



Effects of Sowing Dates on Wheat Phenology, Thermal Indices, Heat Use Efficiency, and Grain Yield under Rising Temperature Conditions

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Abstract

Climate change has significantly altered wheat phenology and productivity, necessitating effective adaptation strategies to sustain crop production. This study evaluated the influence of different sowing dates on wheat phenological development, thermal indices, heat use efficiency, and grain yield under changing climatic conditions, supported by an analysis of long-term temperature trends. Field experiments were conducted using three sowing dates: 20 November (SD1), 30 November (SD2), and 10 December (SD3). Phenological observations were used to estimate growing degree days, photothermal index (PTI), and heat use efficiency (HUE), while long-term climatic records were analyzed to assess decadal warming trends and their implications for wheat production. The results showed that PTI decreased during the early growth stages (germination to tillering) but increased from tillering to flowering across all sowing dates. The highest grain heat use efficiency ($4.74 \text{ kg ha}^{-1} \text{ }^{\circ}\text{C}^{-1} \text{ day}^{-1}$) was recorded under SD2, followed by SD3 ($4.08 \text{ kg ha}^{-1} \text{ }^{\circ}\text{C}^{-1} \text{ day}^{-1}$) and SD1 ($2.79 \text{ kg ha}^{-1} \text{ }^{\circ}\text{C}^{-1} \text{ day}^{-1}$). Grain yield was significantly affected by sowing date, with the maximum yield ($13,982 \text{ kg ha}^{-1}$) obtained under SD2, declining significantly to $12,029 \text{ kg ha}^{-1}$ under SD3. These findings indicate that optimizing sowing time is an effective adaptation strategy for mitigating the adverse effects of rising temperatures on wheat phenology and productivity. Based on the present study, sowing around 30 November is recommended to improve thermal use efficiency and maximize grain yield under warming climatic conditions.

1. Introduction

Intergovernmental Panel on Climate Change (IPCC) reported that global warming will continue to increase in the coming years. It has been predicted that global warming is likely to reach 1.5°C above pre-industrial levels by the early 2030s and the severity of the warming after that depends on the emissions in the coming decades (IPCC, 2023). In addition to this the IPCC latest report stated that last decade (2010-2019) was decade of climate extreme events as world have seen rise in temperature, changes in rainfall and largest ever increase in global greenhouse gas emissions (Aslam et al., 2017; Fatima et al., 2020).

Climate change is a significant threat to agricultural productivity at the global, regional, and local scales (Ahmad et al., 2015; Abbas et al., 2017; Liu et al., 2018). The decade of the 2000s was the warmest on record, and 2016 was the hottest year ever. Over the last three decades, the temperature has risen by 0.78 to 1.5°C and by the end of this century, it will be increasing by 2 to 4°C as per projection (Bokhari et al., 2017; Abbas et al., 2017). This increase in temperature will have significant effect on agriculture, especially in arid and semi-arid regions (Tariq et al., 2018). The agriculture sector is highly vulnerable to climate change as it is directly affected by the anthropogenic impacts of

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global warming. The phenology and yield of important crops have been impacted by undeniable global warming since the 1950s (Field and Barros, 2014; Liu et al., 2017; Lobell and Field, 2007; Shi et al., 2013). Phenology, which is defined as the duration of a plant's life cycle events (Porter and Gawith, 1999; Stucky et al., 2018), is crucial in determining how plants divide their biomass to various parts and ultimately, their yield (Asseng et al., 2013; Brisson et al., 2010). Ritchie (1991) found that changes in crop growing season temperature have the greatest impact on phenology.

The growth stages of wheat crop may be exposed to an unknown climatic condition due to the advanced or delayed phenological phases as reported by (Visser and Both, 2005). Thus, phenology of crops may be used as a background to reveal how successfully a given species is to cope with climate change (Khan et al., 2021 and Tao et al., 2022). Changes in temperature have been observed to have impact on phenology regardless of geography or cultivar and it was stated that changes in temperature related phenology mean reduction final yield (Menzel et al., 2020). Global warming has resulted into alteration of phenophase of crops all over the world (Ahmad et al., 2017). In the course of the growing season, the general wheat temperature increases by 1°C will lead to the decrease in yield by 6% based on the studies by: Aslam et al., 2017; Asseng et al., 2015; Yang et al., 2017. In view of this, the yield and phenology of the wheat crop in particular have been realized to be directly affected by the recent global increase in temperature. In this regard, a warmer setting impacts crop yields and improves crop phenology as identified by Fatima et al. (2020) and Tao et al. (2006). Warming resulted to the shrinking of growing season, promoted leaf aging/senescence and reductions in biomass and yield (Song et al., 2019).

GDD is an agro meteorological index that has been developed on the basics of temperature and which has been used to describe changes in growth parameters and phenological trends. The values of accumulated GDD differ from one cultivar to another in wheat crop and are not significantly affected by the Sowing date for each phenology stage (Aslam et al., Accessed 2017). Regarding wheat crop, the right temperature for anthesis and grain filling is between 12 °C and 22 °C. Wheat exposure to temperatures above 30 °C before and after anthesis results to a decline in the grain filling rate and therefore reducing grain yield (Barnabás et al., 2008). Changing crop phenology is considered an important bio-indicator of climate change, with the recent warming trend causing an advancement in crop phenology. Little is known about the contributions of changes in sowing dates and cultivars to long-term trends in crop phenology, particularly for winter crops such as winter wheat. The phenology of crop plants affects total biomass and grain yield and is important for adaptation of individual crops and

cropping systems to environmental vagaries (Ahmed et al., 2016; Hu et al., 2005; Menzel et al., 2006; Moriondo and Bindi, 2007; Madan et al., 2012; Mueller et al., 2014; Liu et al., 2018). The environmental conditions, thermal time requirements, and crop management practices (cultivar features and transplanting/sowing dates) have a significant effect on crop phenological stages and phases (Liu et al., 2018). Matching optimum levels of weather components such as temperature and rainfall at or during critical crop growth stages is crucial for the maximum expression of the genetic potential of various cropping systems (Amin et al., 2018). With climate warming, changes in crop phenological stages and phases are reducing crop growth and development cycles and decreasing the time and rate for biomass accumulation (Figueiredo et al., 2015; Abbas et al., 2017).

A better understanding of the response of crop phenological stages and phases to changing temperatures would improve agronomic management practices and crop breeding to mitigate the effects of climate change (Abbas et al., 2017; Ahmad et al., 2015; Hoffmann and Sgro, 2011). Crop growth and development could be accelerated due to the thermal warming trend, and negative effects of warming could be minimized by sowing crops later and by introducing new cultivars with high thermal time requirements (Asseng et al., 2011; Li et al., 2014; Rezaei et al., 2015). Phenological changes in crops affect efficient agricultural production and can be used as important biological indicators of local and regional climate change. Although crop phenological changes and their responses to climate change, especially temperature, have been investigated, the impact of agronomic practice such as cultivar shifts and planted date changes on crop phenology remains unclear.

The effects of climate change such as rising temperatures affect the growth of wheat and thus climate change is a threat to food security. Addressing the negative impacts entails the use of agro-techniques, variety development for heat resistance and improved conservation and management of land and water to promote the coping capacity of wheat production systems for climate volatility and change. Based upon above circumstances it is now well documented that climate change is showing great impact on wheat phenology and yield. Hence present study was conducted with the objectives (i) to evaluate the heat unit efficiency under different sowing dates (ii) to evaluate the long-term impact of rise in temperature on wheat phenology and yield, (iii) to observe the variability in heat units and its relationship with phenology and grain yield. The outcome will suggest the farming community for optimum sowing optimum date for better wheat production under changing climate conditions.

2. Materials and Methods

2.1. Experimental Site, Climate and Soil Properties

A field experiment was conducted with objective to study the impact of sowing dates wheat crop phenology and yield. Research experiment was conducted at Research Station Department of Agronomy, Faculty of Agricultural Sciences (Figure 1). The average maximum and minimum temperature are 41.3°C and 6.7°C. The daily temperature record for crop season was presented in fig.2. Plot of 10 x 30 m was allocated for experiment as depicted in figure 2.

2.2. Crop Management Practices

The experiment was run from November 20, 2023 to April 26, 2024. All agricultural processes, from clearing the land to harvesting, were carried out in compliance with the experiment's guidelines. To get the seedbed ready, the field was first irrigated with 10 cm of pre-soaking water. After utilizing a tractor-mounted cultivator to plough the ground



Figure 1. Geographical location and experimental plot layout of the study area

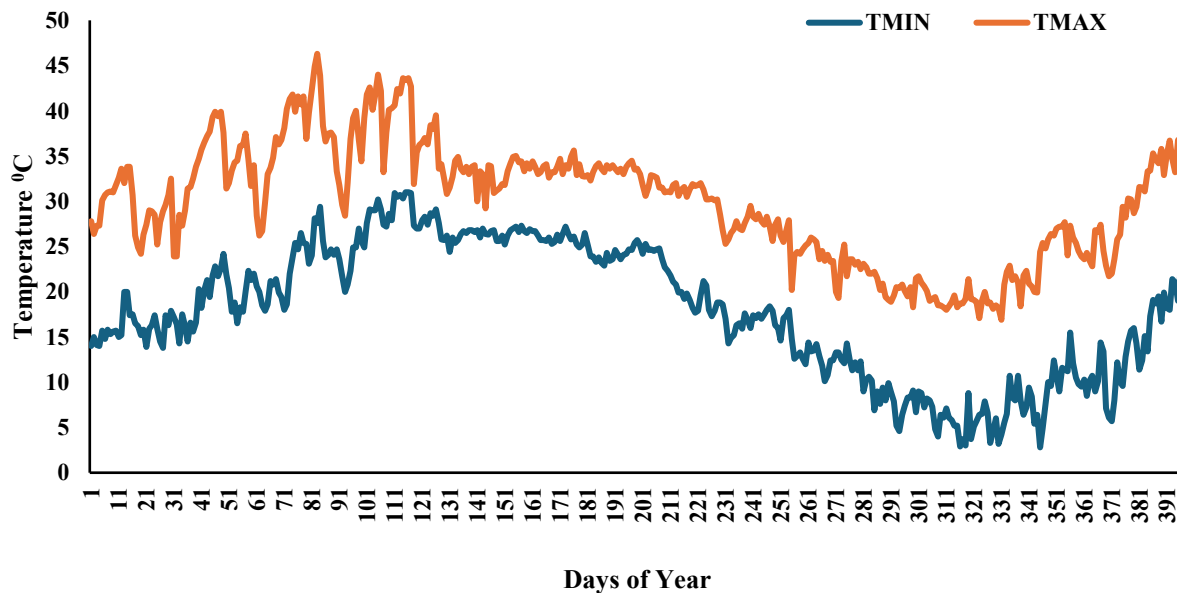


Figure 2. Temperature data during the study period

twice, planking was applied. 50 kg of seed per acre was used as the seed type for the wheat variety Akbar-2019 for this investigation. A total of 4 kg of seed was distributed across the 36 plots, or 111.15 g of seed each plot. On three separate scheduled sowing dates, the seeds were line-sown in the prepared seedbed. A basal dose of fertilizers was administered during seedbed preparation at the suggested rate of 120:90:60 kg ha⁻¹ of N, P₂O₅, and K₂O.

In addition to the prescribed dosages of biochar, fertilizers such as diammonium phosphate (DAP) and sulphate of potash (SOP) were used to apply half of the nitrogen and the full amounts of potassium and phosphorus. Throughout the growth season, there were five irrigations applied. On January 12, post-emergence weedicide was sprayed, and hand weeding was done to guarantee total weed elimination. Following the three distinct sowing dates, on April 22nd, 24th, and 26th 2024, wheat was physically picked from each plot when it reached maturity. A 1 ft² patch was randomly selected from each plot to harvest the wheat. The experiment was finished by hand threshing the wheat bundles after harvesting.

2.3. Measured parameters:

Agrometeorological indicators: maximum, minimum and average daily temperatures during the plant cycle and calculation of growing degree days (GDD), phenothermal index (PTI), and heat use efficiency (HUE) which were calculated based on the following formulas:

2.3.1. Growing degree days:

Cardinal temperature concept was used to consider minimum, optimum and ceiling temperature of wheat crop which was afterwards used to calculate seasonal GDD. Wheat sowing time vary in different regions of Pakistan, but in rainfed regions it starts from 15 October. Hence GDD was calculated from 15 October to 30 April to obtain total heat units from sowing to maturity. Thus, total wheat growing season of 196 days (from 15 October to 30 April of the next year) was used in this study. The maximum temperature of 35°C was considered as ceiling temperature and days in which temperature was greater than 35°C, GDD value was considered as zero. Following equation (1) was used to calculate GDD by using 4°C as a base temperature.

$$GDD = \frac{(T_{\max} + T_{\min})}{2} - T_{\text{base}}$$

Where,

$T_{\max}$ = Daily maximum Temperature (°C)

$T_{\min}$ = Daily minimum Temperature (°C)

T_{base} = Base Temperature (4 °C)

2.2.2. Sowing dates scenarios

Based upon the recommended wheat sowing date three scenarios were developed to determine the impact of average temperature on wheat anthesis. Three scenarios include 20 November as sowing date one (SD1), 30 November (SD2), 10 December (SD3). Long-term average temperature for each sowing date scenario was determined by taking average from date of sowing to average date of anthesis. Furthermore, long-term seasonal average rainfall during vegetative and reproductive phases were used to see presence or absence of water stress under mentioned sowing dates scenarios.

2.2.3. Phenothermal index (PTI):

The temperature units accumulated for the days between the two phenological phases were used to calculate the phenothermal index (PTI) and it is expressed in active temperatures per day (degree-days) per growth day: Its calculation was based on formulas proposed by Nuttonson (1948), Chakravarty and Sastry (1983).

$$PTI = \frac{\text{GDD between two Phenological stages}}{\text{no. of days taken between two phenotypes}}$$

2.2.4. Heat use efficiency (HUE):

It was used to compare the relative performance of the cultivar in different planting periods, in relation to the utilization of heat in terms of GDD during the period of the wheat plant cycle. HUE was calculated based on the formula proposed by Sastry et al. (1985).

$$HUE = \frac{\text{Grain Yield (kg/ha)}}{\text{Accumulated heat units } ^\circ\text{C day}}$$

2.2.5. Wheat Yield Data:

Long-term (1984-2024) wheat phenology and yield data for location was collected from the Economic survey of Pakistan (Pakistan, 2022-23), FAOSTAT (Food and Nations, 2022), Agriculture Marketing Information System (<http://www.amis.pk/Agristatistics/Statistics.aspx>), previous published articles and thesis searched by using ScienceDirect, Springer and HEC repository (<http://pr.hec.gov.pk/jspui/handle/123456789/9>).

2.2.6. Daily Temperature Data:

Daily Tmax and Tmin data was collected from Pakistan Metrological Department (PMD) from 1984-2024. Data was further subdivided to see seasonal trend during wheat growing period. Furthermore, average temperature pre anthesis and prematurity were calculated to see trend in the terminal heat stress before flowering and maturity. Base line values for days to anthesis (DTA) and days to maturity (DTM) were obtained by averaging the long-term DTA and DTM data for study sites. Similarly long-term average

temperature and rainfall were also calculated to observe the variability in temperature and rainfall.

2.3. Statistical Analysis:

The linear regression analysis was conducted to evaluate the agro-climate parameters, phenology, and grain yield variability during (1984-2024). Furthermore, Pearson correlation was calculated to observe the impact of agro-metrological parameters on wheat phenology and grain yield. Descriptive statistics were applied to see the relationship between crop phenology, yield and climatic variables.

3. Results

3.1. Effect of Sowing Time on Phenology

Sowing date significantly influenced the phenological development of wheat (Table 1). The crop sown on 20 November reached tillering on 12 December 2023, anthesis on 15 January 2024, and maturity on 21 February 2024, while harvesting was completed on 22 April 2024. Delayed sowing progressively shifted all developmental stages. Wheat planted on 30 November reached tillering, anthesis, and maturity on 22 December 2023, 18 January 2024, and 22 February 2024, respectively, whereas the crop sown on 10 December attained these stages on 1 January 2024, 4 February 2024, and 6 March 2024.

The duration from sowing to maturity was longest in the 20 November planting and shortest in the 10 December planting,

indicating accelerated crop development under delayed sowing conditions.

3.2. Growing Degree Days (GDD) Requirement at Different Growth Stages

Thermal time accumulation varied considerably among sowing dates and growth stages. For the tillering stage, the highest GDD accumulation was observed in the 20 November sowing (292.68 °C days), followed by the 30 November (257.59 °C days) and 10 December sowing dates (221.32 °C days). At anthesis, the 20 November planting accumulated 322.36 °C days, whereas the 30 November and 10 December sowings accumulated 250.32 and 299.57 °C days, respectively. Similarly, GDD accumulation at maturity was highest for the 20 November sowing (373.76 °C days) and lowest for the 10 December sowing (343.54 °C days). Overall, the crop sown on 20 November required the greatest thermal accumulation to complete its developmental stages (Table 2).

3.3. Grain Yield under Different Sowing Dates

Grain yield was significantly affected by planting date (Table 3). The highest grain yield (4226.12 kg ha⁻¹) was recorded in the crop sown on 30 November. Yield declined to 3780.56 kg ha⁻¹ when sowing was delayed to 10 December. The lowest grain yield (3687.32 kg ha⁻¹) was observed in the 20 November sowing treatment. These results indicate that the 30 November sowing date provided the most favorable

Table 1. Effect of Planting Date on Phonological Stages of Wheat

Sr. no.	Sowing date	Tillering date	Anthesis date	Maturity date	Harvesting date
1	20 Nov 2023	12 Dec 2023	15 Jan 2024	21 Feb 2024	22 April 2024
2	30 Nov 2023	22 Dec 2023	18 Jan 2024	22 Feb 2024	24 April 2024
3	10 Dec 2023	1 Jan 2024	4 Feb 2024	6 Mar 2024	26 April 2024

Table 2. Requirement of GDD for different growth stages

Sr. no.	Growth stages	Sowing dates		
		20 November	30 November	10 December
1	Tillering	292.68	257.59	221.32
2	Anthesis	322.36	250.32	299.57
3	Maturity	373.76	360.39	343.54

conditions for grain production among the tested planting windows.

fluctuations were observed, the overall trend indicated a decline in rainfall relative to the long-term average, with

Table 3. Grain yield (kg/ha) under different sowing window

S. no.	Sowing date	Grain yield (kg/ha)
1	20 November	3687.32
2	30 November	4226.12
3	10 December	3780.56

3.4. Heat Use Efficiency and Photothermal Index

Heat use efficiency (HUE) differed among sowing dates. The highest HUE value ($4.741\text{ kg ha}^{-1}\text{ }^{\circ}\text{C}^{-1}\text{ day}^{-1}$) was recorded in the 30 November sowing treatment, followed by the 10 December sowing ($4.079\text{ kg ha}^{-1}\text{ }^{\circ}\text{C}^{-1}\text{ day}^{-1}$). The lowest HUE value ($2.788\text{ kg ha}^{-1}\text{ }^{\circ}\text{C}^{-1}\text{ day}^{-1}$) was observed in the 20 November sowing. The photothermal index (PTI) from tillering to anthesis ranged from 8.559 to 9.210, while PTI values from anthesis to maturity ranged from 9.836 to 10.735. The highest PTI during the anthesis-to-maturity period was recorded for the 10 December sowing treatment (Table 4).

3.5. Decadal Changes in Wheat Seasonal Temperature and Rainfall (1984–2024)

Analysis of long-term climatic data revealed a significant increase in wheat-season temperature during the study period. Seasonal mean temperature increased by approximately $0.86\text{ }^{\circ}\text{C}$ between 1984 and 2024 (Figure 3). The warming trend was most pronounced during the period from March to May, with temperatures increasing substantially during the reproductive and grain-filling stages of wheat. The rate of temperature increase was estimated at $0.74\text{ }^{\circ}\text{C}$ per decade. Seasonal rainfall exhibited considerable interannual variability throughout the study period. Although

notable high-rainfall years occurring in 1995, 2007, and 2014 (Figure 3).

3.6. Relationship between Grain Yield and Climatic Variability

The analysis indicated a positive association between grain yield and seasonal climatic conditions. Wheat yield exhibited an increasing trend during the recent two decades, coinciding with changes in seasonal temperature patterns. Variations in seasonal temperature were associated with corresponding changes in crop productivity, suggesting a strong linkage between climatic conditions and wheat yield performance at the study site (Figure 5).

3.7. Relationship between Grain Yield and Growing Degree Days

A positive relationship was observed between grain yield and accumulated growing degree days. Treatments with higher thermal accumulation generally produce higher grain yields. Reduced GDD accumulation was associated with shortened crop duration and lower yield performance. The results indicate that thermal time accumulation played an important role in determining wheat productivity (Figure 5).

Table 4. Effect of planting windows on grain yield (Kg ha^{-1}), heat use efficiency ($\text{kg/ha/}^{\circ}\text{C}^0$), Photothermal index (tillering to anthesis) and photothermal index (anthesis to maturity)

Sr. no.	Sowing date	Grain yield (kg/ha)	HUE (kg/ha/ $^{\circ}\text{C}^0$)	PTI (T -A)	PTI (A-M)
1	20 November	3687.32	2.788	9.210286	9.835658
2	30 November	4226.12	4.741	8.939821	10.01083
3	10 December	3780.56	4.079	8.559	10.73547

Note: T-A=tillering to Anthesis, A-M=Anthesis to Maturity

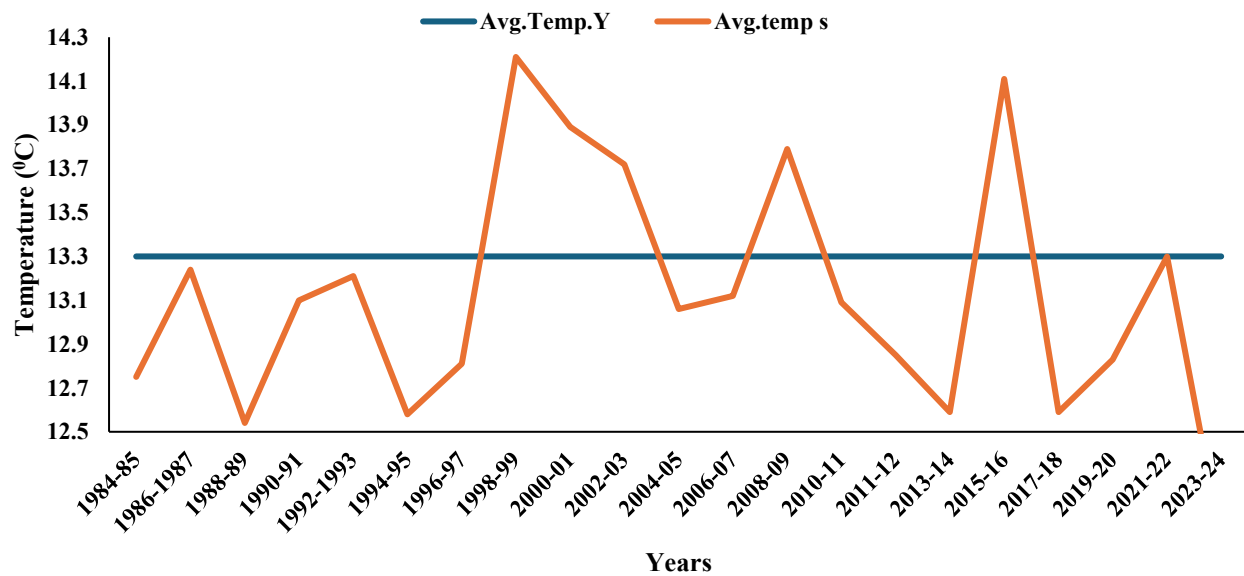


Figure 3. Seasonal Average Temperature

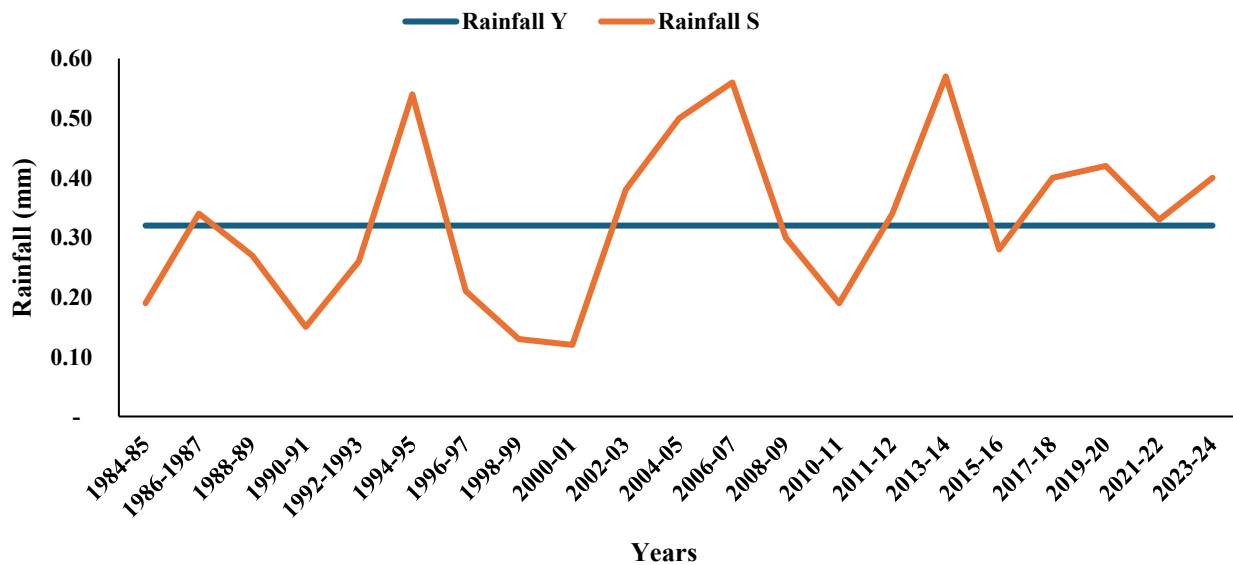


Figure 4. Seasonal Average Rainfall

3.8. Relationship between Grain Yield and Crop Phenology

Days to maturity (DTM) showed a strong positive relationship with grain yield. Regression analysis produced an equation of $y = 0.0722x - 6.2414$ with an R^2 value of 0.8822, indicating a close association between maturity

duration and grain yield. Longer crop duration was generally associated with higher grain yield, whereas shortened phenological periods corresponded to reduced productivity. These findings highlight the importance of crop developmental duration in determining wheat yield under varying climatic conditions (Figure 5).

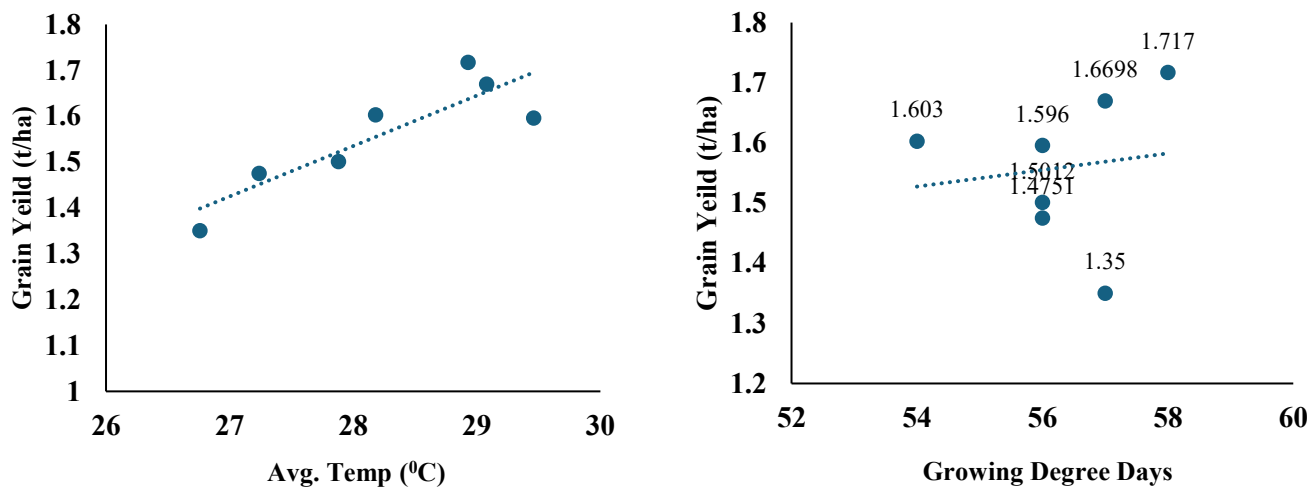


Figure 5. Relationship of wheat grain yield with climatic variability and growing degree days (GDD) during the study period

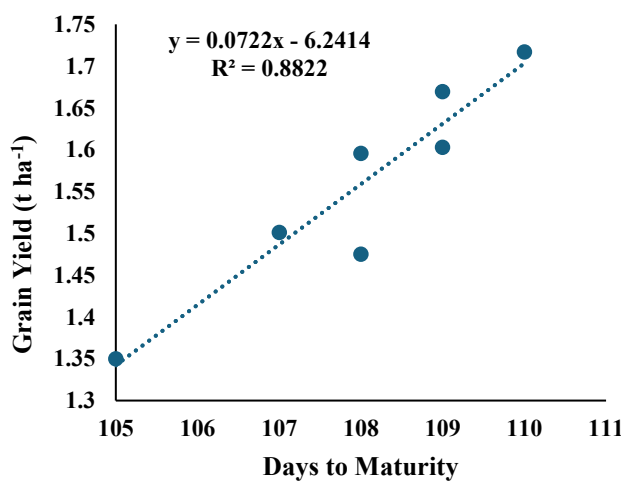


Figure 6. Grain Yield Relation to Crop Phenology

4. Discussion

Climate change has emerged as a major challenge for sustainable wheat production, particularly in regions where rising temperatures coincide with critical crop growth stages. The present study demonstrated that variations in sowing time, thermal accumulation, and long-term climatic trends significantly influenced wheat phenology and grain yield. The observed changes in crop duration and yield performance indicate that temperature-driven alterations in developmental processes are becoming increasingly important determinants

of wheat productivity under changing climatic conditions. The significant variation in phenological development among different sowing dates highlights the sensitivity of wheat growth stages to temperature fluctuations. The delayed sowing treatments showed accelerated progression from vegetative to reproductive stages, resulting in shortened crop duration. This response can be attributed to increased temperature exposure during later growth periods, which enhanced developmental rates and caused earlier anthesis and maturity. Similar findings have been reported by Menzel et al. (2020) and Tao et al. (2022), who observed that warming

trends advance crop phenological stages across different geographical regions. Reduced crop duration under warmer conditions limits the time available for biomass accumulation and grain filling, ultimately affecting yield potential.

The relationship between temperature and crop phenology is particularly important in wheat because grain yield depends strongly on the duration and environmental conditions during reproductive growth. In the present study, delayed sowing exposed wheat plants to higher temperatures during anthesis and grain filling, resulting in reduced productivity. High temperatures during these stages accelerate senescence, decrease photosynthetic activity, reduce assimilate translocation, and shorten grain filling duration. These findings are consistent with previous reports indicating that each 1°C increase in wheat growing season temperature can significantly reduce yield due to accelerated development and reduced grain weight (Asseng et al., 2015; Yang et al., 2017). Growing Degree Days (GDD) provided an effective measure for evaluating temperature-driven crop development. The greater thermal requirement observed under early sowing indicates that crops experienced a longer and more favorable developmental period, allowing efficient biomass production. In contrast, late-sown crops accumulated fewer heat units before maturity because elevated temperatures accelerated physiological processes. Similar results have been reported by Aslam et al. (2017), who demonstrated that thermal time requirements vary according to environmental conditions and crop developmental stages. The present findings confirm that accumulated heat units are closely associated with crop phenology and can be used as a reliable indicator for predicting wheat development under variable climatic conditions.

Heat Use Efficiency (HUE) further explained the impact of sowing time on the conversion of thermal resources into economic yield. The highest HUE observed under optimum sowing conditions indicates that favorable temperature regimes enhanced physiological activities and improved the conversion efficiency of accumulated heat into grain production. Conversely, deviations from optimum sowing time reduced HUE due to increased exposure to temperature stress and shortened growth duration. Similar observations have been reported by Pal and Murty (2010), who emphasized that crops with greater efficiency in utilizing available thermal energy generally achieve higher productivity. The photothermal index (PTI) also reflected the interaction between temperature and photoperiod in regulating wheat development. Higher PTI values under delayed sowing suggest that crops experienced increased thermal pressure during shortened developmental periods. Since wheat phenology is controlled by both temperature and day length, changes in environmental conditions can modify

the timing of critical growth stages. These alterations may expose reproductive phases to unfavorable climatic conditions, increasing the risk of yield losses under future warming scenarios.

The long-term climatic analysis conducted in the present study revealed a significant increasing trend in wheat-season temperature during 1984–2024. The increase in seasonal temperature, particularly during March to May, coincided with the reproductive and grain-filling stages of wheat. Rising temperature during these stages is a major concern because wheat is highly sensitive to terminal heat stress. Previous studies have reported that increased frequency of temperatures above 30–35°C during grain filling reduces grain-filling rate, accelerates maturity, and decreases final yield (Barnabás et al., 2008; Prasad and Djanaguiraman, 2014). Therefore, the warming trend observed at the study site may have important implications for future wheat production stability. Rainfall variability during the study period further indicates the increasing uncertainty associated with climate change. Although wheat production in the region is largely dependent on irrigation, variations in rainfall patterns can influence soil moisture availability and modify the crop response to temperature stress. The combined occurrence of high temperature and moisture stress can intensify yield reduction by affecting photosynthesis, nutrient uptake, and reproductive success.

The positive relationship between grain yield and thermal accumulation observed in this study emphasizes the importance of maintaining an appropriate balance between temperature availability and crop duration. Adequate GDD accumulation allows wheat plants to complete developmental stages under favorable conditions, whereas excessive temperature accelerates maturity and reduces yield potential. Similarly, the strong association between maturity duration and grain yield indicates that maintaining sufficient grain-filling time is essential for achieving higher productivity. The findings suggest that adjustment of sowing dates is an effective adaptation strategy for reducing climate-induced yield losses. Selection of an optimum planting window enables wheat crops to avoid exposure to extreme temperatures during sensitive developmental stages and improves thermal resource utilization. However, long-term adaptation to climate change will require integrated approaches, including development of heat-tolerant cultivars, improved water management, and climate-smart agronomic practices. Overall, the present study demonstrates that understanding temperature-driven changes in wheat phenology and thermal efficiency is essential for sustaining wheat production under future climate scenarios.

5. Conclusion

In conclusion to the conducted study, long-term dataset of phenology, yield and metrological observations, highlighted how the wheat phenology and yield affected at study site (Lahore) in last four decades (1984-2024). Such rise in temperature during the wheat growing season has caused a reduction in DTA, DTM and yield. A further rise in temperature will cause an upsetting in vernalization requirement for wheat which negatively impacted on phenology and yield. Additionally, the increased in trend of days with high temperatures above threshold 35 °C during the maturity stage (March-April) is an important factor affecting grain yield. Subsequently, to minimize the impacts of above-mentioned rise in temperature on wheat phenology and yield it is recommended that sowing date as an adaptation strategy should be adopted. Furthermore, we also recommended that sowing date should be shifted before November 20 with use of short duration and heat-resistant cultivars.

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8. Conflict of Interest

The authors declare no conflict of interest.

9. Authors' Contribution

Sajid Ali and Adnan Zahid designed the study, performed chemical analyses, and wrote the manuscript. Momna Arif analyzed data, prepared graphs, and contributed to writing. Ammara Fatima analyzed data and contributed to manuscript preparation. Brira Hareem collected, organized, and analyzed data. All authors reviewed and approved the final manuscript.

10. SDGs Addressed

This study aligns with SDG 2 (Zero Hunger) by promoting sustainable wheat production through optimized sowing time and improved yield potential under changing climatic conditions. It also contributes to SDG 13 (Climate Action) by enhancing climate resilience through adaptation strategies that mitigate the adverse effects of rising temperatures on wheat growth and productivity.

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