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Thermal requirements of wheat (*Triticum aestivum* L.) cultivars under different growing environments

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Abstract
Global warming is changing climate in term of increased frequency of extreme weather events as well as increased air temperature and vapour pressure deficit of air and spatial and temporal change in rainfall. The immediate adverse impact of climate change would be decline in production and productivity of wheat grown in subtropical and tropical region of the world. The paper reviews the current state of knowledge on thermal requirements of wheat (*Triticum Aestivum* L.) under different growing environments. The review identifies research gaps and suggested temperature plays significant role in physiological, chemical and biological processes of plants. The occurrence of different phenological events during a growing season of crop and the effect of temperature on plant growth can be explained using accrued heat units. Growing degree days are based on the concept that the real time to attain a phenological stage is linearly related to temperature in the range between base temperature and optimum temperature. The heat unit concept assumes that a direct and linear relationship between growth and temperature is advantageous for the assessment of yield potential of a crop in different weather conditions. The duration of each phenophase determines the accumulation and partitioning of dry matter in different parts as well as crop responses to environmental and external factors.

Keywords: Thermal requirements, wheat (*Triticum aestivum* l.), different growing environments

Introduction
Wheat is a thermo-sensitive long-day crop. Temperature is a major determinant of its growth and productivity. Late sown wheat in rice-wheat system exposes preanthesis phenological events to high temperature that influence grain development and ultimately the yield (Nagarajan *et al.*, 2008) [28]. Phenological development from sowing to maturity is related to accumulation of heat or temperature units above threshold or base temperature (below which no growth occurs). A quantified value of heat or temperature units is required to reach a particular phenophase. The various meteorological factors such as temperature influence the physiological and morphological development of plant. During growth and development of a cereal crop several growth stages are distinguishable in which important physiological processes occur (Sikder, 2008) [50].
It is well known fact that there is a definite temperature requirement by plants to attain certain phenological stages. Several research findings noticed that temperature below (<10 °C) or above (>25 °C) the optimum (12-25 °C) alter phenology, growth and development and finally reduce the yield of wheat varieties (Hakim *et al.*, 2012) [14]. Influence of temperature on phenology and yield of crop plants can be studied under field condition through accumulated heat units system (Bishnoi *et al.*, 1995) [9]. The reduction in the duration of later growth under late sowing caused by severe temperature stress which resulted in acquision of fewer days to sowing and maturity dates of crops can be predicted by applying heat unit concept through correlating its phenological developments (Mills, 1964, Nuttonson, 1955) [29]. Air temperature based agromet indices, viz., growing degree days (GDD), photothermal units (PTU) (Esfandiary *et al.*, 2009, Bazgeer *et al.* 2008 and Khichar and Niwas, 2007) [10, 7, 21], heliothermal units (HTU), Phenothermal index (PTI) have been used to describe changes in phenological behavior and growth parameters (Kumar *et al.*, 2010) [23]. The values of accumulated GDD, HTU and PTU for each phenophases are relatively constant and independent of sowing date but vary in a crop from variety to variety (Phadnawis and Saini, 1992) [36, 27]. Agronomic application of temperature effect on plant is the concept of heat unit or growing degree days and heat stress in wheat can be mitigated in two ways: heat management or the development of heat-tolerant

cultivars. Evaluation of high yielding, stable genotypes having good quality are considered pre-requisite for increasing crop production in any region. So there is a need to broader genetic base and to replace old varieties with new and improved ones (Jat *et al.,* 2003) [17]. Recommendation of several varieties will also help farmers to select best one and also adequate supply of improved varieties to farmers.

Phenological development

Temperature is an important weather parameter that affects plant growth, development and yield. Winter crops are vulnerable to high temperature during reproductive stages and differential response of temperature change (rise) to various crops has been noticed under different production environments (Kalra *et al.,* 2008) [19]. (Hundal, 2004) [16] observed that a 2^0C increase in temperature in wheat or rice resulted in 15-17 percent decrease in grain yield of both crops but beyond that the decrease was very high in wheat. Cool weather during vegetative period and warm weather during maturity are ideal requirements for wheat (Mavi, 1986) [26]. (Jhanji and Gill, 2011) [18] stated that the days for attainment of different phenological stage differed significantly between the two cultivars. The timely sown cultivar, PBW -343 took 4 days for seedling emergence, 16 days for CRI, 95 days for leaf development, 68 days for tillering, 51 days for stem elongation, 112 days for booting, 120 days for heading, 125 days for anthesis, 131 days for grain development and 163 days for maturity, whereas for WH-542 the respective growth duration were 4,15,80,65,42,109,117,124,129,and 161days with delay in sowing, there was decrease in the requirement of days for attaining different phenological stages of growth for both the cultivars. The late sown PBW-343 took more days for attaining all the phenological stage of growth than WH-542. (Singh *et al.,* 2001) [61] and (Ghosh *et al.,* 2000) [12] also reported that low temperature at the early vegetative phase and high temperature at the reproductive phase of wheat due to late sowing reduced the number of days for attaining different phenological stages. (Ram *et al.,* 2012) [39] reported higher GDD requirement for wheat crop for normal sowing conditions than the later growing conditions. Late sowing decreased the duration of phenology as compared to normal sowing due to fluctuated unfavorable high temperature during the growing period.

Growing degree days (GDD)

GDD requirement of different phenophases of wheat with two genotypes viz. PBW-343 and WH-542 as influenced by three sowing dates viz. 20 November, 15 December and 09 January along with three replications (Shanker *et al.,* 1996) [46]. The heat unit or GDD was proposed to explain the relationship between growth duration and temperature. This concept assumes a direct and linear relationship between growth and temperature (Nuttonson, 1955) [29]. (Amrawat *et al.,* 2013) [5] Show that the MP-1203 registered maximum accumulated GDD (1637°C day) followed by Raj 4037 (1569°C day) and HI-1544 (1539°C day). According to (Jhanji and Gill, 2011) [18] the cultivar PBW-343 took more heat units at all the phenological stage as compared to WH-542. The GDD values in PBW- 343 were 1880, 1622 and 1583 respectively, for attaining maturity, compared with 1748, 1560 and 1457 for WH-542. The requirement of heat unit was higher for timely sown crop than late sown crop due to longer period for all the phenological stages in the timely sown crop. A progressive delay in sowing decreased the duration of phenophases which caused a decrease in accumulation of GDD during various phenophases and forced the crop to attain maturity. This decline in GDD accumulation was due to prevailing low temperature during vegetative phases and high temperature during reproductive phases of development in late sown crop (Khichar and Niwas, 2007) [21]. The cultivar PBW-542 for their longer phenological stages. (Paul and Sarker, 2000) [35] and (Sandhu *et al.,* 1999) [43] also reported that the requirement of heat units decreased for different phenological stages with delay in sowing.

(Pal and Murty, 2009) [30] recorded that the higher GDD was recorded with 20^{th} November sowing followed by 15^{th} December sowing at almost all the phenophases of wheat, while the lowest GDD was obtained with sowing done on 09^{th} January in both the years. At maturity stage, higher GDD was recorded in case of genotype PBW-343 followed by genotype WH-542 among all the sowing dates tried. In 2007-08 maximum GDD (1601.35) was recorded for PBW-343 followed by WH-542 (1548.80) on 20^{th} November sowing. Also, similar results were found for 2008-09 that GDD decreased with late sowing for all the genotypes in both the years. Decreased heat units requirement with delay in sowing were also reported by (Rajput *et al.,* 1987, Agrawal *et al.,* 1999 and Singh *et al.,* 2008) [38, 1].

(Sourour et al., 2016) reported the differences in GDD to attain heading were noted for used genotypes. According to results, the heading date could be successfully predicted using GDD accumulated. This approach of GDD accumulation has also been reported by others studies in wheat (Anjum *et al.,* 2014) [14] and other crops (Snyder *et al.,* 1999; Ruml *et al.,* 2010) [55, 41]. According (Salazar et al., 2013) differential response of genotypes for winter wheat was reported and the average GDD requirement from planting to heading was 2705°C. According to (Zhang *et al.,* 2009) [59] heading dates are affected by genetics and environmental conditions. A strong interaction between genetics and the temperature occurs when the crop is exposed to low temperatures during vegetative and reproductive development, which is affected by sowing dates, seeding rate, fertilizer applications, irrigation and fluctuations in short term weather and long-term climate conditions (Hu *et al.,* 2005) [15]. In fact, the heat unit system or growing degree days (GDDs) shows a direct and linear relationship among plant growth and temperature (Parthasarathi *et al.,* 2013) [34]. These authors found that same cultivar showed similar phenology and have similar heading dates independent of the growing season. In contrast, changes in the heading date would indicate changes in temperatures, particularly during spring. Early sowing dates result on higher heat units as GDD than late sowing dates. Every crop needs a specific amount of GDD to start reproductive phase from vegetative phase. Similar results were observed by (Amrawat *et al.,* 2013) [5]. (Pandey *et al.,* 2010) [33] also reported lower consumption of heat units under delayed sowing. Heat tolerant wheat cultivars had greater growing degree day (GDD) and heat use efficiency than sensitive (HUE) cultivars (Sikder, 2009) [49].

(Ahmed and Farooq, 2013) observed that the early sown wheat has availed the longest period for completion of phenological stages and thus attained maximum values for GDD and it appeared to be reduced with subsequent delayed sowing. The highest GDD for maturity (1715) were recorded for Chakwal-50 and lowest (1432) for NR-268. The results were similar to those of (Pal *et al.,* 1996) who reported that GDD requirement were dependent on genetic constitution. The results were contradictory to the findings of (Phadnawis and Saini, 1992) [36, 37], they observed independence of accumulation of growing degree days to sowing dates but cultivars might modify it. (Yajam and Madani, 2013) revealed that the accumulation of maximum GDD (2236 GDD) were recorded for early sowing date (23th September) and it decreased to (1398 GDD) for late sowing. The 11th December sowing date accounted for lowest GDD (1398) from sowing to maturity stage.

Pheno-thermal index (PTI)

(Jhanji and Gill, 2011) [18] reported that the cultivar PBW-343 had the highest PTI (14.01) at grain filling to maturity of late sown crop. There was variation in PTI up to tillering stage in both the cultivars under D_1, D_2 and D_3. But thereafter, late-sown crop showed PTI compared to timely sown crop. Thus, the trend of duration and GDD supported the values of PTI under all dates of sowing (Rajput *et al.,* 1987) [38]. (Pal and Murty, 2009) [30] Suggested that the phenol thermal index mostly decreased till jointing to 50% flowering stage during all the sowing dates and genotypes in both the years. Maximum PTI (13.31-22.51 in 2007-08 and 17.46-24.43 in 2008-09) was recorded during maturity stage. In the year 2007-08, among the sowing dates, maximum PTI (22.51) was recorded at 09th January sowing for the genotype PBW-343 followed WH542 (21.34). Also similar results were found in the year 2008-09; maximum PTI (24.43) was recorded for PBW-343 followed by WH-542 (22.94) on 09th January sowing. (Kumari *et al.,* 2009) [24] Also reported similar results. Differences between durum wheat varieties for PTI were noted by (Sourour *et al.,* 2016) [56]. (Gill *et al.*, 2014) [13 found that the phenol thermal index (PTI) is affected by the growing environment and cultivars. Same authors reported also that temperature increases physiological activities which results a higher grain yield. According to these results, genotypes with low value of PTI and high value of HUE showed more important yield, which strengthened the previous deduction of (Pal and Murty, 2010) [30].

Photothermal units (PTU)

(Sharma *et al.,* 2003) reported that the phenophases cumulative values of photothermal unit (PTU) were higher in crop sown on 25th November as compared to 10th December and 25th December sown crop. Values of photothermal unit (PTU) at maturity were 16212.4±510, 15915.9±480 and 14249.5±370ºC day's hours. Among the cultivars PBW 343 required more PTU at all the phenophases as compared to other cultivars. Similar result was carried out by (Singh, 1981) under different environmental conditions. (Amrawat *et al.,* 2013) [5] show that the varieties sown on 5th November required maximum PTU till maturity which was superior over 20th November, 5th and 20th December sown crop at all stages. MP-1203 requires maximum PTU at flag leaf, heading and milking stage which was significantly superior over HI-1544 and Raj 4037. The higher PTU value in early sown crop may be due to fact that crop took longer duration to reach phenological stages.

Helio thermal units (HTU)

(Amrawat *et al.,* 2013) [5] Show that the accumulated Helio thermal units required to attain different phenological stages of wheat varieties are shows that the highest Helio thermal unit 14440°C day hours were required for maturity in MP-1203 when sown on 5th November. Variety HI-1544 and Raj-4037 also required more helio thermal units for attaining maturity under 5th November sown crop as compared to delay sowing. This might be due to delayed maturity in early sown as compare to late sown wheat crop. It was reported that HTU for different phenological stages decreased with delay in sowing (Masoni *et al.,* 1990) [25]. (Gill *et al.,* 2014) [14] observed that the HTU requirement was maximum in November 15 sowing among the sowing dates and decreased with delay in sowing followed by November 25 and December 5. The variety PBW 343 recorded more heat units as compared to variety PBW 621. The HTU accumulated by the variety PBW 343 from sowing till maturity at Ludhiana station remained 9552.71, 9650.94 and 9270.59 and for variety PBW 621 9075.39, 9225.93 and 9039.31 HTU units were recorded for November 15, November 25 and December 5 respectively.

Heat use efficiency (HUE)

The timely sown crop used heat more efficiently than late sown crop. The timely sown crop of the cultivar PBW-343 had significantly higher HUE (3.16) than WH-542 (3.10). The HUE of both cultivars decreased significantly with delay in sowing. These reductions were 3.16, to 2.55 to 1.62 for PBW-343 and from 3.10 to 2.53 to 1.57 for WH-542, respectively (Jhanji and Gill, 2011) [18]. Amongst the date of sowing, timely sown wheat crop (20th November) exhibited maximum HUE of (2.93 kg grain ha^{-1}deg. $days^{-1}$) for the genotype PBW-343 followed by WH-542 (2.89 kg grain ha^{-1} deg. $days^{-1}$) in both the years (Pal and Murty, 2009) [30]. (Sourour *et al.,* 2016) reported the differential behavior of durum wheat genotypes for HUE could be attributed to their genetic potential (Bhat *et al.,* 2015; Sattar *et al.,* 2015) [8, 24]. Heat use efficiency (HUE) quantification is necessary for a crop yield potential assessment in different growing conditions (Pal and Murty, 2010) [31]. (Kingra and Kaur, 2012) [22] Reported that HUE affects dry matter accumulation and depends on genetic factors and practical application. (Rani *et al.,* 2012) [40] Reported that the heat and radiation use efficiencies decreased with delay in sowing. (Amrawat *et al.,* 2013) [5] Show that the highest HUE for total dry matter (10.2 kg ha^{-1}°C days) as well as grain yields (3.4 kg ha^{-1}°C^{-1} days) was recorded under 20th November sown crop. With respect to varieties, however, maximum HUE for grain yield was recorded in variety HI-1544 and Raj-4037 and lowest HUE was recorded in variety MP-1203. The higher HUE in 20th November sown crop could be ascribed by proportionate increasing dry matter per each heat unit absorbed. The results are in close agreement with those of (Pandey *et al.,* 2010) [33].

Grain yield

(Amrawat *et al.,* 2013) [5] Show that the crop sown on 5th November recorded the highest grain (64.86 q ha^{-1}) and straw (108.84 q ha^{-1}) yield which was statistically at par with 20th November sowing, but significantly higher than recorded in late sowing dates. It might be due to higher GDD, PTU, and days taken to attain physiological maturity stage in these sowing dates. The grain yield was significantly influenced by different varieties and all varieties were noticed significant difference to each other. The highest grain yield was produced by Raj-4037 (62.81 q ha^{-1}) followed by HI- 1544 (58.75 q ha^{-1}) and MP-1203 (50.32 q ha^{-1}). High yield of Raj-4037 may be attributed to its higher biomass accumulation and due to genetic potential difference. Delayed sowing hastened the crop phenological development, thereby causing significant reduction in wheat yields (Singh and Paul, 2003) [51]. (Kaur *et al.,* 2010) and (Pandey *et al.,* 2010) [33] also reported the similar observation under delayed sowing. The detrimental effect of heat at a later stage of crop development and earing in delayed sowing had an adverse effect on grain yield. (Wardlaw and Wringley, 1994) reported 3 to 4% decrease in grain yield for each 1°C rise in ambient temperature above 15°C during grain filling. The grain yield is the sum total of different yield contributing factors controlled both genetically and environmentally (Shirpurkar *et al.*, 2008). Since wheat yield formation is a complex process and interaction governed by the complimentary interaction between source (photosynthesis and availability of assimilates) and sink component (storage organs). Correlation values were observed between yield and meteorological indices reinforcing the previous observed relationship found by (Ganajaxi *et al.*, 2001) and (Shamim *et al.*, 2013). However, (Al-Karaki, 2012) showed that grain yield was positively correlated with GDD to heading. In this context, (Amrawat *et al.*, 2013) [5] reported that long growth duration provides for plant an opportunity to accumulate maximum of biomass. (Pal and Murty, 2009) [30] observed that timely sown wheat crop (20th November) with an average seasonal air temperature of 16.3 ^{O}C produced highest yield of (4691.53 kg ha^{-1}) in 2007-08 and (4191.53 kg ha^{-1}) in 2008-09 with an average seasonal air temperature of 17.9 ^{O}C. With every 25 days delay in sowings an increase in average seasonal air temperature (17 to 18.6 ^{O}C) caused reduction in yield by 13 to 26 percent in the year 2007-08, whereas in 2008-09 an increase in average seasonal air temperature (18.8 to 20.4 ^{O}C) caused reduction in yield by 15to29 percent. (Jhanji and Gill, 2011) [18] reported that the highest yield was obtained under early sowing but thereafter it showed a significant reduction with each delay in sowing from D_1 to D_2 for both cultivars. PBW-343 yielded (0.59 t ha^{-1}) under D_1 and the yield decreased to (0.4 t ha^{-1}) under D_2 and (0.25 tha^{-1}) under D_3. On the other hand WH-542 yielded (0.54 t ha^{-1}) under D_1 and the yield decreased to (0.39 t ha^{-1}) under D_2 and (0.23 t ha^{-1}) under D_3. The rate of decline with first delay in sowing from D_1 to D_2 was relatively smaller (28.8%) but thereafter it was sharper (40.4%). (Akhtar *et al.*, 2006) also found that the late sown crop had lower grain yield than timely sown crop as late sown crop got exposure to high temperature during reproductive phase.

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