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# Correlation between physiological and yield attributes in bread wheat genotypes for high temperature tolerance

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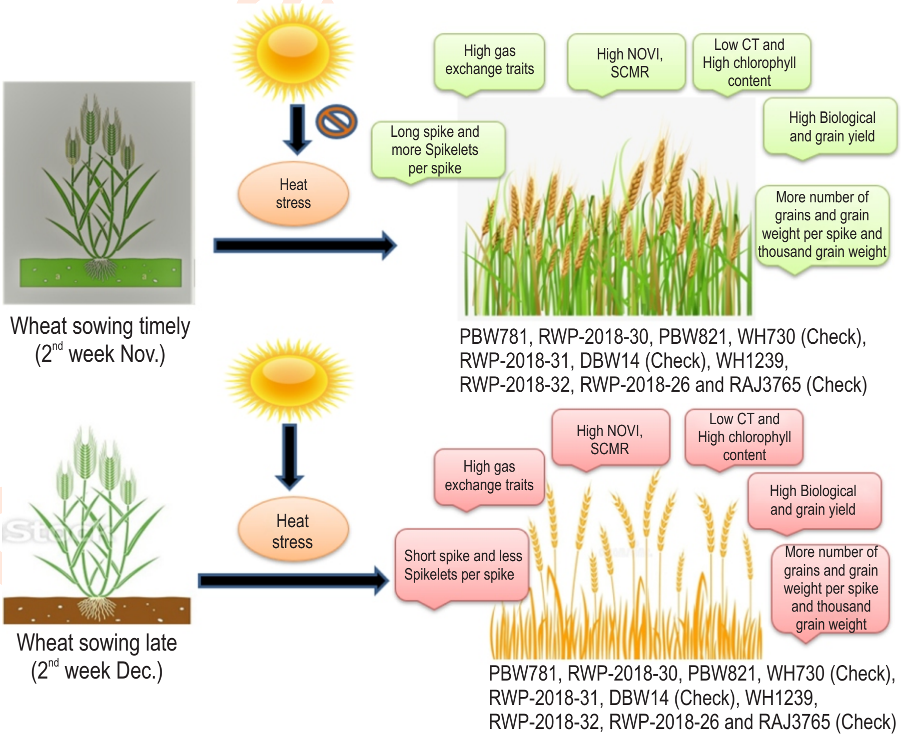
## Abstract

**Aim:** The aim of the present study was to observe the role of heat stress in the correlation of physiological and yield attributes in bread wheat genotypes.

**Methodology:** Seven wheat genotypes (PBW781, RWP-2018-30, PBW821, RWP-2018-31, WH1239, RWP-2018-26, and RWP-2018-32) along with three check varities namely DBW14, WH730, and RAJ3765 were grown under timely sown (TS) and late sown (LS) conditions in the field research area of Wheat Section, CCS HAU, Hisar (2018-19). For generating heat stress, delay in sowing (4 weeks) was done in late sown from timely sown. These wheat lines were assessed for several physiological and yield attributes under both conditions and one genotype was found to be heat-tolerant under late sown condition.

**Results:** PBW821 was classified as thermo-tolerant due to maximum grain yield, higher normalized difference vegetation index, photosynthetic rate, chlorophyll content, and lower canopy temperature compared to other varieties under late sown conditions.

**Interpretation:** Identification of a heat-resistant wheat genotype would be a valuable resource for developing high-yielding cultivars under high-temperature conditions, and these findings might also be used in breeding programs.



**Key words:** Grain yield, Heat tolerance, Physiological traits, *Triticum aestivum*

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## Introduction

Abiotic constraints such as temperature (both low and high), salinity, drought and high concentrations of toxic metals have restrained crop production (Thilert, 2006; Rani *et al.,* 2018). Among these stresses, high temperature is a major concern as global air temperature has significantly increased during the last decades (Masson-Delmotte *et al.,* 2018). So, due to the anticipated increase in temperature, the losses in crop production will also increase by 2080-2110. Wheat is a winter season crop and rotation patterns lead to its late sowing in the month of December/January, resulting in a shorter crop period and facing high temperature at reproductive stage (Singh and Jaiswal, 2013). Under late sown condition (heat stress), reproductive stage is the main cause of yield reduction and is responsible for the shortening of grain growth duration and improper grain filling under heat stress in wheat (Reynolds *et al.,* 2001; Rane *et al.,* 2007). The optimum temperature required for the growth of wheat is 18-24$^0$C, but if there is a rise in temperature, *i.e.,* 28-32$^0$C even for a short period (5-6 days), it causes a reduction of 20% or more in yield (Rane *et al.,* 2007).

Heat stress leads to different anatomical, morphological, biochemical and physiological changes in wheat, influencing grain yield and quality (DuPont and Altenbach, 2003; Barnabas *et al.,* 2008). It has a complex effect on the photosynthetic activity of wheat plants (Liu,2017; Djanaguiraman, 2018) as it is one of the chief metabolic processes that affect grain yield (Ristic *et al.,* 2007), so net photosynthetic activity and chlorophyll content are important parameters for the modification of wheat to heat stress and other abiotic stress factors (Khan *et al.,* 2014). In addition, there is a decrease in net photosynthetic rate due to the changes in the light-dependent and dark reactions (Ashraf and Harris, 2013). In photosynthesis, photosystem II (PSII) is the prominent heat-sensitive component that restrains the photochemistry by increasing the temperature (Zhou *et al.,* 2017). 'Chlorophyll a fluorescence' is one of the ways which commonly accessed the changes in PSII, as it is a quick non-destructive method for stress tolerance analysis (Baker and Rosenqvist, 2004). Heat stress inhibits the activity of carbohydrate enzymes, *i.e.,* sucrose synthase and invertase and also restrain sucrose content and metabolism (Dai *et al.,* 2015).

Moreover, high temperature also reduces chlorophyll biosynthesis and content, leading to early crop maturation (Farooq *et al.,* 2011). Rahman *et al.* (2009) reported that heat stress hastens the process of development, flowering, and ripening. During reproductive stage, wheat plant suffers greater damage than the vegetative stage as it directly affects the grain number and grain weight (Wollenweber *et al.,* 2003). Liu *et al.* (2017) and Balla *et al.* (2019) reported that due to heat stress there is a degradation leaf chlorophyll content during anthesis and grain filling period, resulting in a decrease in both leaf photosynthetic activity and final biomass. Wheat production is also limited by other abiotic factors such as drought, salinity, etc., which is also a current and upcoming challenge. Therefore, to meet the food requirement of 950 million people by 2050, it is necessary to double the quantity of global food production (Pandey *et al.,* 2019). Hence, there is a necessity to evolve wheat genotypes that are tolerant to high temperatures (Sattar *et al.,* 2020; Nyol *et al.,* 2020). Developments of thermo-tolerant varieties of wheat are one of the major steps toward yield improvement of wheat. Since there is a significant genotypic variation among wheat cultivars in the physiological and agronomical traits across the main developmental stages (Vignejevic *et al.,* 2015), further analysis of different wheat gene pools is necessary to identify tolerant wheat genotypes that can be included in breeding activities. Under late sown field conditions, winter wheat cultivars are likely to encounter prolonged heat stress during flowering and grain filling growth stages. Knowledge about the changes in wheat physiological response to heat stress can be used to adjust breeding strategies and improve wheat cultivars adapted to heat-prone environments. In view of this, the present study aimed to analyze the physiological responses to heat stress in ten winter wheat genotypes in terms of photosynthesis, chlorophyll content, NDVI, canopy temperature, stomatal conductance, transpiration rate and grain yield traits at anthesis stage.

## Materials and Methods

**Meteorological data:** Temperature and rainfall data during the season was obtained from the observatory, Department of Meteorological Science, CCSHAU, Hisar. The data indicated that there was no rainfall in the month of November and December (2018). Minimum temperature (19.2$^0$C) was observed during the month of January, 2019, while, the maximum temperature (36.6$^0$C) was observed during the month of April, 2019. Experiments faced short episode of higher temperature (>25$^0$C) during the month of March and April, 2019. These periods coincide for taking physiological observation under both timely sown (TS) and late sown (LS) conditions. Fig. 1 shows the daily maximum temperature, minimum temperature and rainfall during the late sown wheat from date of sowing, *i.e.,* 11th December 2018 the date of harvesting, *i.e.,* 20th April 2019.

**Plant material and Experimental layout:** Ten wheat genotypes viz. PBW781, RWP-2018-30, PBW821, WH730 (Check), RWP-2018-31, DBW14 (Check), WH1239, RWP-2018-32, RWP-2018-26 and RAJ3765 (Check) were obtained from wheat section, Department of Genetics and Plant Breeding, CCS HAU, Hisar. The crop was sown in two environments *viz.* Timely sown (TS) condition (first fortnight of November 2018) and late sown (LS) condition (first fortnight of December 2018). The experiment was conducted in three replicates; in randomized block design with 6 rows of 3 m length with a 20 cm and 5 cm spacing between rows and plants, respectively. From the selected plants, flag leaf was selected randomly and tagged. Physiological traits were measured on tagged flag leaves at anthesis and yield attributes were taken at maturity from selected plants. Normalized difference vegetation index (NDVI) measurements were made using a green seeker, hand held optical sensor unit (Model 505, NTech Industries, Inc., Ukiah, CA, USA). SPAD chlorophyll meter reading (SCMR) was taken by chlorophyll meter, *i.e.,* SPAD (model no. Minolta SPAD-502 Plus) which measure the greenness or the relative chlorophyll content of leaves. In fully expanded leaf gas exchange attributes viz stomatal conductance (gs), transpiration rate (E), and photosynthetic rate (A) were measured by the infrared gas analyzer (IRGA LCi-SD, ADC Biosciences). Infrared thermometer (IRT), model AG-42, Tele temp crop Fullerton was used for the measurement of canopy temperature (CT). Following yield traits were recorded during the study spike length (SL), number of spikelets per spike (SS), number of grains per spike (NGS), grain weight per spike (GWS), grain yield (GY) and 1000-grain weight (TGW).

**Statistical analysis:** Statistical analysis was done by using OPSTAT software available on CCS HAU, Hisar, (www. hau. ernet. in) and heat map & PCA biplot were made using Origin software 2021b.

## Results and Discussion

In Indian climate, wheat is the main crop of winter season and its production potential depends upon sowing time and varietal selection. High-temperature stress causes alterations in various physiological, biochemical and molecular processes of crop plants resulting in the reduction of crop yield. Keeping this in view the present investigation was conducted to evaluate the physiological traits and different yield attributes under TS and LS conditions. A correlation between physiological traits and high temperature tolerance in wheat was studied. Physiological traits like NDVI, SCMR, and photosynthetic rate (A), transpiration rate (E), stomatal conductance (gs), and CT were observed at anthesis stage in all wheat genotypes under TS and LS conditions (Table 1). Photosynthetic rate and chlorophyll content decreased under LS condition whereas NDVI increased under LS condition as compared to TS condition at anthesis stage. Maximum NDVI, SCMR and A were observed in wheat genotype PBW821 (0.77), PBW821 (50.2), PBW821 (18.9) respectively under TS condition and PBW821 (0.83), PBW821 (44.6), PBW821 (14.8), respectively, under LS condition. Photosynthetic rate (A) (µ mole $m^{-2}$ $s^{-1}$) was maximum in PBW821 (18.9), followed by RAJ3765 (18.4) and DBW14 (17.9) under TS condition and in PBW821 (14.8), followed by RAJ3765 (13.4) and DBW14 (12.7) under LS conditions. The transpiration rate (mole $m^{-2}$ $s^{-1}$) ranged from 4.83 (WH1239) to 8.10 (RAJ3765) and 3.89 (WH1239) to 6.59 (PBW821) under TS and LS conditions, respectively. Among ten wheat genotypes, the maximum stomatal conductance (m mole

**Table 1:** Physiological traits like NDVI, Spade chlorophyll meter reading (SCMR), and Photosynthetic rate (A), Transpiration rate (E), Stomatal conductance (gs) and Canopy temperature (°C) (CT) under TS and LS conditions at anthesis stage in wheat genotypes

| Genotypes | NDVI | | CT(°C) | | A (µ mole $m^{-2}$ $s^{-1}$) | | E (mole $m^{-2}$ $s^{-1}$) | | gs (m mole $m^{-2}$ $s^{-1}$) | | SCMR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TS | LS | TS | LS | TS | LS | TS | LS | TS | LS | TS | LS |
| DBW14 (Check) | 0.73± 0.009 | 0.81± 0.020 | 12.5± 0.085 | 19.3± 0.483 | 17.9± 0.166 | 12.7± 0.274 | 6.95± 0.030 | 5.69± 0.095 | 0.37± 0.002 | 0.21± 0.001 | 47.9± 0.591 | 40.4± 0.473 |
| PBW781 | 0.67± 0.013 | 0.78± 0.010 | 15.6± 0.024 | 20.9± 0.412 | 16.3± 0.085 | 6.4± 0.037 | 6.98± 0.080 | 4.78± 0.102 | 0.35± 0.005 | 0.14± 0.002 | 44.9± 0.444 | 40.0± 0.458 |
| PBW821 | 0.77± 0.012 | 0.83± 0.021 | 12.2± 0.215 | 19.0± 0.386 | 18.9± 0.059 | 14.8± 0.162 | 7.45± 0.074 | 6.59± 0.137 | 0.41± 0.010 | 0.31± 0.004 | 50.2± 0.940 | 44.6± 0.395 |
| RAJ3765 (Check) | 0.76± 0.007 | 0.80± 0.013 | 12.7± 0.112 | 19.6± 0.082 | 18.4± 0.421 | 13.4± 0.258 | 8.10± 0.194 | 6.47± 0.084 | 0.43± 0.004 | 0.29± 0.003 | 46.6± 0.655 | 39.3± 0.205 |
| RWP-2018-26 | 0.65± 0.005 | 0.79± 0.012 | 15.4± 0.184 | 20.6± 0.182 | 12.5± 0.241 | 8.3± 0.138 | 6.47± 0.060 | 4.92± 0.005 | 0.19± 0.002 | 0.12± 0.001 | 43.4± 0.542 | 33.8± 0.633 |
| RWP-2018-30 | 0.65± 0.001 | 0.71± 0.009 | 13.8± 0.266 | 23.8± 0.049 | 12.7± 0.185 | 9.1± 0.095 | 6.22± 0.045 | 5.02± 0.034 | 0.28± 0.005 | 0.17± 0.003 | 42.4± 0.596 | 35.2± 0.366 |
| RWP-2018-31 | 0.69± 0.012 | 0.79± 0.017 | 13.4± 0.285 | 20.5± 0.500 | 17.8± 0.435 | 11.2± 0.186 | 6.87± 0.014 | 4.57± 0.026 | 0.35± 0.002 | 0.16± 0.004 | 44.6± 1.044 | 36.9± 0.480 |
| RWP-2018-32 | 0.65± 0.016 | 0.71± 0.001 | 14.3± 0.126 | 19.6± 0.488 | 15.1± 0.259 | 10.3± 0.236 | 5.93± 0.120 | 4.56± 0.035 | 0.29± 0.001 | 0.14± 0.003 | 43.0± 0.268 | 31.8± 0.695 |
| WH1239 | 0.71± 0.008 | 0.69± 0.015 | 18.1± 0.169 | 21.0± 0.185 | 16.7± 0.209 | 5.9± 0.021 | 4.83± 0.063 | 3.89± 0.087 | 0.29± 0.000 | 0.12± 0.002 | 42.7± 0.111 | 34.8± 0.290 |
| Wh730 (Check) | 0.68± 0.004 | 0.71± 0.011 | 14.2± 0.015 | 21.2± 0.418 | 11.6± 0.193 | 7.5± 0.051 | 6.44± 0.107 | 5.17± 0.116 | 0.26± 0.002 | 0.16± 0.002 | 40.4± 0.525 | 33.8± 0.229 |
| Mean | 0.7 | 0.76 | 14.2 | 20.5 | 15.5 | 10 | 6.62 | 5.17 | 0.32 | 0.18 | 44.61 | 37.06 |
| Range | 0.65-0.77 | 0.69-0.83 | 12.2-18.1 | 19.0-23.8 | 11.6-18.9 | 5.9-14.8 | 4.83-8.10 | 3.89-6.59 | 0.19-0.43 | 0.12-0.31 | 40.4-50.2 | 31.8-44.6 |
| CD at 5% | G=0.025, GxE=0.036 | E=0.011, | G=0.58, GxE=0.83 | E=0.26, | G=0.45, GxE =0.65 | E= 0.20, | G=0.18, GxE=0.27 | E=0.08, | G=0.007, GXE=0.011 | E=0.003, | G=1.11, GxE=1.7 | E= 0.50, |

*G-genotype, E-Environment

**Table 2:** Grain yield (GY), Biological yield (BY), Number of grains per spike (NGS), Grain weight per spike (GWS), 1000-grain weight (TGW), Number of spikelets per spike (SS) and Spike length (SL) (cm) under TS and LS in wheat genotypes

| Genotypes | GY(g m$^{-2}$) | | BY (g m$^{-2}$) | | NGS | | GWS (g) | | TGW (g) | | SS | | SL (cm) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TS | LS | TS | LS | TS | LS | TS | LS | TS | LS | TS | LS | TS | LS |
| DBW14 (Check) | 520.0 ±4.54 | 344.0 ±6.68 | 921.7 ±2.01 | 693.3 ±15.98 | 63.00 ±0.93 | 53.50 ±0.56 | 3.24± 0.06 | 2.68 ±0.05 | 47.64 ±0.52 | 42.44 ±0.22 | 22.5 ±0.24 | 20.5 ±0.01 | 10.8 ±0.19 | 10.5± 0.19 |
| PBW781 | 460.0 ±5.99 | 327.1 ±2.72 | 782.3 ±17.91 | 506.0 ±0.26 | 58.00 ±1.48 | 48.50 ±1.19 | 2.05 ±0.02 | 1.39 ±0.03 | 47.38 ±0.91 | 41.07 ±0.41 | 20.5 ±0.19 | 13.5 ±0.34 | 10.5 ±0.10 | 9.3± 0.07 |
| PBW821 | 537.8 ±11.48 | 396.5 ±8.87 | 898.3 ±10.75 | 759.7 ±15.42 | 77.00 ±1.96 | 68.00 ±1.06 | 3.65 ±0.03 | 3.05 ±0.06 | 48.17 ±0.43 | 43.56 ±0.25 | 20.0 ±0.38 | 19.0 ±0.38 | 11.5 ±0.08 | 11.0± 0.07 |
| RAJ3765 (Check) | 529.1 ±6.61 | 345.8 ±2.16 | 880.0 ±8.70 | 653.0 ±7.48 | 66.00 ±0.72 | 58.50 ±0.21 | 2.74 ±0.05 | 2.34 ±0.01 | 50.35 ±0.05 | 45.17 ±0.52 | 20.5 ±0.29 | 20.0 ±0.17 | 12.0 ±0.24 | 11.0± 0.05 |
| RWP-2018-26 | 470.5 ±2.20 | 282.1 ±1.91 | 752.3 ±6.26 | 557.3 ±0.88 | 53.00 ±0.55 | 46.50 ±0.44 | 2.04 ±0.03 | 1.60 ±0.03 | 42.25 ±0.15 | 36.93 ±0.79 | 18.5 ±0.46 | 15.5 ±0.36 | 9.3 ±0.23 | 7.8± 0.06 |
| RWP-2018-30 | 487.7 ±6.85 | 279.4 ±2.62 | 725.0 ±10.94 | 534.0 ±12.51 | 38.50 ±0.70 | 33.00 ±0.24 | 2.18 ±0.02 | 1.70 ±0.03 | 45.51 ±0.59 | 39.35 ±0.96 | 14.5 ±0.02 | 13.0 ±0.17 | 10.0 ±0.16 | 8.3± 0.19 |
| RWP-2018-31 | 435.4 ±4.99 | 243.0 ±0.51 | 714.0 ±8.55 | 482.3 ±7.78 | 51.00 ±0.98 | 42.50 ±0.04 | 2.49 ±0.02 | 1.89 ±0.00 | 36.91 ±0.69 | 33.00 ±0.00 | 20.0 ±0.02 | 15.0 ±0.16 | 9.5± 0.09 | 8.0± 0.03 |
| RWP-2018-32 | 498.4 ±7.78 | 313.8 ±7.51 | 790.0 ±6.58 | 564.0 ±9.39 | 43.00 ±0.90 | 37.00 ±0.94 | 2.09 ±0.05 | 1.67 ±0.01 | 44.40 ±0.02 | 38.55 ±0.86 | 18.0± 0.12 | 16.0± 0.09 | 10.0 ±0.05 | 8.8± 0.02 |
| Wh1239 | 477.0 ±5.96 | 307.0 ±1.44 | 763.3 ±5.16 | 552.0 ±4.02 | 56.00 ±0.06 | 40.50 ±0.95 | 2.03 ±0.04 | 1.61 ±0.02 | 40.96 ±0.43 | 35.34 ±0.11 | 17.0 ±0.14 | 14.5 ±0.35 | 9.5± 0.14 | 7.8± 0.09 |
| Wh730 (Check) | 478.4 ±0.25 | 282.8 ±5.15 | 755.7 ±5.51 | 535.0 ±10.02 | 46.50 ±0.39 | 41.50 ±0.84 | 2.19 ±0.03 | 1.84 ±0.04 | 43.38 ±0.20 | 38.21 ±0.64 | 19.0 ±0.18 | 16.5± 0.16 | 10.0± 0.02 | 8.0± 0.09 |
| **Mean** | 489.4 | 312.2 | 798.3 | 583.7 | 55.2 | 46.95 | 2.47 | 1.98 | 44.7 | 39.36 | 19.1 | 16.4 | 10.31 | 9.1 |
| **Range** | 435.4-537.8 | 243.0-396.5 | 714.0-921.7 | 482.3-759.7 | 38.50-77.00 | 33.00-68.00 | 2.03-3.65 | 1.39-3.05 | 36.91-50.35 | 33.00-45.17 | 14.5-22.5 | 13.0-20.5 | 9.3-12.0 | 7.8-11.0 |
| CD at 5% | G=11.1,<br>GXE=15.7 | E=5.0, | G=19.7,<br>GXE=27.9 | E=8.8, | G=1.84,<br>GXE=2.60 | E=0.82, | G=0.07,<br>GxE=0.10 | E=0.03, | G=1.10,<br>GXE=NS | E=0.49, | G=0.50,<br>GXE=0.71 | E=0.23, | G=0.25<br>GxE=0.36 | E=011, |

*G-genotype; E-Environment

m$^{-2}$ s$^{-1}$) was found in wheat genotype RAJ3765 (0.43) under TS condition, while in PBW821 (0.31) under LS condition. However, minimum stomatal conductance was found in RWP-2018-26 (0.19) under TS condition, while in WH1239 and RWP-2018-26 (0.12) under LS condition. The genotype WH1239 (18.1$^{0}$C) showed maximum CT under TS, while RWP-2018- 30 (23.8$^{0}$C) under LS condition. Minimum CT was observed in wheat genotype PBW821 (12.2$^{0}$C) under TS, while in PBW821 (19.0$^{0}$C) under LS condition at anthesis stage.

In the present investigation, the chlorophyll content and photosynthetic rate decreased under LS condition as compared to TS conditions. High chlorophyll content, cooler canopy and maximum NDVI is associated with heat tolerance (Ramya *et al.,* 2015; Munjal and Dhanda, 2016). Heat stress drastically affects chlorophyll content and is higher in tolerant genotypes under late sown conditions (Dhyani *et al.,* 2013). Reduction in chlorophyll content during grain filling under heat stress in field condition is reported to be associated with reduced yield (Reynolds *et al.,* 1994; Ram *et al.,* 2017). Photosynthetic capacity depends on the chlorophyll content, corresponding to greenness of vegetation. Under heat stress, there is breakdown of chlorophyll present in the leaves (Dwivedi *et al.,* 2017). At high temperature under LS condition, the grain filling stage inhibits the leaf photosynthesis up to 50% in most of the wheat genotypes in the present study. The net photosynthesis during the wheat crop cycle is essential in controlling the crop biomass and grain yield under high temperature. Larger NDVI values are associated with greater biomass accumulation, photosynthates accumulation and a faster growth rate (Babar *et al.,* 2006; Sharma *et al.,* 2018). NDVI measured at early grain filling (*i.e.,* milky stage) was strongly positively correlated to biomass and yield at maturity (Marti *et al.,* 2007). Canopy temperature (CT) is a tool which is used for indirect selection of genotypes tolerant to drought and heat stressed environments (Reynolds *et al.,* 2009).

It is highly dependent on stomatal conductance and the plants access to water. Our results corroborates with the study of Munjal and Rana (2003); Bilge *et al.* (2008) and Ray and Ahmed (2015) who suggested that maintaining cooler canopy during grain filling period in wheat is an important physiological principle for high temperature stress tolerance. The results showed a reduction in stomatal conductance under LS condition as compared to TS condition. Stomatal conductance could be valuable selection criteria for higher yields in wheat grown at supra-optimal temperatures (Zhenmin *et al.,* 1998).

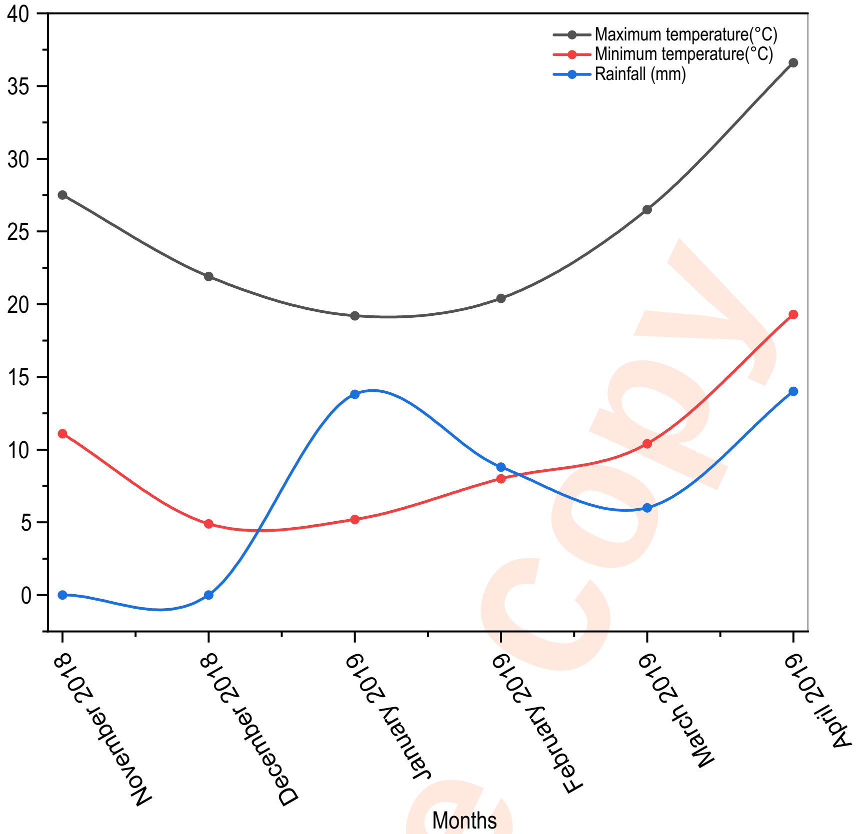


**Fig.1:** Maximum temperature, minimum temperature and Rainfall during wheat crop season 2018- 2019.

Gupta *et al.* (2015) observed that stomatal conductance and photosynthetic rate decreased significantly under LS condition, however, heat tolerance genotypes maintain higher rate of stomatal conductance and photosynthesis under LS condition. Similar results were also reported by researchers (Schapendonk *et al.,* 2007; Feng *et al.,* 2014; Saxena *et al.*, 2016; Pooja and Munjal, 2019). In the present investigation, transpiration rate was higher under TS condition as comparatively to LS condition. Simoes-Araujo *et al.* (2003) and Dwivedi *et al.* (2017) reported that there was a reduction in the transpiration rate under heat stress due to unavailability of enough water caused by lower conductance. It was inferred that enhanced transpiration may help tolerant genotype to maintain higher rate of photosynthesis through cooling effect. Increased stomatal conductance leads to transpiration cooling and canopy temperature depression (Munjal and Dhanda, 2004). A significant difference in grain yield potential among the genotypes was observed under both environmental conditions (Table 2). Grain yield ranged from 435.4 to 537.8 g m$^2$ and 243.0 to 396.5 g m$^2$ under TS and LS conditions respectively. Grain yield was reduced in all the genotypes under LS condition as compared to TS condition. Among 10 genotypes, the maximum grain yield was observed in PBW821 under both TS (537.8 g m$^2$) and LS (396.5 g m$^2$) conditions. The maximum number of spikelets per spike (SS) was observed in genotype DBW14 under both TS (22.5) and under LS (20.5) conditions. Spike length (SL) ranged from RWP-2018-26 (9.3 cm) to RAJ3765 (12.0 cm) and RWP-2018-26, WH1239 (7.8 cm) to RAJ3765, PBW821 (11.0 cm) under TS and LS conditions, respectively. The number of grains per spike (NGS) ranged from 38.50 (RWP- 2018-30) to 77.0 (PBW821) and 33.0 (RWP-2018-30) to 68.0 (PBW821) under TS and LS conditions, respectively. The maximum grain weight per spike (GWS) was observed in PBW821 under TS (3.65 g) and LS (3.05 g) condition. However, minimum GWS was observed in WH1239 (2.03 g) under TS condition whereas PBW781 (1.39 g) under LS condition. GWS ranged from 2.03-3.65 and 1.39-3.05 under TS and LS conditions. 1000-grain weight (TGW) ranged from 36.91 g (RWP-2018-31) to 50.35 g (RAJ3765) and 33.0g (RWP-2018-31) to 45.17g (RAJ3765) under TS and LS conditions, respectively. The maximum biological yield (BY) was observed in wheat genotype DBW14 (921.7 g m$^2$) under TS, while in PBW821 (759.7 g m$^2$) under LS condition. Heat map indicated the relative performance of all genotypes, based on colour difference for different physiological and yield traits studied under both TS and LS conditions (Fig 2a, 2b, 2c and 2d). It was also observed from heat maps that all traits were affected under LS as compared to TS conditions.

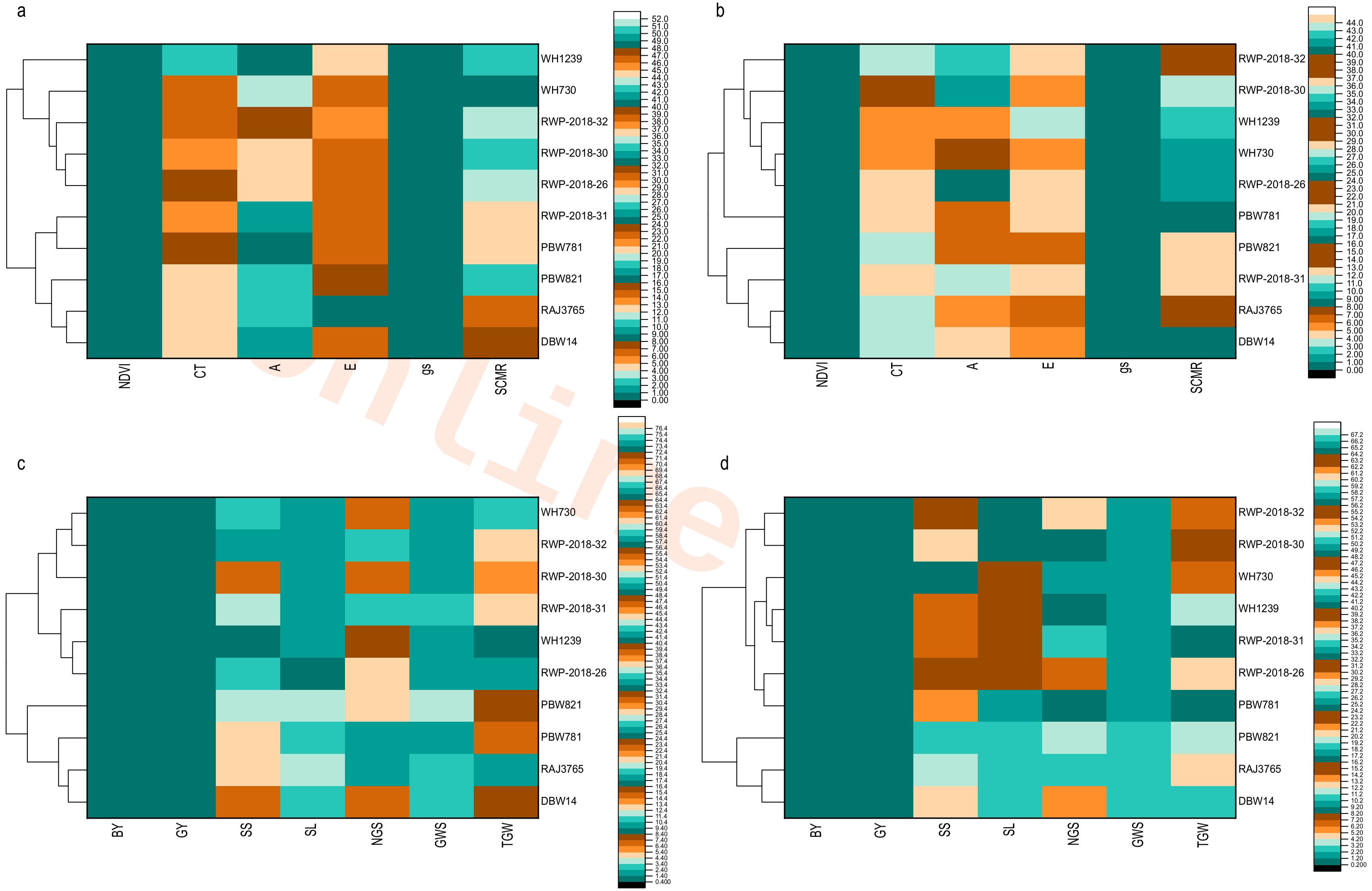
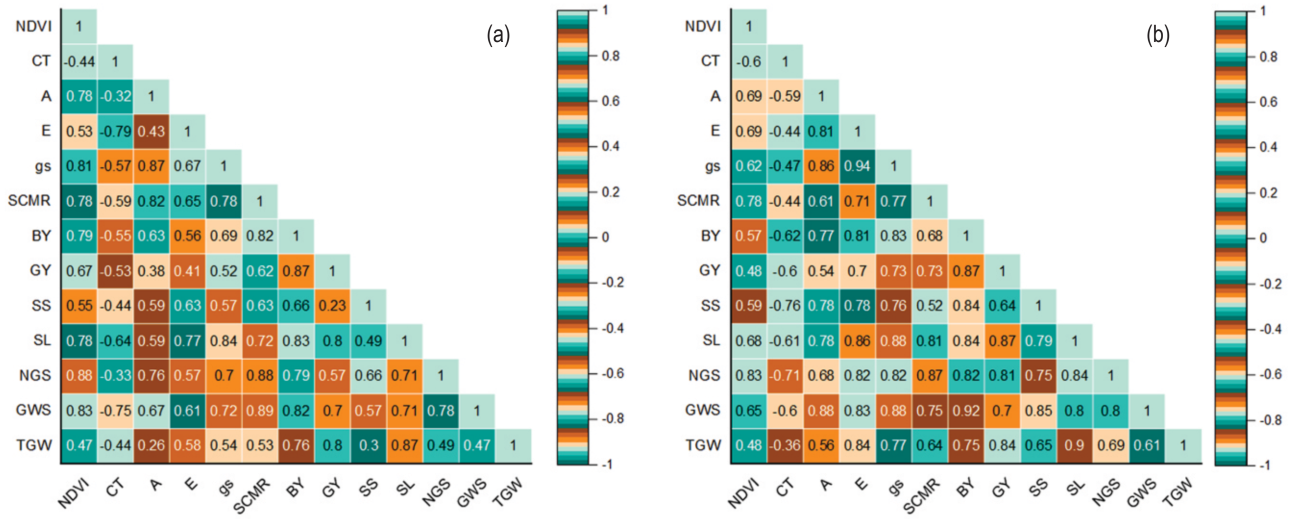


**Fig. 2:** Heat maps of different physiological traits at anthesis under TS condition (a), LS condition (b) and yield and its components under TS condition (c) and LS condition (d). The dendrogram represents a hierarchical clustering analysis (Euclidean distances) of the difference between genotypes.



(a)

| | NDVI | CT | A | E | gs | SCMR | BY | GY | SS | SL | NGS | GWS | TGW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NDVI | 1 | | | | | | | | | | | | |
| CT | -0.44 | 1 | | | | | | | | | | | |
| A | 0.78 | -0.32 | 1 | | | | | | | | | | |
| E | 0.53 | -0.79 | 0.43 | 1 | | | | | | | | | |
| gs | 0.81 | -0.57 | 0.87 | 0.67 | 1 | | | | | | | | |
| SCMR | 0.78 | -0.59 | 0.82 | 0.65 | 0.78 | 1 | | | | | | | |
| BY | 0.79 | -0.55 | 0.63 | 0.56 | 0.69 | 0.82 | 1 | | | | | | |
| GY | 0.67 | -0.53 | 0.38 | 0.41 | 0.52 | 0.62 | 0.87 | 1 | | | | | |
| SS | 0.55 | -0.44 | 0.59 | 0.63 | 0.57 | 0.63 | 0.66 | 0.23 | 1 | | | | |
| SL | 0.78 | -0.64 | 0.59 | 0.77 | 0.84 | 0.72 | 0.83 | 0.8 | 0.49 | 1 | | | |
| NGS | 0.88 | -0.33 | 0.76 | 0.57 | 0.7 | 0.88 | 0.79 | 0.57 | 0.66 | 0.71 | 1 | | |
| GWS | 0.83 | -0.75 | 0.67 | 0.61 | 0.72 | 0.89 | 0.82 | 0.7 | 0.57 | 0.71 | 0.78 | 1 | |
| TGW | 0.47 | -0.44 | 0.26 | 0.58 | 0.54 | 0.53 | 0.76 | 0.8 | 0.3 | 0.87 | 0.49 | 0.47 | 1 |

(b)

| | NDVI | CT | A | E | gs | SCMR | BY | GY | SS | SL | NGS | GWS | TGW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NDVI | 1 | | | | | | | | | | | | |
| CT | -0.6 | 1 | | | | | | | | | | | |
| A | 0.69 | -0.59 | 1 | | | | | | | | | | |
| E | 0.69 | -0.44 | 0.81 | 1 | | | | | | | | | |
| gs | 0.62 | -0.47 | 0.86 | 0.94 | 1 | | | | | | | | |
| SCMR | 0.78 | -0.44 | 0.61 | 0.71 | 0.77 | 1 | | | | | | | |
| BY | 0.57 | -0.62 | 0.77 | 0.81 | 0.83 | 0.68 | 1 | | | | | | |
| GY | 0.48 | -0.6 | 0.54 | 0.7 | 0.73 | 0.73 | 0.87 | 1 | | | | | |
| SS | 0.59 | -0.76 | 0.78 | 0.78 | 0.76 | 0.52 | 0.84 | 0.64 | 1 | | | | |
| SL | 0.68 | -0.61 | 0.78 | 0.86 | 0.88 | 0.81 | 0.84 | 0.87 | 0.79 | 1 | | | |
| NGS | 0.83 | -0.71 | 0.68 | 0.82 | 0.82 | 0.87 | 0.82 | 0.81 | 0.75 | 0.84 | 1 | | |
| GWS | 0.65 | -0.6 | 0.88 | 0.83 | 0.88 | 0.75 | 0.92 | 0.7 | 0.85 | 0.8 | 0.8 | 1 | |
| TGW | 0.48 | -0.36 | 0.56 | 0.84 | 0.77 | 0.64 | 0.75 | 0.84 | 0.65 | 0.9 | 0.69 | 0.61 | 1 |

**Fig. 3:** Correlation among studied physiological and yield components. (a) Correlation among studied physiological and yield components under TS condition and (b) Correlation among studied physiological and yield components under LS condition.

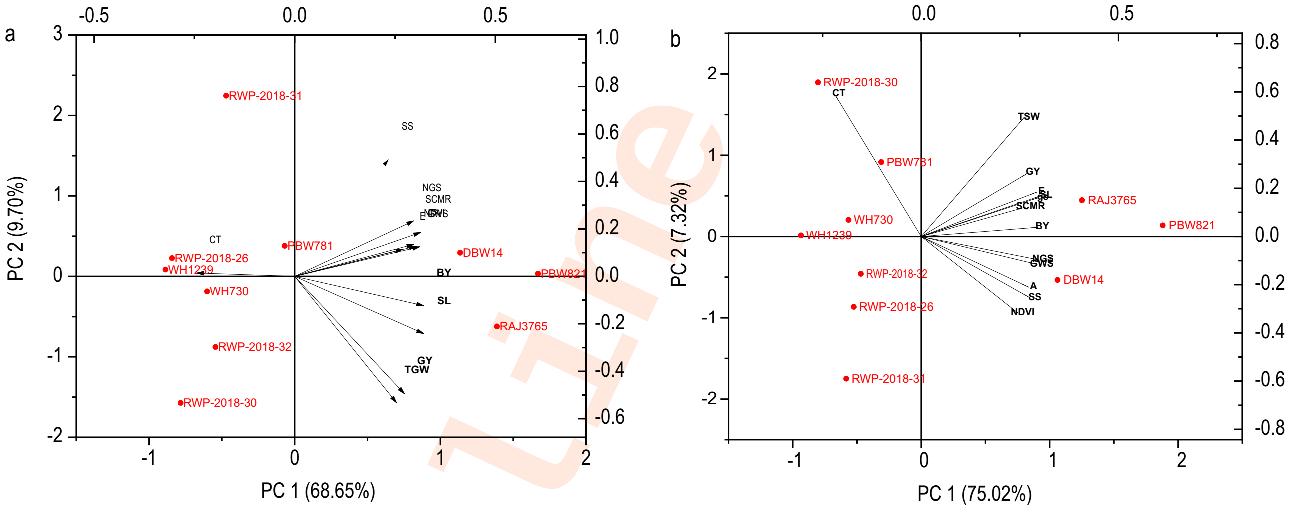


**Fig. 4:** Principle Component Analysis (PCA) at anthesis under TS condition (a) and LS condition (b) of different physiological and yield traits (arrow) and wheat genotypes (points). Genotypes are dispersed in different in ordinate based on dissimilarity among them. The magnitude of vectors (lines) shows strength of their contribution to each PCA. The angle between the vectors derived from the middle point of bioplot exhibit positive or negative interaction of studied trait. The close variable (vector) forming acute angle represents a highly positive relation among them.

**Correlation of physiological and yield attributes:** Under TS condition, NDVI showed a strong positive correlation with A, gs, SCMR, BY,SL,NGS and GWS whereas under LS condition it showed positive correlation with SCMR and NGS. Canopy Temperature (CT) showed negative relation with all other traits under both TS and LS conditions. Photosynthetic rate (A) showed strong association with gs, SCMR and NGS in TS and with E, gs, BY, SS, SL and GWS in LS condition. Transpiration Rate (E) had a positive relation with SL in TS and with gs, SCMR, GY, BY, SS, SL, NGS, GWS and TWS in LS. Stomatal conductance (gs) was related with SCMR, SL, NGS and GWS in TS and in LS with SCMR, BY, GY, SS, SL, NGS, GWS and TGW. SCMR was positively correlated with BY, NGS and GWS in TS and with SL, GY, GWS and NGS (Fig. 3a, 3b). The results of principle component analysis demonstrated that in TS condition first two PCAs had Eigen value greater than one. PCA 1 and PCA 2 contributed 68.65 % and 9.70 % to variation. PCA 1 principally combines SL, GY and TGW whereas PC2 is composed NGS, SCMR, NDVI, A, E, gs and CT. Three major groups were projected, the first group composed of traits gs,

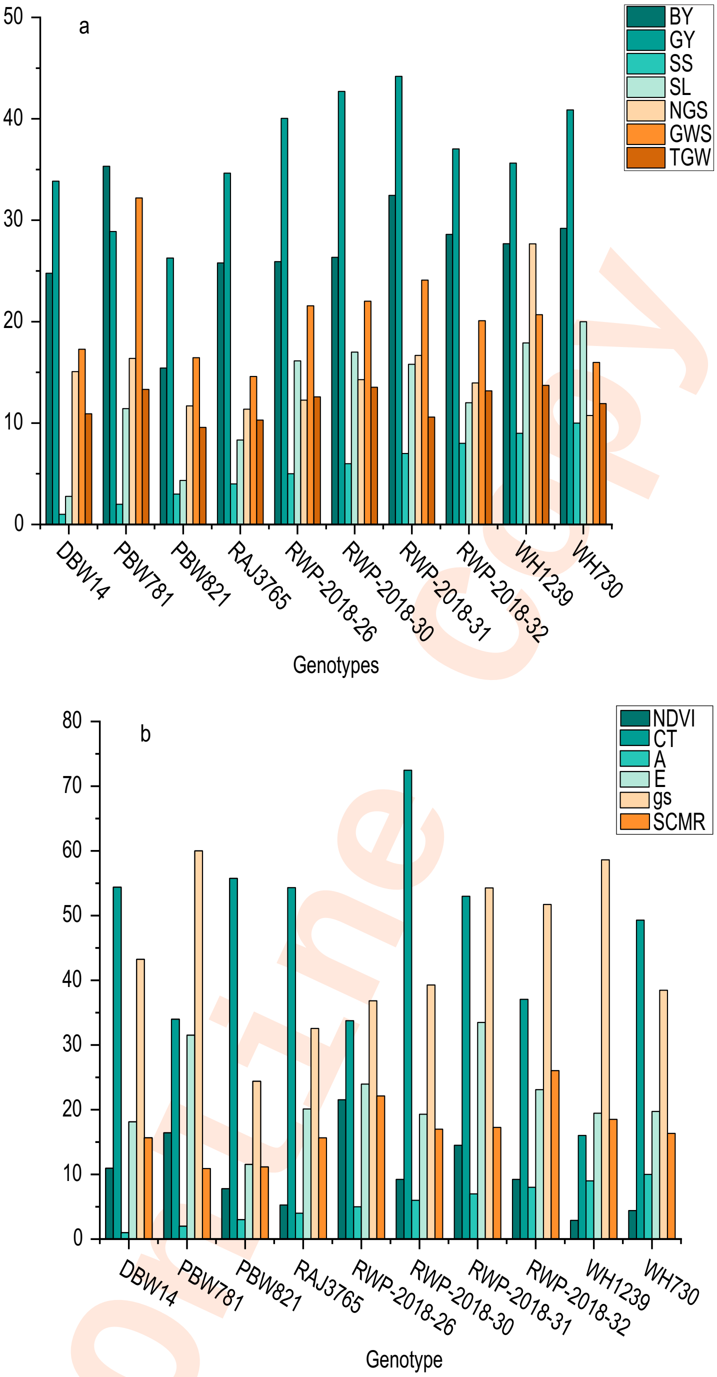


**Fig. 5:** Percentage change in physiological traits (a) and yield and its components (b) of wheat genotypes under TS and LS conditions.

NDVI and E, the second group combined BY and SL, and the last group had GY and TGW. The traits were positioned maintaining an acute angle among themselves, showing their positive relation whereas CT forms an obtuse angle showing a negative relation with all the parameters. Under LS condition, only first PCA had Eigen value greater than one. The two PCAs, PCA1 and 2 contributed 75.02% and 7.32 %, respectively. Like in TS condition, PCA 1 principally combined NGS, GWS, A, SS and NDVI whereas PC2 is only composed of BY, SCMR, E, GY, TGW and CT. Two major groups were projected. First group composed of NDVI, SS, A, GWS and NGS, second group composed of GY, E, SCMR and E. they showed as strong positive association whereas CT showed negative association in LS condition also (Fig 4a, 4b).

The percent change in wheat genotype PBW 821 showed a minimum reduction in A (21.7%), E (11.5%),gs(24.4%), BY (15.4%), GY (26.3%), SS (5.0%), SL (4.3%) and TGW (10.8%). WH 1239 showed minimum reduction in NDVI (2.9%) and minimum increase in CT (16.0%). Minimum reduction in NGS (14.6%), GWS (9.6%) was observed in genotype WH 730 and Raj 3765 (Fig. 5a, 5b). Bahar *et al.* (2009) and Sabagh *et al.* (2017) reported positive correlation of stomatal conductance with grain yield, grain numbers per spike, spike yield and spike length. Singh *et al.* (2017) reported higher stomatal conductance in high-temperature condition as compared to ambient condition. Reduction in spike length, number of spikelets per spike, grain weight per spike, number of grains per spike, biomass, grain yield and 1000 grain weight under LS condition as compared to TS condition (Table 2) corroborates with the results of many previous studies (Modarresi *et al.,* 2010; Islam *et al.,* 2018; Irfan *et al.,* 2018; Jaiswal *et al.,* 2018). High-temperature stress affects growth phases of wheat by accelerating floral initiation, reducing spike development period, shorting spike due to lower number of spikelets, and adverse pollen development (Ayeneh *et al.,* 2002; Wahid *et al.,* 2007; Mitra and Bhatia, 2008).

Reduced test weight, individual seed size and seed weight are the product of accumulative effects of all metabolic processes under LS condition (Dias *et al*., 2008; Pooja *et al*., 2017). Yield traits are considered as an important component for increasing the yield, which can be achieved by manipulating the yield traits like grains/spike, spike length and spikelet/spike. During stress condition, reduction in food reserve (Sinclair and Jamieson, 2006), production of sterile tillers (Duggan, 2005), increase in pollen abortion (Ji *et al.,* 2010), ultimately reduces crop yield. Intensity and duration of stress decides the reduction in the yield traits (Barnabás *et al.,* 2008). However, the impact of high-temperature stress on crops depends upon the intensity, duration of stress and stage of crop development (Wahid *et al.,* 2007; Djanaguiraman and Prasad, 2010).

A significant impact of heat stress was observed as the grain yield reduced under heat stress condition. All the traits under study showed significant variation under TS and LS conditions. Wheat genotype PBW821 was identified as thermo-tolerant on the basis of high photosynthetic rate, cell membrane stability and yield and its attributes under late sown condition. The present study has showed that physiological traits NDVI and canopy temperature were associated with grain yield, wheat genotype, which was identified as heat tolerant would form an important resource for the development of high yielding varieties under high temperature conditions.

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