype under stress conditions.

### Number of grains per spike

The number of grains per spike also demonstrated significant variability among treatments. UP2865 (V1) recorded the highest number of grains per spike (69.67) under D3V1, while PBW343 (V6) exhibited the lowest (36.33) under D3V6. The higher number of grains per spike in UP2865 under D3V1 indicates that this variety may possess some tolerance to heat stress, allowing it to maintain reproductive success better than others.

**Table 2.** Analysis of variance (ANOVA) for agronomic traits of wheat under different sowing dates

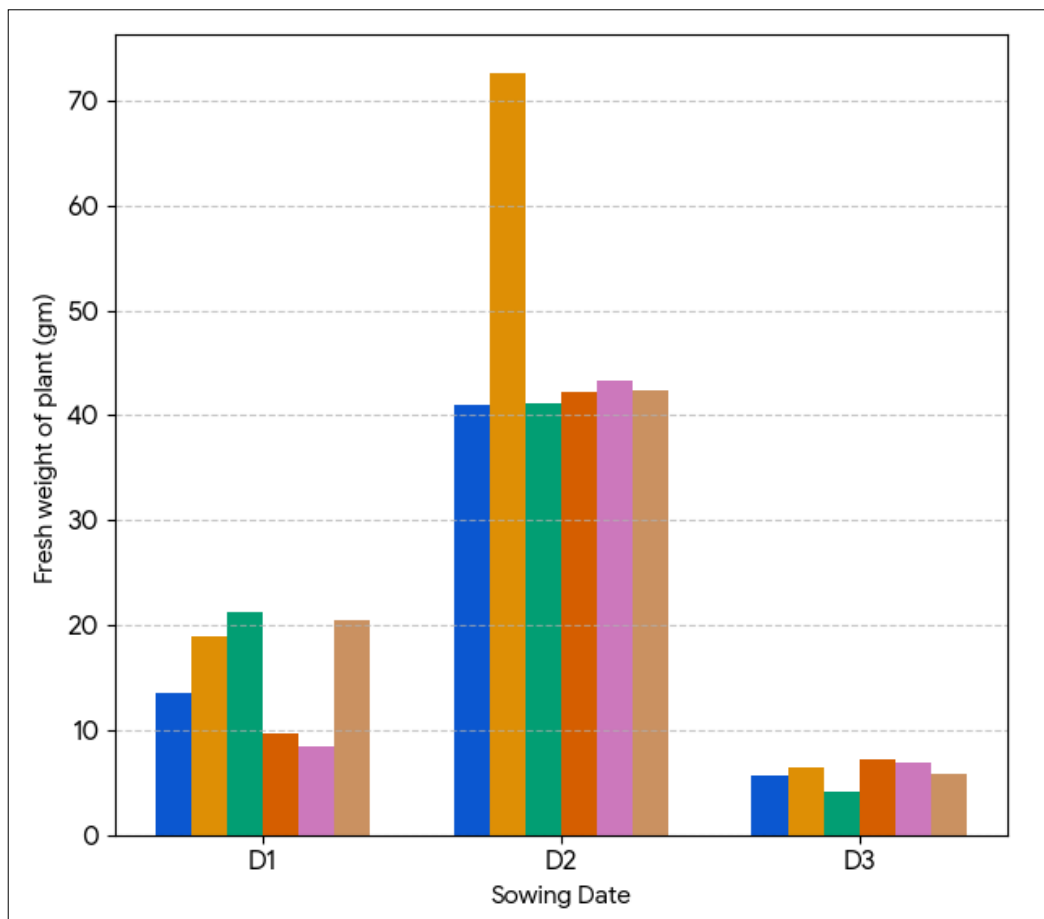
| Source of variation | df | Plant height (60 DAS) | Plant height (120 DAS) | Fresh weight | Dry matter | Days to anthesis | Spike length |
|---------------------|----|-----------------------|------------------------|--------------|------------|------------------|--------------|
| Replication         | 2  | ns                    | ns                     | ns           | ns         | ns               | ns           |
| Sowing dates (D)    | 2  | *                     | *                      | *            | *          | *                | *            |
| Genotypes (V)       | 5  | *                     | *                      | *            | *          | *                | *            |
| D × V               | 10 | *                     | *                      | *            | *          | *                | *            |
| Error               | 34 | -                     | -                      | -            | -          | -                | -            |
| Total               | 53 | -                     | -                      | -            | -          | -                | -            |

\* Significant at  $p \leq 0.05$ ; ns; non-significant.

**Table 3.** Effect of terminal heat stress induced by different sowing dates on chlorophyll content and yield attributes

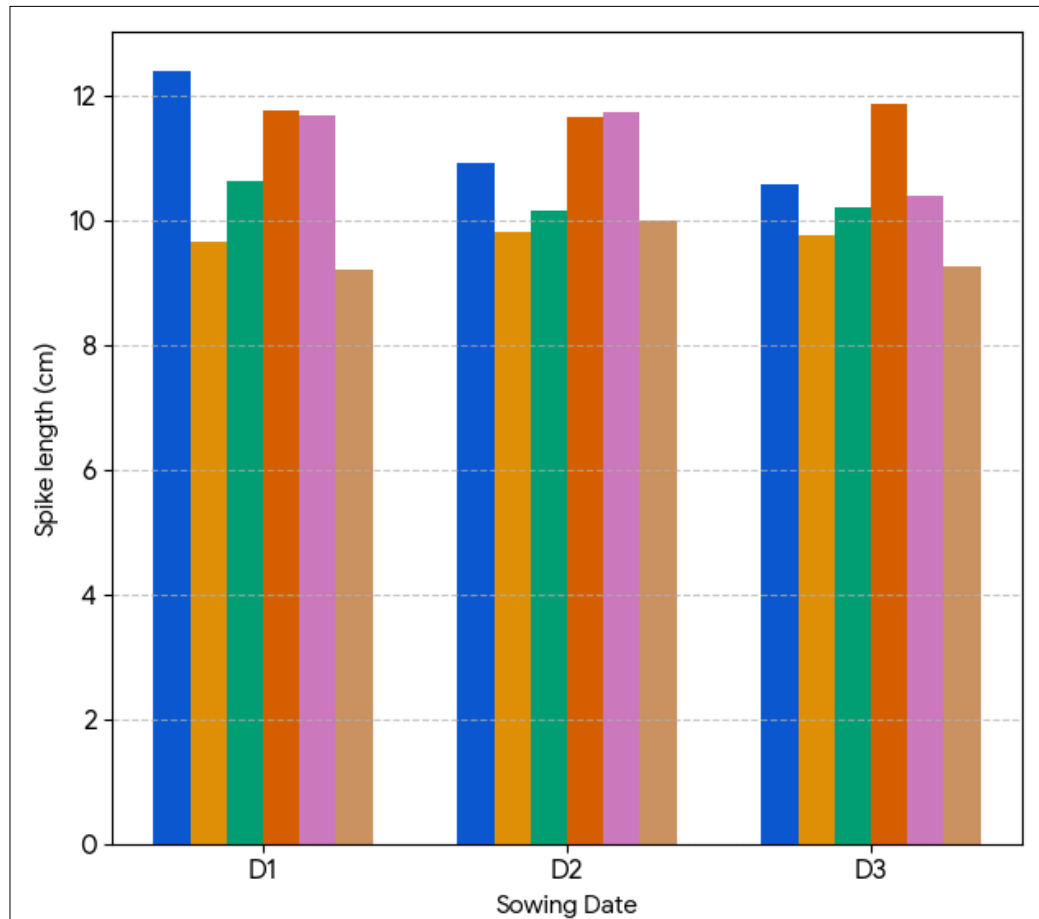
| Varieties   | Treatments | Grain weight per spike (gm) | Number of grains per spike | Chlorophyll content | Test weight (gm) | Yield per hectare (t/ha) | Plant stand |
|-------------|------------|-----------------------------|----------------------------|---------------------|------------------|--------------------------|-------------|
| UP2865(V1)  | D1V1       | 3.073                       | 59.67                      | 21.91               | 50.9             | 4.17                     | 35.7        |
| UP2565 (V2) | D1V2       | 3.33                        | 55.67                      | 31.27               | 46               | 4.49                     | 38          |
| PBW373(V3)  | D1V3       | 2.84                        | 52.33                      | <b>34.29</b>        | 45               | 4.77                     | 32          |
| UP2844(V4)  | D1V4       | 3.19                        | 54                         | 24.23               | 47               | 4.8                      | 41.67       |
| UP2855(V5)  | D1V5       | 2.33                        | 58.67                      | 26.23               | 45               | 5.16                     | 33.3        |
| PBW343(V6)  | D1V6       | 1.74                        | <b>33.67</b>               | 24.1                | 41               | 4.02                     | 37.3        |
| UP2865(V1)  | D2V1       | 2.366                       | 55.33                      | 24.27               | 45.7             | 4.3                      | 47          |
| UP2565 (V2) | D2V2       | 2.64                        | 55.67                      | 23.48               | 43.3             | 4.53                     | <b>55</b>   |
| PBW373(V3)  | D2V3       | 3.033                       | <b>62.67</b>               | 30.17               | 48.3             | 4.87                     | 40          |
| UP2844(V4)  | D2V4       | <b>3.23</b>                 | <b>64.67</b>               | 25.15               | 48.7             | <b>5.17</b>              | 48.3        |
| UP2855(V5)  | D2V5       | 2.68                        | 58.67                      | 25.67               | <b>51.7</b>      | 4.67                     | 47          |
| PBW343(V6)  | D2V6       | 1.556                       | 49                         | 24.33               | 46.7             | 3.77                     | 34.67       |
| UP2865(V1)  | D3V1       | 1.91                        | <b>69.67</b>               | 23.67               | 40.3             | 2.7                      | 36.33       |
| UP2565 (V2) | D3V2       | 2.12                        | 62                         | 28.67               | 46.3             | 2.53                     | 38.87       |
| PBW373(V3)  | D3V3       | 0.453                       | 43.67                      | <b>32.67</b>        | 31.7             | 0.88                     | 28          |
| UP2844(V4)  | D3V4       | 0.36                        | 46.67                      | 25.48               | 29.7             | 0.7                      | 33.33       |
| UP2855(V5)  | D3V5       | 0.42                        | 47.67                      | 25.33               | 35               | 1.07                     | 31          |
| PBW343(V6)  | D3V6       | 0.26                        | 36.33                      | 24.67               | 35               | 0.63                     | <b>61</b>   |
|             | S.Em       | 0.44                        | 1.19                       | 1.91                | 2.42             | 0.64                     | ns          |
|             | CD         | 1.3                         | 3.4                        | 5.1                 | 7.5              | 9.5                      | ns          |
|             | D1         | 2.75                        | 52.33                      | 27.00               | 45.81            | 4.56                     | 36.32       |
|             | D2         | 2.584                       | 57.66                      | 25.51               | 47.40            | 4.55                     | 45.32       |
|             | D3         | 0.92                        | 51.00                      | 26.74               | 36.33            | 1.41                     | 38.08       |

1. Bold values indicate significant differences at  $p \leq 0.05$  (based on CD). 2. Rows represent interaction treatments (D × V).



■ UP2865 (V1) ■ UP2565 (V2) ■ PBW373 (V3) ■ UP2844 (V4) ■ UP2855 (V5) ■ PBW343 (V6)

**Fig. 2.** Effect of terminal heat stress on fresh weight (gm) in six wheat genotypes across different sowing dates.



■ UP2865 (V1) ■ UP2565 (V2) ■ PBW373 (V3) ■ UP2844 (V4) ■ UP2855 (V5) ■ PBW343 (V6)

**Fig. 3.** Effect of terminal heat stress on spike length in six wheat genotypes across different sowing dates.

**Table 4.** Analysis of variance (ANOVA) for yield and physiological traits

| Source of variation | df | Grain weight / spike | Grains / spike | Chlorophyll content | Test weight | Yield (t ha <sup>-1</sup> ) | Plant stand |
|---------------------|----|----------------------|----------------|---------------------|-------------|-----------------------------|-------------|
| Replication         | 2  | ns                   | ns             | ns                  | ns          | ns                          | ns          |
| Sowing dates (D)    | 2  | *                    | *              | ns                  | *           | *                           | *           |
| Genotypes (V)       | 5  | *                    | *              | *                   | *           | *                           | *           |
| D × V               | 10 | *                    | *              | ns                  | *           | *                           | *           |
| Error               | 34 | -                    | -              | -                   | -           | -                           | -           |
| Total               | 53 | -                    | -              | -                   | -           | -                           | -           |

\* Significant at  $p \leq 0.05$ ; ns; non-significant.

### Test weight

Test weight, an important quality parameter, also varied significantly among treatments (Table 3 & 4). The maximum test weight was recorded in UP2865 (V1) under D1V1 (50.9 g), while the minimum was observed in PBW343 (V6) under D3V6 (35 g). Test weight ranged from 29.7 g (UP2844, D3V4) to 51.7 g (UP2855, D2V5). The highest mean test weight was observed in D2 (47.40 g), followed by D1 (45.81 g), while the late sowing date D3 resulted in a significant reduction (36.33 g).

### Plant stand

Plant stand, which reflects the establishment success of the wheat crop, showed notable differences across treatments. Plant stand, which reflects crop establishment success, showed variation among treatments but the differences were statistically non-significant ( $p > 0.05$ ). The highest plant stand was recorded for UP2565 (V2) under D2V2 (55 plants m<sup>-2</sup>), while PBW343 (V6) under D3V6 recorded the highest numerical value (61 plants m<sup>-2</sup>).

This variation illustrates how sowing date impacts the establishment and overall health of the crop. Plant stand varied from 28 plants m<sup>-2</sup> (PBW373, D3V3) to 61 plants m<sup>-2</sup> (PBW343, D3V6). Sowing date D2 supported the highest mean Plant stand (45.32 plants m<sup>-2</sup>), while D1 and D3 had lower averages (36.32 and 38.08 plants m<sup>-2</sup>, respectively), though differences were statistically non-significant (ns) (Table 1 and 2).

### Chlorophyll content

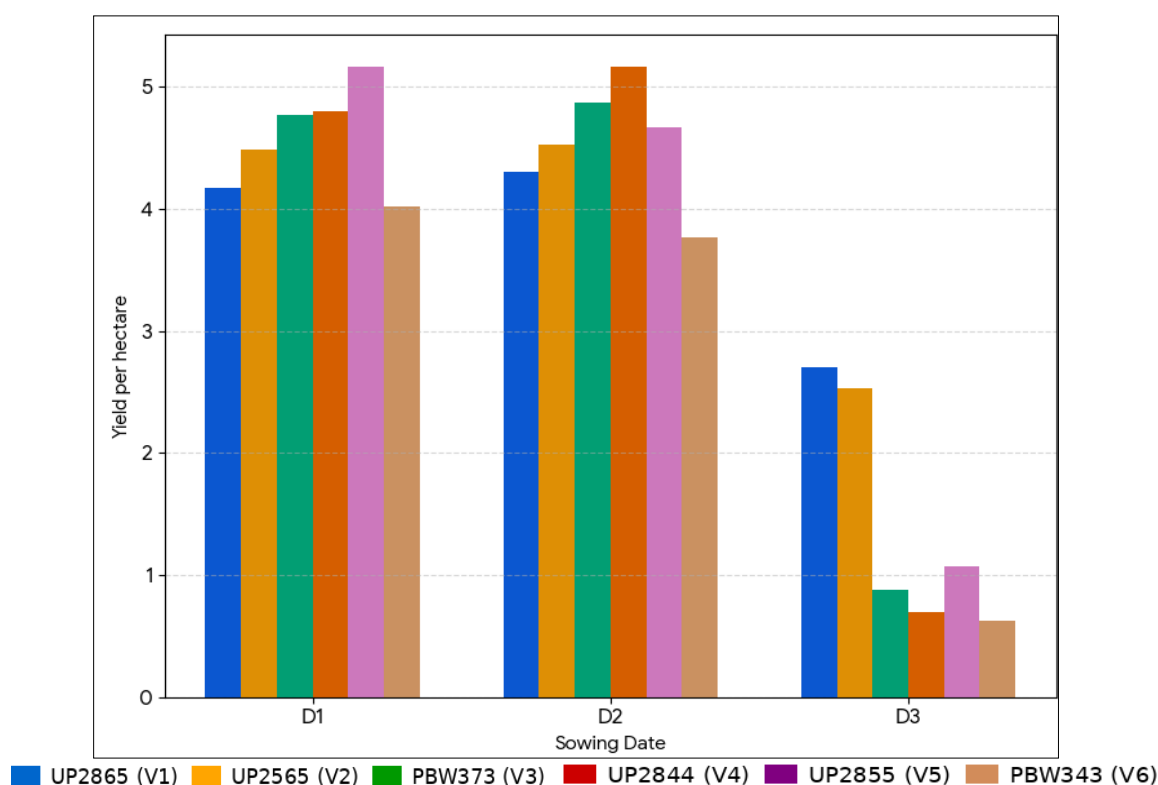
Chlorophyll content is a critical indicator of plant health and photosynthetic efficiency. The highest chlorophyll content was observed in PBW373 (V3) under D1V3 (34.29), while the lowest was found in UP2865 (V1) under D3V1 (23.67). The mean chlorophyll content was comparable across sowing dates (D1: 27.00; D2: 25.51; D3: 26.74), indicating minor variations in chlorophyll retention despite terminal heat stress.

### Yield per hectare

The yield per hectare data reveals a significant decline associated with terminal heat stress (Table 3 and 4, Fig. 4). UP2855 (V5) achieved the highest yield of 5.16 tonnes per hectare under D1V5, whereas the lowest yield was recorded for PBW343 (V6) at 0.63 tonnes per hectare under D3V6. Mean yields were D1: 4.56 t/ha, D2: 4.55 t/ha and D3: 1.41 t/ha, highlighting the severe impact of terminal heat stress. The substantial yield loss under D3 treatments points to the critical need for managing sowing dates to mitigate heat stress effects.

### Discussion

The present study demonstrates the substantial impact of terminal heat stress, induced by delayed sowing, on growth, physiological



**Fig. 4.** Yield (t/ha) after sowing of six wheat genotypes under three different sowing dates.

traits and yield of 6 wheat varieties. Plant height, a key indicator of vegetative growth, was significantly affected by sowing dates. At 60 DAS, UP2565 (V2) under D2V2 exhibited the tallest plants (22.91 cm), indicating its strong adaptability to early growth conditions, while PBW343 (V6) under D3V6 recorded the shortest height (12.26 cm), highlighting the adverse effects of delayed sowing. These differences were even more pronounced at 120 DAS, with UP2565 (V2) reaching 109.86 cm and PBW343 (V6) limited to 67.86 cm. Mean plant heights were highest under D2 (19.13 cm at 60 DAS; 98.61 cm at 120 DAS) and lowest under D3 (13.77 cm at 60 DAS; 76.71 cm at 120 DAS), confirming that late sowing negatively impacts growth by exposing plants to terminal heat stress. These observations align with previous reports indicating that high temperatures during vegetative and reproductive stages limit biomass accumulation and plant stature (13). The statistical significance of these responses, confirmed through ANOVA and mean separation using CD values, validates that the observed differences among sowing dates and genotypes were driven by treatment effects rather than random variation.

Biomass accumulation, including fresh and dry matter, mirrored the trends observed in plant height. Maximum fresh weight was recorded in UP2565 (V2) under D2V2 (72.67 g), whereas D3 treatments, particularly PBW373 (V3) with 4.17 g, showed severely reduced biomass. Dry matter accumulation followed a similar pattern, with UP2565 (V2) achieving 15.71 g and PBW343 (V6) only 0.86 g under D3V6. These results indicate that early sowing promotes better nutrient absorption, growth conditions and biomass accumulation, while late sowing exacerbates stress effects, reducing vegetative development and plant vigour (14).

Reproductive development, assessed through days to anthesis and spike characteristics, was also influenced by sowing date. Early anthesis was observed in UP2565 (V2) under D2 (100.33 days), whereas PBW343 (V6) under D1 had delayed flowering (136 days). Spike length varied among genotypes and sowing dates, with D1 recording the highest mean (10.89 cm) and D3 the lowest (10.35 cm). Terminal heat stress during late sowing likely accelerated reproductive stress, reducing spike elongation and subsequent grain-bearing capacity, consistent with earlier studies linking heat stress to compromised spike development (15, 16).

Grain yield components, including grain weight per spike, number of grains per spike and test weight, were markedly affected. UP2565 (V2) under D1V2 recorded the highest grain weight per spike (3.33 g), while PBW343 (V6) under D3V6 had the lowest (0.26 g). Grain number per spike was highest in UP2865 (V1) under D3V1 (69.67) and lowest in PBW343 (V6) under D3V6 (36.33), suggesting varietal differences in tolerance to heat stress. Test weight, a quality parameter, was highest in UP2855 (V5) under D2V5 (51.7 g) and lowest in PBW343 (V6) under D3V6 (35 g). The reduction in grain filling and quality under D3 indicates the negative impact of terminal heat stress on carbohydrate accumulation, pollination and grain maturation (17).

Chlorophyll content, an indicator of photosynthetic efficiency, showed minor variation among sowing dates but was reduced in late-sown treatments (D3), particularly in UP2865 (V1) under D3V1 (23.67), suggesting impaired photosynthesis under heat stress. Early sowing facilitated better chlorophyll retention, supporting higher photosynthetic capacity and plant vigour (18).

Yield per hectare exhibited significant reductions under terminal heat stress. UP2855 (V5) under D1V5 produced the highest

yield (5.16 t/ha), whereas PBW343 (V6) under D3V6 yielded only 0.63 t/ha. Mean yields for D1, D2 and D3 were 4.56, 4.55 and 1.41 t/ha, respectively, highlighting the critical effect of delayed sowing on wheat productivity. These results are consistent with previous findings that terminal heat stress reduces spike density, grain number, kernel weight and grain filling duration (19-21).

Plant stand varied across treatments but was not statistically significant, indicating that while establishment was slightly affected, the major yield losses under D3 were primarily due to stress-induced reductions in growth and reproductive development.

The varietal differences observed under terminal heat stress can be physiologically and genetically interpreted as differential capacities for heat tolerance, assimilate partitioning and phenological adjustment. Varieties such as UP2565 and UP2855 that maintained greater plant height, biomass, chlorophyll content and grain yield under delayed sowing likely possess superior heat-stress adaptation mechanisms, including more efficient canopy temperature regulation, sustained photosynthetic enzyme activity and enhanced antioxidant defence systems that protect cellular membranes and chloroplasts during high-temperature exposure. Their relatively stable chlorophyll levels suggest reduced heat-induced chlorophyll degradation and better maintenance of photosystem II efficiency, enabling continued carbon assimilation during grain filling.

In contrast, sensitive varieties like PBW343 showed sharp reductions in growth and yield traits, which may be attributed to accelerated senescence, impaired pollen viability, shortened grain-filling duration and reduced translocation of assimilates to developing grains under heat stress. Genetically, tolerant varieties may harbour alleles associated with heat-shock protein expression, improved membrane thermostability and favourable phenological plasticity that allows partial escape or tolerance to terminal heat.

Thus, the observed varietal responses are not merely descriptive outcomes of sowing date variation but reflect inherent physiological resilience and genetic potential to withstand high-temperature stress, underscoring their relevance for selection and breeding of heat-tolerant wheat cultivars.

Overall, the findings emphasise the importance of timely sowing to mitigate terminal heat stress and maintain optimal growth, physiological function and yield in wheat. Varietal differences observed in the study suggest that UP2565 and UP2844 are relatively more tolerant to heat stress, indicating their potential use in breeding programs aimed at improving resilience under high-temperature conditions.

## Conclusion

This research provides strong evidence that terminal heat stress, triggered by delayed sowing, has major detrimental effects on wheat growth, physiology and productivity. Key traits such as plant height, biomass accumulation, spike development, chlorophyll content and yield attributes declined sharply under late sowing (D3), highlighting the crop's sensitivity to elevated temperatures during critical growth stages. By contrast, timely sowing (D1 and D2) supported greater biomass, higher chlorophyll retention and stable yields. Genotypic variation was evident, with UP2565 and UP2844 showing comparatively better tolerance to heat stress than the highly susceptible PBW343, which recorded significant reductions

in growth, physiological traits and yield under delayed sowing. These findings confirm that genetic differences are crucial for wheat adaptation to heat-prone environments.

Overall, the study emphasises the importance of optimising sowing time as a practical management strategy to mitigate yield losses under rising temperatures. Furthermore, the identification of heat-tolerant genotypes such as UP2565 and UP2844 provides valuable germplasm for future breeding programs aimed at improving resilience and sustaining wheat productivity under climate variability. These results highlight the combined importance of appropriate sowing time and genotype selection as practical, field-level strategies for sustaining wheat productivity under climate variability.

## Acknowledgements

The authors thank the Dean, School of Agricultural Sciences, Shri Guru Ram Rai University, Dehradun, for permission to conduct the study and acknowledge the field staff for their assistance during the inquiry.

## Authors' contributions

KDJ and RP carried out site selection, sampling and data collection. HK and GC contributed to the study design and statistical analysis. SS<sup>1</sup>, RK and SS<sup>2</sup> helped in final manuscript preparation. All authors read and approved the final manuscript. [SS<sup>1</sup>-Sarvesh Suyal and SS<sup>2</sup>-Shweta Sahn].

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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