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# Phenotypic Correlation, Path Analysis, and Quantitative Trait-Based Selection of Elite Wheat Genotypes Under Heat Stress Conditions in The Terai Region of Nepal

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## Abstract

Wheat is one of the most important cereal crops worldwide, but the production and productivity of wheat is affected by heat stress. A field experiment using an alpha lattice design with seven blocks was conducted on 35 elite wheat genotypes in the Terai region of Nepal to identify the most appropriate trait resulting in a high-yielding wheat genotype with high tolerance to heat stress. Correlation analysis revealed that booting-to-heading duration (BtoH), booting-to-anthesis duration (BtoA), plant height (Ph), spike length (SL), spike weight (SW), thousand grain weight (TGW), straw yield (SY), and total biomass yield (TY) had a significant positive correlation with grain yield (GY), whereas days to booting (DTB), days to heading (DTH), and days to anthesis (DTA) had significant negative correlations with GY ($p \leq 0.05$). Path analysis revealed that DTB and DTA had a direct negative effect on the GY, whereas DTH had an indirect negative effect on yield via DTB. BtoA, Ph, SL, SW, and TGW had direct positive effects on yield, whereas BtoH had an indirect positive effect on yield via DTB. Principal component analysis demonstrated that high-yielding genotypes can be selected using DTB, DTH, DTA, BtoH, BtoA, and Ph. Taller and earlier genotype with long BtoH and BtoA would produce high yield under heat stress.

*Keywords: earlier, heat stress, taller, trait, longer inter-phenological stage, wheat*

## Introduction

Wheat (*Triticum aestivum* L.) is the most widely cultivated cereal worldwide, constituting approximately 28% of the global cereal production and 41.5% of the global trade. It is a major source of calories for 35% of the global population and is consumed as a staple food crop in more than 40 countries [1–3]. Temperature is a major abiotic factor that regulates plant growth, development, and yield [4–6]. However, temperature above 24 °C has become a serious threat to global wheat production [7, 8], affecting approximately 57% (200 million hectares) of the global wheat-growing area each year [9, 10]. Wheat is extremely sensitive to heat stress [11, 12], and a temperature 5 °C–10 °C above the optimal range (18 °C–24 °C) is considered heat stress in wheat cultivation. Moreover, heat stress causes irreversible changes in the growth, morphology, phenology, and yield performance of wheat [13, 14]. An increase in temperature above 24 °C in wheat generally induces pollen sterility [15], pollen unviability [15], and causes grain shrinkage [16], ultimately reducing yield [17]. The global temperature was raised approximately 1.09 °C from 1850–1900 to 2011–2020 [18]. The warmest year on record is 2020, with an average increase in temperature of 1.39 °C [18]. By 2050 the annual temperature is projected to increase by 1.6 °C in South Asia, increasing by 6°C by the end of the 21st century [19]. In Nepal, the mean temperature is rising at a rate of 0.06 °C per year [20]. The temperature of the Terai region of Nepal has increased by 1 °C in the last three decades. The IPCC forecasted that heat waves would be more intense and warmer and might convert long-productive-season and mega environments into short-season heat-stressed environments [18]. Owing to gradually increasing temperature, the frequency of terminal heat waves is increasing in South Asian regions, including Nepal. Terminal heat stress during the reproductive and ripening stages of wheat has posed a serious threat to the nation's wheat production [21], and yield decreases by 6% each degree rise in temperature [22]. The severity of yield reduction is predicted to decrease by up to 17% in the Indo-Gangetic

Plains of South Asia [23]. Hence, breeding climate-resilient heat-stress-tolerant genotypes is crucial.

Increase in temperature decreases the net leaf area for photosynthesis, induces early leaf senescence [24], shortens grain-filling duration [25], increases net photorespiration, and promotes male sterility in wheat [26]. Ultimately, the effects would be observed on spike length (SL), spikelets per spike (SPS), net spike weight (SW) [27], number of grains per spike (GPS), and net grain weight [28].

To provide people with all necessary carbohydrates, proteins, and calories, wheat production should be increased by 16% (118 million metric tons) and is predicted to increase up to 198 million tons by 2050 [29]. Heat stress is the major abiotic stress leading to poor wheat production [30]. Thus, identifying climate-resilient wheat cultivars is crucial for global food and nutritional security [31]. Heat stress influences all the morphological parameters of wheat and reduces yield by up to 24%–48%, causing an annual economic loss of US$10.66–12.78 billion on the global scale. Phenotypic correlation and path analysis would facilitate the identification of climate-resilient wheat genotypes based on various independent morphological traits [32], and identifying the most appropriate traits would help to enhance the production and productivity of wheat, helping to achieve the goal of SDG 2.0 [31].

## Materials and Methods

The field experiment was carried out at the Institute of Agriculture and Animal Science (IAAS), Paklihawa Campus, in 2022. The experimental site (27°29′02″N, 83°27′17″E) is in the western region of Nepal, with a tropical climate and elevation of 104 m above sea level.

The agrometeorological data of the experimental site were obtained from the Department of Hydrology and Meteorology, Bhairahawa (Figure 1).

A total of 35 elite wheat genotypes were provided by the National Wheat Research Program, Bhairahawa, including three commercial check varieties: viz, Bhrikuti and Gautam, and RR 21 was used in the study (Table 1).

The experiment was conducted using a serpentine alpha lattice design and replicated twice with seven blocks. Each block contained five plots. Each genotype was planted in a plot size of 10 m² (4 m × 2.5 m). Wheat genotypes were sowed on 25th December. Wheat was sowed later so that the flowering and grain-filling periods of the wheat genotypes coincided with the terminal heat stress event in February and March. Each plot had a row-to-row spacing of 25 cm, and continuous sowing was done using line sowing method. The plots were 50 cm apart, and two replicates were 1 m apart. The recommended fertilizer dose (100:60:40 NPK kg per hectare) and 10 tons per hectare farm yard manure were applied [33]. The plants were irrigated at the field preparation, crown root initiation, booting, heading, and grain-filling stages. Intercultural operation (weeding) was performed manually at 21 and 40 days after sowing.

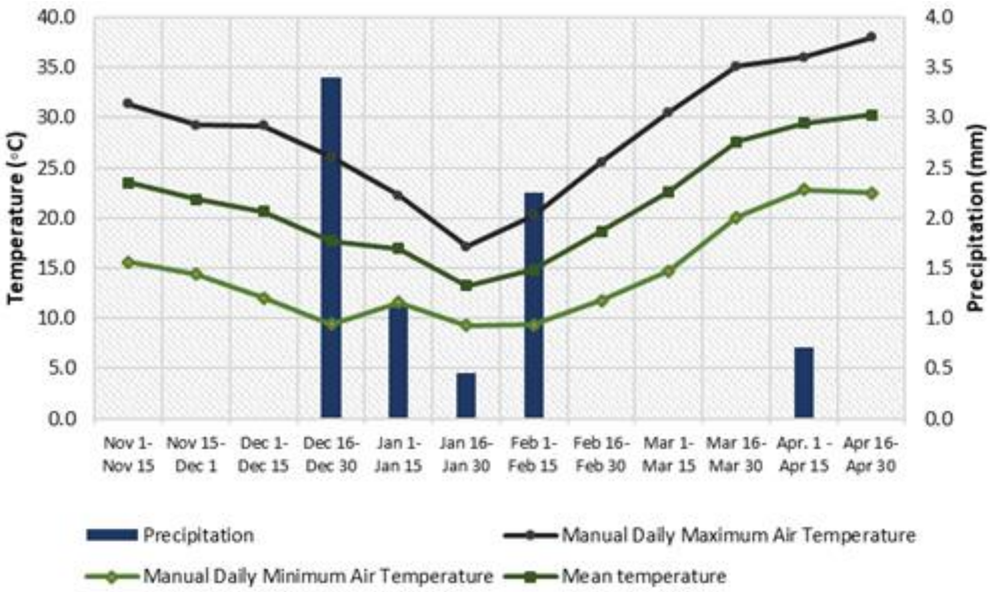


**Figure 1. Agrometeorological Parameters in the Experimental Site**

**Table 1. List of Plant Materials used in the Experiment**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Bhrikuti | NWRP, BHW | CIMMYT, Mexico | 1994 | 19 | NL 1417 | NWRP | CIMMYT, Mexico | Not released |
| 2 | BL 4407 | NWRP | Nepal | Not released yet | 20 | NL 1420 | NWRP | CIMMYT, Mexico | Not released yet |
| 3 | BL 4669 | NWRP | Nepal | Not released yet | 21 | BL 5099 | NWRP | Nepal | Not released yet |
| 4 | BL 4919 | NWRP | Nepal | Not released yet | 22 | BL 5106 | NWRP | Nepal | Not released yet |
| 5 | Gautam | NWRP | Nepal | 2004 | 23 | BL 5116 | NWRP | Nepal | Not released yet |
| 6 | NL 1179 | NWRP | CIMMYT, Mexico | Not released yet | 24 | NL 1445 | NWRP | CIMMYT, Mexico | Not released yet |
| 7 | NL 1346 | NWRP | CIMMYT, Mexico | Not released yet | 25 | NL 1447 | NWRP | CIMMYT, Mexico | Not released yet |
| 8 | NL 1350 | NWRP | CIMMYT, Mexico | Not released yet | 26 | NL 1488 | NWRP | CIMMYT, Mexico | Not released yet |
| 9 | NL 1368 | NWRP | CIMMYT, Mexico | Not released yet | 27 | NL1492 | NWRP | CIMMYT, Mexico | Not released yet |
| 10 | NL 1369 | NWRP | CIMMYT, Mexico | Not released yet | 28 | NL1501 | NWRP | CIMMYT, Mexico | Not released yet |
| 11 | NL 1376 | NWRP | CIMMYT, Mexico | Not released yet | 29 | NL 1503 | NWRP | CIMMYT, Mexico | Not released yet |
| 12 | NL 1381 | NWRP | CIMMYT, Mexico | Not released yet | 30 | NL 1504 | NWRP | CIMMYT, Mexico | Not released yet |
| 13 | NL 1384 | NWRP | CIMMYT, Mexico | Not released yet | 31 | NL 1506 | NWRP | CIMMYT, Mexico | Not released yet |
| 14 | NL 1386 | NWRP | CIMMYT, Mexico | Not released yet | 32 | NL 1508 | NWRP | CIMMYT, Mexico | Not released yet |
| 15 | NL 1387 | NWRP | CIMMYT, Mexico | Not released yet | 33 | NL 1509 | NWRP | CIMMYT, Mexico | Not released yet |
| 16 | NL 1404 | NWRP | CIMMYT, Mexico | Not released yet | 34 | NL 1512 | NWRP | CIMMYT, Mexico | Not released yet |
| 17 | NL 1412 | NWRP | CIMMYT, Mexico | Not released yet | 35 | RR 21 | NWRP | CIMMYT, Mexico | 197218 |
| 18 | NL 1413 | NWRP | CIMMYT, Mexico | Not released yet | | | | | |

When the crop reached harvestable maturity, the grains were dried and harvested manually with serrated sickles. The harvested wheat was threshed on the floor by beating with sticks and hands. Phenological data days to booting (DTB), days to heading (DTH), and days to anthesis (DTA) were determined when 50% of the whole population reached their respective stages. Booting-to-heading duration (BtoH), booting-to-anthesis duration (BtoA), and heading-to-anthesis duration (HtoA) were determined by observing consecutive phenological stages. Plant height (Ph), SL, SPS, GPS, SW, thousand grains weight (TGW), grain yield (GY), straw yield (SY), and total biological yield (BY) were determined at the time of harvest at physiological maturity. Data entry and processing were performed using Microsoft Excel 2016. Correlation analysis was performed using IBM SPSS Statistics version 26.0, and path analysis was performed using Microsoft Excel 2016.

## Results and Discussion

The result of analysis of variance (ANOVA) among 35 wheat genotypes showed significant differences in the yield-attributing characteristics, except SY, among the tested genotypes (Table 2). This result indicated sufficient variability among the tested genotypes. Hence, these characteristics are useful in selecting cultivars that can tolerate heat stress.

GY exhibited significant positive correlation with BtoH, BtoA, Ph, SL, SW, TGW, SY, and total biomass yield (TY; $p \leq 0.05$). GY showed a significant negative correlation with DTB, DTH, and DTA ($p \leq 0.05$; Table 3). The results suggest the selection of taller and early maturing genotypes that have long SL, high net SW, and TGW values should be promoted. The selection of earlier genotypes with high yields under heat stress has been suggested [34], and it has been reported that, a genotype that produces a TGW of 38.5 under heat stress will have a TGW of approximately 45 and yield of up to 5 tons per hectare under irrigated conditions [35]. Figure 1 shows that the temperature at the booting and heading stages was 25.5 °C and the anthesis was 30.5 °C. A temperature above 24 °C at the reproductive and grain ripening period is detrimental to wheat and promotes earlier senescence, reducing the net grain-filling period of wheat [36, 37]. The net grain-filling period decreases with increasing DTB because the temperature increases from mid-January when wheat grown under heat stress is in the jointing stage. A genotype with earlier booting and heading would not be subjected to terminal heat stress, which occurs in March (Figure 1) [35]. The performance of crops under heat stress conditions is mainly determined by canopy temperature, which facilitates the development and growth. Tall plants are often associated with cool canopy temperatures [38, 39]. Tall wheat genotypes perform well under heat stress conditions [27, 34]. Cooler temperature reduces heat shock on growing cells and facilitates optimum photosynthesis and sink transport [40, 41]. Similarly, high biomass and SY are associated with cool canopy temperatures and high levels of net photosynthesis and sink transport. Hence, a genotype with high SY and biomass produces high yields under heat stress (Table 2). Genotypes with long spikes have high yield under heat stress conditions [42] because spikes have photosynthetic cells and are associated with photosynthesis and contribute to approximately 20.1% of the yield.

BtoH and BtoA had significant positive contributions to the GY of wheat. A genotype with long BtoH and BtoA would have sufficient time for pollen formation, pollen maturation, and ovule maturation and effective pollination. The effect of BtoH is indirect via DTB because a genotype with delayed booting would suffer from terminal heat stress. To cope with such an effect, a genotype should grow its pollen and ovule inside the flag leaf before emergence. Flag leaf sheath protects maturing pollens and ovules from heat waves. BtoA has a positive direct effect on the GY of wheat (Table 4) and promotes efficient pollen and ovule maturation inside the flag leaf sheath and a longer time for pollination that promotes net GPS of the grains via effective pollination and There is a positive association between BtoA with net GPS of wheat as well (Table 3).

DTB, DTA, BtoH, HtoA, and SPS exerted a negative direct effect and thus had negative contribution to the GY of wheat. By contrast, DTH, BtoA, Ph, SL, net spike per meter square (NSPMS), SW, GPS, and TGW had positive direct effect and hence, positive contribution to the GY of wheat.

However, DTH had an overall negative association with the GY of wheat (Table 3), that is, DTH had an indirect effect on the GY of wheat via DTB (Table 4). BtoH had an overall positive association with the yield of wheat but a direct negative effect, indicating that BtoH duration affects yield via DTB (Table 4). Thus, a genotype with a short DTB generally preferred in environments under heat stress (Table 3 and Table 4) and should have a long BtoH to increase yield under these environments. [42] reported that earlier genotypes have high yields because DTB has a directly negative effect on yield given that temperature in a field increases after the jointing period of wheat and delayed DTB would lead to a terminal heat stress in February and March.

**Table 2. Analysis of Variance (ANOVA) of Yield-Attributing Traits in 35 Wheat Genotypes**

| Genotypes | DTB | DTH | DTA | BtoH | HtoA | BtoA | Ph (cm) | SL (cm) | NSPMS | SW (g) | SPS | GPS | TGW (g) | GY (kg ha$^{-1}$) | SY (kg ha$^{-1}$) | TW (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bhrikuti | 67.5 | 71.0 | 73.5 | 3.5 | 2.5 | 6.0 | 100.85 | 13.37 | 321.50 | 25.37 | 20.30 | 51.90 | 36.80 | 4053.00 | 6262.25 | 11715.00 |
| BL 4407 | 65.5 | 70.5 | 73.0 | 5.0 | 2.5 | 7.5 | 92.71 | 10.88 | 377.50 | 24.01 | 18.20 | 41.55 | 28.75 | 3113.10 | 5986.90 | 9100.00 |
| BL 4669 | 68.5 | 73.5 | 75.0 | 5.0 | 1.5 | 6.5 | 93.35 | 10.58 | 348.00 | 19.62 | 19.60 | 46.60 | 29.78 | 2702.50 | 6137.50 | 8840.00 |
| BL 4919 | 64.0 | 70.0 | 73.0 | 6.0 | 3.0 | 9.0 | 98.60 | 10.66 | 311.00 | 25.46 | 18.05 | 48.05 | 37.34 | 3920.00 | 6945.00 | 10865.00 |
| Gautam | 68.5 | 73.5 | 75.0 | 5.0 | 1.5 | 6.5 | 90.69 | 10.20 | 324.50 | 21.51 | 17.15 | 41.40 | 35.97 | 3431.50 | 6848.50 | 10280.00 |
| NL 1179 | 69.0 | 72.5 | 75.5 | 3.5 | 3.0 | 6.5 | 80.58 | 10.29 | 288.00 | 22.27 | 18.40 | 49.55 | 33.70 | 2798.50 | 6211.50 | 9010.00 |
| NL 1346 | 65.0 | 70.5 | 73.5 | 5.5 | 3.0 | 8.5 | 86.50 | 10.91 | 287.00 | 20.91 | 19.10 | 51.20 | 32.25 | 3111.00 | 7136.50 | 8335.00 |
| NL 1350 | 62.0 | 70.0 | 73.0 | 8.0 | 3.0 | 11.0 | 110.30 | 12.77 | 269.50 | 34.42 | 17.50 | 52.35 | 45.25 | 4075.00 | 7225.00 | 11300.00 |
| NL 1368 | 69.0 | 73.0 | 76.5 | 4.0 | 3.5 | 7.5 | 91.81 | 10.42 | 313.50 | 19.66 | 18.70 | 32.38 | 36.53 | 2661.50 | 5703.50 | 8365.00 |
| NL 1369 | 69.5 | 73.5 | 75.5 | 4.0 | 2.0 | 6.0 | 93.28 | 11.44 | 239.00 | 26.61 | 17.95 | 45.20 | 38.40 | 3659.50 | 5620.50 | 9280.00 |
| NL 1376 | 70.0 | 73.5 | 75.5 | 3.5 | 2.0 | 5.5 | 93.04 | 10.09 | 288.50 | 19.87 | 17.85 | 38.45 | 34.92 | 3134.50 | 6945.50 | 10080.00 |
| NL 1381 | 64.5 | 72.0 | 74.0 | 7.5 | 2.0 | 9.5 | 92.01 | 11.09 | 198.00 | 23.82 | 18.85 | 52.20 | 34.80 | 2445.50 | 5019.50 | 7465.00 |
| NL 1384 | 70.0 | 73.5 | 77.0 | 3.5 | 3.5 | 7.0 | 95.15 | 11.48 | 330.50 | 21.72 | 18.65 | 42.20 | 30.50 | 2776.50 | 6428.50 | 9205.00 |
| NL 1386 | 72.0 | 74.0 | 77.0 | 2.0 | 3.0 | 5.0 | 87.19 | 10.58 | 288.50 | 20.17 | 17.86 | 31.15 | 39.61 | 2694.00 | 5526.00 | 8220.00 |
| NL 1387 | 69.5 | 73.5 | 75.5 | 4.0 | 2.0 | 6.0 | 85.16 | 10.89 | 271.50 | 22.47 | 18.45 | 42.30 | 35.88 | 2531.00 | 6004.00 | 8535.00 |
| NL 1404 | 65.5 | 70.5 | 74.0 | 5.0 | 3.5 | 8.5 | 83.34 | 10.15 | 387.50 | 21.82 | 18.55 | 42.70 | 35.51 | 3340.50 | 7094.50 | 10435.00 |
| NL 1412 | 68.0 | 73.0 | 75.5 | 5.0 | 2.5 | 7.5 | 94.51 | 10.50 | 303.50 | 20.41 | 17.70 | 38.45 | 31.67 | 2594.00 | 5001.00 | 7595.00 |
| NL 1413 | 69.0 | 74.0 | 75.5 | 5.0 | 1.5 | 6.5 | 88.68 | 9.92 | 352.00 | 20.41 | 17.50 | 43.85 | 34.22 | 2820.00 | 6855.00 | 9675.00 |
| NL 1417 | 67.0 | 73.0 | 75.5 | 6.0 | 2.5 | 8.5 | 90.12 | 10.93 | 318.00 | 21.62 | 17.70 | 52.80 | 30.09 | 2705.50 | 5814.50 | 8520.00 |
| NL 1420 | 69.0 | 73.0 | 75.5 | 4.0 | 2.5 | 6.5 | 84.49 | 9.95 | 390.50 | 14.86 | 16.60 | 38.70 | 27.63 | 2554.00 | 5817.50 | 8371.50 |
| BL 5099 | 71.0 | 74.0 | 75.5 | 3.0 | 1.5 | 4.5 | 90.10 | 9.98 | 318.00 | 14.82 | 17.10 | 39.60 | 33.84 | 2887.00 | 5508.00 | 8395.00 |
| BL 5106 | 69.5 | 73.5 | 75.5 | 4.0 | 2.0 | 6.0 | 85.54 | 9.81 | 275.50 | 17.67 | 20.68 | 45.30 | 34.69 | 2288.00 | 4907.00 | 7195.00 |
| BL 5116 | 68.0 | 73.5 | 76.0 | 5.5 | 2.5 | 8.0 | 79.35 | 9.96 | 380.50 | 17.17 | 17.37 | 43.35 | 29.95 | 2885.50 | 5369.50 | 8255.00 |
| NL 1445 | 71.0 | 74.5 | 77.0 | 3.5 | 2.5 | 6.0 | 91.47 | 9.38 | 244.00 | 26.17 | 18.45 | 49.50 | 35.99 | 2677.50 | 6247.50 | 8925.00 |
| NL 1447 | 66.0 | 71.0 | 74.5 | 5.0 | 3.5 | 8.5 | 90.06 | 10.67 | 255.50 | 26.82 | 17.80 | 52.75 | 36.04 | 3187.00 | 5463.00 | 8650.00 |
| NL 1488 | 66.5 | 72.0 | 74.0 | 5.5 | 2.0 | 7.5 | 95.12 | 10.36 | 331.00 | 21.61 | 17.15 | 39.55 | 40.10 | 3367.50 | 6572.50 | 9940.00 |
| NL 1492 | 68.0 | 73.5 | 75.5 | 5.5 | 2.0 | 7.5 | 95.72 | 10.71 | 361.50 | 17.82 | 16.80 | 51.20 | 27.99 | 3280.50 | 5724.50 | 9005.00 |
| NL 1501 | 64.0 | 70.0 | 73.0 | 6.0 | 3.0 | 9.0 | 94.50 | 9.99 | 348.00 | 25.71 | 16.75 | 38.00 | 41.53 | 3666.50 | 6398.50 | 10065.00 |
| NL 1503 | 69.5 | 73.5 | 75.5 | 4.0 | 2.0 | 6.0 | 91.15 | 10.12 | 323.00 | 23.91 | 17.45 | 52.05 | 32.72 | 1980.00 | 5550.00 | 7530.00 |
| NL 1504 | 70.0 | 74.5 | 79.0 | 4.5 | 4.5 | 9.0 | 85.79 | 10.36 | 314.00 | 23.92 | 18.90 | 44.70 | 38.57 | 3166.50 | 7078.50 | 8520.00 |
| NL 1506 | 67.5 | 73.0 | 74.5 | 5.5 | 1.5 | 7.0 | 82.96 | 10.32 | 286.00 | 23.41 | 20.00 | 44.30 | 39.43 | 3287.00 | 6843.00 | 10130.00 |
| NL 1508 | 70.5 | 73.5 | 75.5 | 3.0 | 2.0 | 5.0 | 84.35 | 10.37 | 303.50 | 21.12 | 20.05 | 46.00 | 33.49 | 2134.50 | 5780.50 | 7915.00 |
| NL 1509 | 64.0 | 71.0 | 73.5 | 7.0 | 2.5 | 9.5 | 86.77 | 9.97 | 308.00 | 24.77 | 17.50 | 47.55 | 41.40 | 2706.00 | 5469.00 | 8175.00 |
| NL 1512 | 66.5 | 73.0 | 75.5 | 6.5 | 2.5 | 9.0 | 93.27 | 10.29 | 296.50 | 25.61 | 17.20 | 52.10 | 28.81 | 3062.50 | 7476.67 | 10539.17 |
| RR 21 | 64.0 | 70.0 | 73.0 | 6.0 | 3.0 | 9.0 | 99.72 | 10.52 | 427.50 | 17.46 | 16.50 | 31.25 | 23.80 | 3253.00 | 8837.00 | 12090.00 |
| **Grand Mean** | **67.69** | **72.53** | **75.03** | **4.84** | **2.50** | **7.34** | **90.81** | **10.57** | **313.73** | **22.14** | **18.12** | **44.58** | **34.51** | **2998.57** | **6263.09** | **9157.73** |
| **STD** | **2.59** | **1.50** | **1.44** | **1.61** | **0.90** | **1.75** | **6.43** | **0.88** | **56.00** | **4.29** | **1.23** | **7.56** | **5.47** | **587.11** | **1216.34** | **1462.65** |
| **CV** | **3.82** | **2.07** | **1.92** | **33.31** | **35.88** | **23.87** | **7.08** | **8.31** | **17.85** | **19.38** | **6.79** | **16.97** | **15.85** | **19.58** | **19.42** | **15.97** |
| **F-value** | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** | ** | **ns** | ** |

Standard deviation (STD), coefficient of variation (CV), days to booting (DTB), days to heading (DTH), days to anthesis (DTA), booting-to-heading duration (BtoH), heading-to-anthesis duration (HtoA), booting-to-anthesis duration (BtoA), plant height (Ph), spike length (SL), net spikes per meter square (NSPMS), spike weight (SW), net spikelet per spike (SPS), grains per spike (GPS), thousand grain weight (TGW), grain yield in kg ha$^{-1}$ (GY), straw yield (SY), total yield (TY); ** indicates level of significance at 1%

**Table 3. Phenotypic Correlations Among the 16 Morphological Traits**

| | DTB | DTH | DTA | BtoH | HtoA | BtoA | Ph | SL | NSPMS | SW | SPS | GPS | TGW | GY | SY | TW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DTB | 1 | .895** | .828** | -.874** | −0.215 | -.862** | -.433** | −0.303 | −0.120 | -.457** | 0.217 | −0.250 | −0.140 | -.509** | -.342* | -.441** |
| DTH | .895** | 1 | .876** | -.565** | -.337* | -.648** | -.408* | -.367* | −0.191 | -.401* | 0.116 | −0.098 | −0.151 | -.551** | -.391* | -.496** |
| DTA | .828** | .876** | 1 | -.576** | 0.158 | -.429* | -.403* | −0.306 | −0.155 | −0.289 | 0.114 | −0.142 | −0.099 | -.472** | −0.295 | -.471** |
| BtoH | -.874** | -.565** | -.576** | 1 | 0.031 | .887** | .356* | 0.160 | 0.014 | .407* | −0.274 | .355* | 0.095 | .341* | 0.206 | 0.274 |
| HtoA | −0.215 | -.337* | 0.158 | 0.031 | 1 | .490** | 0.048 | 0.154 | 0.088 | 0.259 | −0.015 | −0.078 | 0.115 | 0.207 | 0.226 | 0.096 |
| BtoA | -.862** | -.648** | -.429* | .887** | .490** | 1 | 0.332 | 0.211 | 0.053 | .474** | −0.246 | 0.274 | 0.136 | .393* | 0.284 | 0.284 |
| Ph | -.433** | -.408* | -.403* | .356* | 0.048 | 0.332 | 1 | .605** | −0.021 | .460** | −0.223 | 0.085 | 0.131 | .550** | .374* | .557** |
| SL | −0.303 | -.367* | −0.306 | 0.160 | 0.154 | 0.211 | .605** | 1 | −0.177 | .482** | 0.241 | 0.308 | 0.182 | .510** | 0.264 | .388* |
| NSPMS | −0.120 | −0.191 | −0.155 | 0.014 | 0.088 | 0.053 | −0.021 | −0.177 | 1 | -.486** | -.371* | -.418* | -.503** | 0.096 | .341* | 0.307 |
| SW | -.457** | -.401* | −0.289 | .407* | 0.259 | .474** | .460** | .482** | -.486** | 1 | 0.088 | .500** | .605** | .467** | 0.211 | .337* |
| SPS | 0.217 | 0.116 | 0.114 | −0.274 | −0.015 | −0.246 | −0.223 | 0.241 | -.371* | 0.088 | 1 | 0.246 | 0.159 | −0.162 | −0.074 | −0.190 |
| GPS | −0.250 | −0.098 | −0.142 | .355* | −0.078 | 0.274 | 0.085 | 0.308 | -.418* | .500** | 0.246 | 1 | 0.047 | 0.066 | −0.057 | −0.062 |
| TGW | −0.140 | −0.151 | −0.099 | 0.095 | 0.115 | 0.136 | 0.131 | 0.182 | -.503** | .605** | 0.159 | 0.047 | 1 | .369* | −0.039 | 0.110 |
| GY | -.509** | -.551** | -.472** | .341* | 0.207 | .393* | .550** | .510** | 0.096 | .467** | −0.162 | 0.066 | .369* | 1 | .593** | .808** |
| SY | -.342* | -.391* | −0.295 | 0.206 | 0.226 | 0.284 | .374* | 0.264 | .341* | 0.211 | −0.074 | −0.057 | −0.039 | .593** | 1 | .868** |
| TW | -.441** | -.496** | -.471** | 0.274 | 0.096 | 0.284 | .557** | .388* | 0.307 | .337* | −0.190 | −0.062 | 0.110 | .808** | .868** | 1 |

*, ** represents significant at 5% and 1% respectively

**Table 4. Path Analysis Among Grain yield and 13 Independent Traits of Wheat**

| | DTB | DTH | DTA | BtoH | HtoA | BtoA | Ph | SL | NSPMS | SW | SPS | GPS | TGW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DTB | **−1.227** | −1.098 | −1.016 | 1.072 | 0.264 | 1.058 | 0.531 | 0.372 | 0.147 | 0.561 | −0.266 | 0.307 | 0.172 |
| DTH | 0.658 | **0.736** | 0.644 | −0.416 | −0.248 | −0.477 | −0.300 | −0.270 | −0.141 | −0.295 | 0.085 | −0.072 | −0.111 |
| DTA | −0.180 | −0.191 | **−0.218** | 0.125 | −0.034 | 0.093 | 0.088 | 0.067 | 0.034 | 0.063 | −0.025 | 0.031 | 0.022 |
| BtoH | 1.098 | 0.710 | 0.723 | **−1.256** | −0.039 | −1.114 | −0.447 | −0.201 | −0.018 | −0.511 | 0.344 | −0.446 | −0.119 |
| HtoA | 0.042 | 0.065 | −0.031 | −0.006 | **−0.193** | −0.095 | −0.009 | −0.030 | −0.017 | −0.050 | 0.003 | 0.015 | −0.022 |
| BtoA | −0.566 | −0.426 | −0.282 | 0.582 | 0.322 | **0.657** | 0.218 | 0.139 | 0.035 | 0.311 | −0.162 | 0.180 | 0.089 |
| Ph | −0.082 | −0.078 | −0.077 | 0.068 | 0.009 | 0.063 | **0.190** | 0.115 | −0.004 | 0.088 | −0.042 | 0.016 | 0.025 |
| SL | −0.088 | −0.107 | −0.089 | 0.047 | 0.045 | 0.062 | 0.176 | **0.291** | −0.052 | 0.140 | 0.070 | 0.090 | 0.053 |
| NSPMS | −0.038 | −0.061 | −0.049 | 0.004 | 0.028 | 0.017 | −0.007 | −0.056 | **0.318** | −0.155 | −0.118 | −0.133 | −0.160 |
| SW | −0.017 | −0.015 | −0.011 | 0.016 | 0.010 | 0.018 | 0.018 | 0.018 | −0.019 | **0.038** | 0.003 | 0.019 | 0.023 |
| SPS | −0.030 | −0.016 | −0.016 | 0.038 | 0.002 | 0.034 | 0.031 | −0.034 | 0.052 | −0.012 | **−0.139** | −0.034 | −0.022 |
| GPS | −0.019 | −0.007 | −0.011 | 0.026 | −0.006 | 0.020 | 0.006 | 0.023 | −0.031 | 0.037 | 0.018 | **0.074** | 0.003 |
| TGW | −0.058 | −0.063 | −0.041 | 0.040 | 0.048 | 0.057 | 0.055 | 0.076 | −0.210 | 0.252 | 0.066 | 0.020 | **0.417** |
| GY | −0.509 | −0.551 | −0.472 | 0.341 | 0.207 | 0.393 | 0.550 | 0.510 | 0.096 | 0.467 | −0.162 | 0.066 | 0.369 |

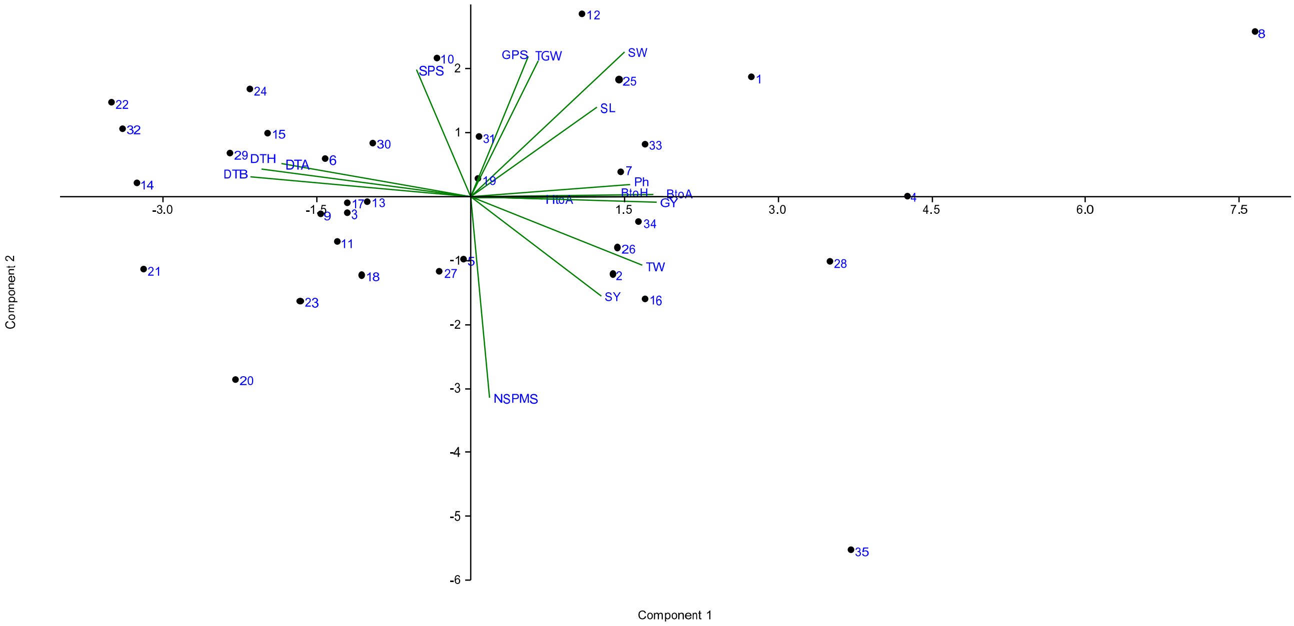


**Figure 2. Biplot Analysis of Morphological Traits and Genotypes**

DTB, DTH, and DTA exhibited a highly significant negative correlation with GY. DTH showed a direct positive effect but an indirect negative effect on GY via DTB, DTA, and BtoH. BtoA and BtoH showed a significant positive correlation with GY through its direct positive effect. However, BtoH showed a direct negative effect but indirect positive effect on GY via DTB, DTA, and BtoA. Ph and SL showed a significant positive effect on GY through their direct positive effect because the increase in Ph resulted in an increase in area exposed to sunlight and facilitated photosynthates. Increase in spikes allowed more grains to be accommodated in the spikes, increasing GPS, which had a positive correlation with GY (Table 3).

**Principal Component Analysis (PCA).** Principal component analysis (PCA) was conducted, and a biplot was constructed to summarize the correlations of various morphological parameters with the GYs of the wheat genotypes. The first six principal components explained 83.57% of the total variation in the data (Figure 2). PCA extracted six principal components, and according to the ranking of PC1 with various morphological parameters, DTB, DTH, BtoA, DTA, BtoH, and Ph were determined. In the biplot of PCA, the correlation among the morphological parameter is given by the angle between their vectors. The indices are significantly positively correlated if the angle between the vectors is less than 90°, significantly negatively correlated if the angle is more than 90°, and independent if the angle between their vectors is 90° [43]. Therefore, DTB, DTH, and DTA were the phenological traits that had a significant negative correlation with the GY of wheat, whereas BtoH and BtoA had a significant positive correlation with the GY of wheat and Ph had a significant positive contribution to the GY of wheat (Figure 2) PCA revealed that the selection should based on the phenological traits DTB, DTH, DTA, interphenological BtoH and BtoA, and growth trait; Ph can be employed for the identification of the high-yielding genotype of wheat under heat stress conditions. Thus, early maturing and tall genotypes that have long BtoH and BtoA would generate high yields under heat stress.

## Conclusion

Heat stress reduces yield up to 46% and affects 42% of the total wheat-growing area of the world. To identify the most appropriate trait for the selection of heat-stress-tolerant genotype of wheat, correlation, and path analysis were performed on the datasheet from thirty-five elite wheat genotypes. Correlation shows, a significant positive correlation of GY with BtoH, BtoA, Ph, SL, SW, TGW, SY, and TY and significant negative correlation with phenological stages, DTB, DTH, and DTA. Path analysis revealed that DTB and DTA have a direct negative effect on the GY of wheat, whereas, DTH has an indirect negative effect on yield via DTB. BtoA, Ph, SL, SW, and TGW had a direct positive effect on yield whereas, BtoH duration had an indirect positive effect on yield via DTB. PCA results showed that DTB, DTH, and DTA had significant negative correlation with GY, whereas BtoH, BtoA, and Ph had a significant positive correlation with GY. In summary, selection based on phenological stages DTB, DTH, DTA, inter-phenological duration BtoA, BtoH, and Ph can be used as morphological traits for the selection of high-yielding wheat genotypes tolerant to heat stress. The taller and earlier maturing genotype that has long BtoH and BtoA would produce high yield under heat stress.

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## Authors Contribution

All authors equally contributed to the study.

## Conflicts of Interest

The authors declare they have no conflicts of interest regarding the publication of this manuscript.

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