IMPACT OF CHANGING CLIMATE ON GRAIN GROWTH CURVE OF RAINFED WHEAT

Muhammad Aqeel Aslam[1,2*], Mukhtar Ahmed[2], Ghulam Qadir[2], Sahir Hameed Khattak[1], Ghassan Zahid[3], Sania Begum[4], Rabia Ikram[4], Sanjeela Sabahat[5], Maryam Murtaza[4], Ammara Zahoor[2], Esha Yaseen[1] and Saida Komal[6*]

[1] *Oilseeds Research Program, CSI, NARC Islamabad, Pakistan*
[2]*Department of Agronomy, PMAS Arid Agriculture University Rawalpindi*
[3]*Department of Biotechnology, The University of Azad Jammu and Kashmir, Muzaffrabad*
[4]*National Institute for Genomics & Advanced Biotechnology, NARC Islamabad, Pakistan*
[5]*NARC, Islamabad, Pakistan*
[6]*Department of Agronomy, University of Poonch, Rawalakot*
*Correspondence: aqeel7016@parc.gov.pk and komalsaida@gmail.com,

Received: September 06, 2025; Accepted: October 10, 2025

ABSTRACT

Understanding the grain growth dynamics of wheat under changing climatic conditions is crucial for predicting yield stability and ensuring food security. Current study investigates the grain growth curve of wheat (*Triticum aestivum* L.) across three varying climatic conditions of Pothwar i.e., Islamabad (33◦ 40′ N, 73◦ 10′ E, 508m a.s.l.), having low temperature/high rainfall, URF-Koont (32◦ 93′ N, 72◦ 86′E, 506m a.s.l.) under variable temperature and moisture regimes associated with climate change. Field experiments were conducted using using Randomized Complete Block Design were conducted using five wheat genotypes (Dharabi, Chakwal-50, NARC-2009, Pakistan-2013 and AUR-809, four sowing dates i.e. SD_1= (20-30 Oct of 2013-14 and 2014- 15, optimum viz. SD_2= 10-20 Nov of 2013-14 and 2014-15, later i.e. SD_3= 01-10 Dec of 2013-14 and 2014- 15 and very late sowing times i.e. SD_4= 20-30 Dec of 2013-14 and 2014- 15 at three varying climatic locations to monitor grain development from anthesis to physiological maturity. Results revealed that rising temperatures shortened the grain-filling duration, while fluctuating moisture availability significantly influenced the maximum grain growth rate and final grain weight. The grain growth curve followed a typical sigmoid pattern; however, under warmer and drier conditions, the curve shifted towards an earlier plateau with reduced asymptotic grain weight. These findings highlight the vulnerability of wheat grain development to climatic variability and suggest that genotypes with extended grain-filling capacity and tolerance to heat and drought stress should be prioritized in breeding programs. The study provides valuable insights for modeling crop growth under climate change and designing adaptive agronomic strategies to sustain wheat productivity.

Keywords: Wheat, Grain Growth Curve, Climate Change, Temperature, Sowing Date

INTRODUCTION

Environment and climate of the globe is changing at adverse rates. Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer) (USEPA, 2011). It can also be defined as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (IPCC, 2007). Climate variability is certainly resulted due to climate change (IPCC, 2013). Climate variability had significant impressions on living systems of small land holders, communities, and in larger term the countries. The variation in rainfall and temperature has direct influence on climate variability. Changes in rainfall intensity and duration during the whole year has relationship with the agricultural products (Thornton *et al.*, 2014). Some positive impacts of climate variability are also there in parts of the world located 55^{o} northern widths (Ewert *et al.*, 2015), while areas under hot and dry climate regions might see negative impacts (Aslam *et al*., 2018; Parry *et al*., 2005).

Underdeveloped countries will be more affected due to less precipitation and raise in temperature. Similarly, intensity and frequency of extremes climatic events such as heat, flood, drought and coldness will be higher in future. Change in any climatic event has direct positive impact on agriculture productivity. Critical growth stages of the crop particularly reproductive phase have sever negative impact due to high temperature, and IPCC (Intergovernmental Panel on Climate Change) has declared heat stress as an alarming threat to food production (IPCC, 2007).

Crop phenology directly affected by change in temperature. Under low temperature conditions crop phenology prolonged while under higher temperature plants fulfill their degree days in less number of days resulting to shorter crop duration (Ludwig and Asseng, 2006). Grain yield may also vary due to variation in genetic make up of genotypes as well (Alam, *et. al*., 2025). Sowing time also influence crop phenology. With late planting due to higher temperature during flowering the growth and development of crop retarded, source to sink activity disturbed, reduction in crop phenology and ultimately decreased economic yield (Sial *et al.*, 2005; Mehmood *et al*., 2021a). Among cereals crop wheat being a basic necessity of Pakistan contributing 14.4 percent into value addition and 3.0 percent to GDP. Introduction of high yielding genotypes with increased use of chemical fertilizer has enhanced the crop productivity in past couple of decades (Curtis, 2002; Aslam *et al*., 2017[a,b]). Under rainfed conditions semi dwarf wheat varieties have key role to increase production. However, in a given environment, wheat growth, development and yield depend on cultivar, management practices, weed management and weather conditions (Ullah, *et al*., 2025). In Pakistan, wheat is sown over a wide range of sowing date in various cropping systems of rainfed and irrigated areas. This variation in sowing time is caused by various factors such as erratic rainfall in rainfed area, late planting or harvesting of preceding crop, lack or unavailability of farm machinery and inputs, etc. The sowing time of wheat in Pakistan generally starts from mid of October and extends until the end of December. Delayed planting reduces wheat yield. The reduction is almost linear (42 kg ha^{-1} day^{-1}) after optimum planting time (generally 10th November) (Ahmed, 2011; Aslam *et al*., 2021; Begum, *et al*., 2025). Delayed sowing of wheat crop suffered from heat stress during grain filling period. Keeping in view the current scenario of changing climate present study was planned to develop grain growth curve for rainfed wheat under different sowing dates and varying climatic locations.

MATERIALS AND METHODS

The present research was carried out at three varied climatic locations of Pothwar, Pakistan, i.e., Islamabad (33◦ 40′ N, 73◦ 10′ E, 508m a.s.l.), having low temperature/high rainfall, URF-Koont (32◦ 93′ N, 72◦ 86′E, 506m a.s.l.), medium temperature/rainfall and Talagang (32◦ 55′ N, 72◦ 25′ E, 458m a.s.l.) with high temperature/low rainfall during wheat growing seasons of 2013-14 and 2014-15. Recommended fertilizer applications were applied i.e. 100 kg nitrogen and 50 kg phosphorus in the form of urea and DAP. Experiments using Randomized Complete Block Design were conducted using five wheat genotypes (Dharabi, Chakwal-50, NARC-2009, Pakistan-2013 and AUR-809 keeping in view the following treatments

Sowing dates were planned in such a manner that early i.e. SD_1= (20-30 Oct of 2013-14 and 2014- 15, optimum viz. SD_2= 10-20 Nov of 2013-14 and 2014- 15, later i.e. SD_3= 01-10 Dec of 2013-14 and 2014- 15 and very late sowing times i.e. SD_4= 20-30 Dec of 2013-14 and 2014- 15 were kept in study. Five wheat genotypes (Dharabi, NARC-2009, Pakistan-2013, Chakwal-50 and AUR-809) at three varying climatic sites (Islamabad (Low temperature), URF-Koont (Medium temperature) and Talagang (High temperature)) were used to study the impact of climate change on wheat grain growth curve during two years (2013-14 and 2014-15).

GRAIN GROWTH CURVE

Individual grain weight was recorded at milky, soft dough, hard dough and maturity stages from all treatments. Based upon grain development stages, grain growth curve was developed for three study sites under four sowing dates.

RESULTS AND DISCUSSION

Wheat Grain Growth Curve

Grain weight at milky, soft dough, hard dough and maturity stage was recorded to develop grain growth curve for three study sites under four sowing dates during 2013-14 and 2014-15. Maximum grain weight was recorded for SD_2 at Islamabad during 2013-14 than all other sowing dates. At URF-Koont and Talagang under SD_2 maximum grain weight was recorded during 2013-14 while minimum grain weight was observed under SD_4 during 2014-15.

Individual grain weight (mg) at milky stage varied considerably among five wheat genotypes (NARC-2009, AUR-809, Pak-13, Dhurabi and Chakwal-50 at varying locations (Islamabad, URF-Koont, and Talagang) under four sowing dates (SD_1, SD_2, SD_3 and SD_4) while during both years (2013-14 and 2014-15). ANOVA table well-defined that main effects of G, L and SD were significantly changed at $p \leq 0.01$ (Table 1). Individual grain weight at milky stage differed considerably among varying study sites (Table 2). Maximum individual grain weight at milky stage observed at Islamabad (10.835 mg) while minimum grain yield recorded at Talagang (6.27 mg). Forty-two % reductions in individual grain weight at milky stage noted at Talagang compared with Islamabad. Similarly, highest individual grain weight at milky stage observed for SD_2 (10.483 mg) followed by SD_1 (10.303 mg) while lowest grain yield was observed under SD_4 (5.768 mg). Individual grain weight at milky stage reduced by 44 % in late sowing date (SD_4) compared with early sowing date (SD_1). Maximum individual grain weight at milky stage recorded for Pak-13 (9.5556 mg) followed by AUR-809 (9.3111 mg) while minimum individual grain weight at milky stage observed for Dhurabi (6.9931 mg). Maximum individual grain weight at milky stage (9.6461 mg) were observed during 2013-14 while minimum individual grain weight at milky stage (72261 mg) was obtained during 2014-15. During 2014-15, 24 % decrease in individual grain weight at milky stage observed than 2013-14. All the interactive effects except SD x G and Y x L x G were highly significant at $p \leq 0.05$.

Individual grain weight at soft dough stage differed significantly among five wheat genotypes (NARC-2009, AUR-809, Pak-13, Dhurabi and Chakwal-50 at varying locations (Islamabad, URF-Koont, and Talagang) under four sowing dates (SD_1, SD_2, SD_3 and SD_4) while during both years (2013-14 and 2014-15). ANOVA table well-defined that main effects of G, L and SD were significantly changed at $p \leq 0.01$ (Table). Individual grain weight at soft dough stage differed substantially among varying study sites (Table 2). Maximum individual grain weight at soft dough stage observed at Islamabad (28.507 mg) while minimum individual grain weight recorded at Talagang (16.635 mg). Forty one percent decrease in individual grain weight at soft dough stage observed at Talagang compared with Islamabad. Similarly, highest individual grain weight at soft dough stage observed for SD_2 (28.222 mg) followed by SD_1 (27.86 mg) while lowest individual grain weight was observed under SD_4 (15.739 mg). Individual grain weight at soft dough stage reduced by 43 % in later sowing date (SD_4) compared with early sowing date (SD_1). Upper limit of individual grain weight at soft dough stage recorded for Pak-13 (26.097 mg) while minimal individual grain weight at soft dough stage observed for Dhurabi (18.843 mg). The percentage difference from maximum to minimum level of individual grain weight at soft dough stage among genotypes was 27 %. Maximum individual grain weight at soft dough stage (25.809 mg) were observed during 2013-14 while minimum individual grain weight at soft dough stage (19.849 mg) was obtained during 2014-15. During 2014-15, 22 % decrease in individual grain weight at soft dough stage observed than 2013-14. All the interactive effects other than Y x L x G were significant at $p \leq 0.05$.

Individual grain weight at hard dough stage varied considerably during both years (2013-14 and 2014-15) among five wheat genotypes (NARC-2009, AUR-809, Pak-13, Dhurabi and Chakwal-50 at varying locations (Islamabad, URF-Koont, and Talagang) under four sowing dates (SD_1, SD_2, SD_3 and SD_4). ANOVA table well-defined that main effects of G, L and SD were significantly changed at $p \leq 0.01$ (Table 1). Maximum individual grain weight at hard dough stage (34.794 mg) were observed during 2013-14 while minimum individual grain weight at hard dough stage (27.264 mg) was obtained during 2014-15. During 2014-15, 20 % decrease in individual grain weight at hard dough stage observed than 2013-14. Individual grain weight at hard dough stage differed considerably among varying study sites (Table 2). Maximum grain weight at hard dough stage observed at Islamabad (38.115 mg) while minimum grain weight recorded at Talagang (22.543 mg). Forty percent reduction in individual grain weight at hard dough stage noted at Talagang compared with Islamabad. Similarly, highest grain weight at hard dough stage observed for SD_2 (38.101 mg) followed by SD_1 (38.087 mg) while lowest individual grain weight was observed under SD_4 (21.32 mg). Individual grain weight at hard dough stage reduced by 44 % in late sowing date (SD_4) compared with early sowing date (SD_1). Maximum individual grain weight at hard dough stage recorded for Pak-13 (35.401 mg) while minimum individual grain weight at hard dough stage observed for Dhurabi (25.522 mg). Other all the interactive remained non-significant at $p \leq 0.05$.

Individual grain weight at maturity differed significantly during both years (2013-14 and 2014-15) among five wheat genotypes (NARC-2009, AUR-809, Pak-13, Dhurabi and Chakwal-50 at varying climatic locations (Islamabad, URF-Koont, and Talagang) under four sowing dates (SD_1, SD_2, SD_3 and SD_4). ANOVA table elaborated that main effects of Y, G, L and SD were significantly changed at $p \leq 0.01$ (Table 1). Grain weight at maturity differed considerably among varying study sites (Table 2). Maximum grain weight at maturity observed at Islamabad (32.192 mg) while minimum grain weight recorded at Talagang (19.264 mg). Forty percent decrease in individual grain weight at maturity recorded at Talagang compared with Islamabad.

Similarly, highest grain weight at maturity observed for SD_2 (33.056 mg) followed by SD_1 (32.747 mg) while lowest grain weight was observed under SD_4 (18.997 mg). Grain weight at maturity reduced by 41 % in late sowing date (SD_4) compared with early sowing date (SD_1). Maximum individual grain weight at maturity recorded for Pak-13 (31.04 mg) whereas minimum grain weight at maturity observed for Dhurabi (24.00 mg). Maximum grain weight at maturity (29.947 mg) was observed during 2013-14 while minimum grain weight at maturity (24.123 mg) was obtained during 2014-15. During 2014-15, 19 percent decrease in grain weight was recorded compared to 2013-14. The interactive effect other than Y x L x G and Y x L x SD x G remained significant at $p \leq 0.05$. Under higher temperature areas grain yield reduced than the low temperature sites. Grain growth curve developed at each study sites (Fig. 1 a-c) for four sowing dates. Grain development stages for all sowing dates at each study site were completed at different days of the year. At Islamabad due to favorable climatic conditions grain development duration was higher than other two study sites so grain weight was higher at Islamabad than other locations.

Table 1. SS and DF table of individual grain weight at Milky, Soft dough, Hard dough and Maturity stages.

Source	**DF**	**SS Milky**	**SS Soft Dough**	**SS Hard Dough**	**SS Maturity**
R	2	813.66	5854.5	11112.8	7918.8
Y	1	527.08***	3196.3***	5103.1***	3052.7***
L	2	1260.11***	8345.6***	14903.7***	11257.3***
SD	3	1471.54***	10420.1***	19225.6***	13242.8***
G	4	357.47***	2752.3***	5148***	4077.9***
YxL	2	537.91***	2056.8***	725.9***	408.5***
YxSD	3	35.62***	233***	369.8***	350.1***
YxG	4	36.5***	235.8***	397.7***	245.4***
LxSD	6	290.69***	1899.8***	2349.1***	2203.3***
LxG	8	20.97***	172.2***	380.6***	332.5***
SDxG	12	15.38NS	111.1*	194.9*	153.2**
YxLxSD	6	292.64***	1500.8***	3948.1***	1095.3***
YxLxG	8	8.02NS	35NS	78.3NS	22NS
YxSDxG	12	43.91***	304***	590.6***	385.2***
LxSDxG	24	37.16**	306.7***	531.2***	411.4***
YxLxSDxG	24	43.81***	192.4*	722.9***	161.5NS
Error	238	225.32	1307	2412.9	1479.7
Total	359	6017.79	38923.5	68195.3	46797.6

Where: Y= Years, G= Genotypes, L= Locations, SD= Sowing dates

Northern Kyushu, Japan, have shown that excessive rainfall during the early vegetative stages can cause waterlogging, which hinders root development and nutrient uptake. . On the other hand, as research from China has shown, sufficient rainfall during the reproductive phases, especially during grain filling, is essential for optimizing grain weight and total production (Cetin *et al*., 2022). The grain growth curve was impacted by variations in rainfall patterns over the course of the various planting dates, according to data from the study locations. Better grain growth was observed in sites with more consistent rainfall during the grain filling stage. These results are consistent with earlier study that found a positive correlation between rainfall consistency and grain weight and yield (Ahmed *et al*., 2010; Sereyrorth *et al*., 2020).

Another important factor impacting the wheat grain growth curve is the temperature data that was gathered from the study sites over the course of the two growing seasons. Many physiological processes, like as germination, tillering, and grain filling, are impacted by temperature. According to research done in Pakistan's semi-arid regions, high temperatures during the grain filling stage can speed up the process but frequently lead to lower grain weight because of shorter filling durations. These experiments showed that grain yield might drop by about 2.5% for every 1°C increase in temperature, particularly when temperatures rose beyond 30°C during crucial growth stages (Ahmed *et al*., 2011a; Hussain *et al*., 2021).

Grain growth curves were developed using the individual grain weights that were recorded at several phases (milky, soft dough, firm dough, and maturity). The curves showed that heavier grains were typically produced by earlier sowing dates, especially in areas where rainfall and temperature were within ideal ranges during the grain filling stage. This trend is consistent with a research conducted in China's Loess Plateau, which discovered that the best grain production outcomes came from early sowing in conjunction with moderate soil moisture conditions. This was ascribed to the longer grain filling period at lower temperatures, which permitted more stable biomass buildup (Ahmed *et al*., 2011b; Li *et al*., 2022).

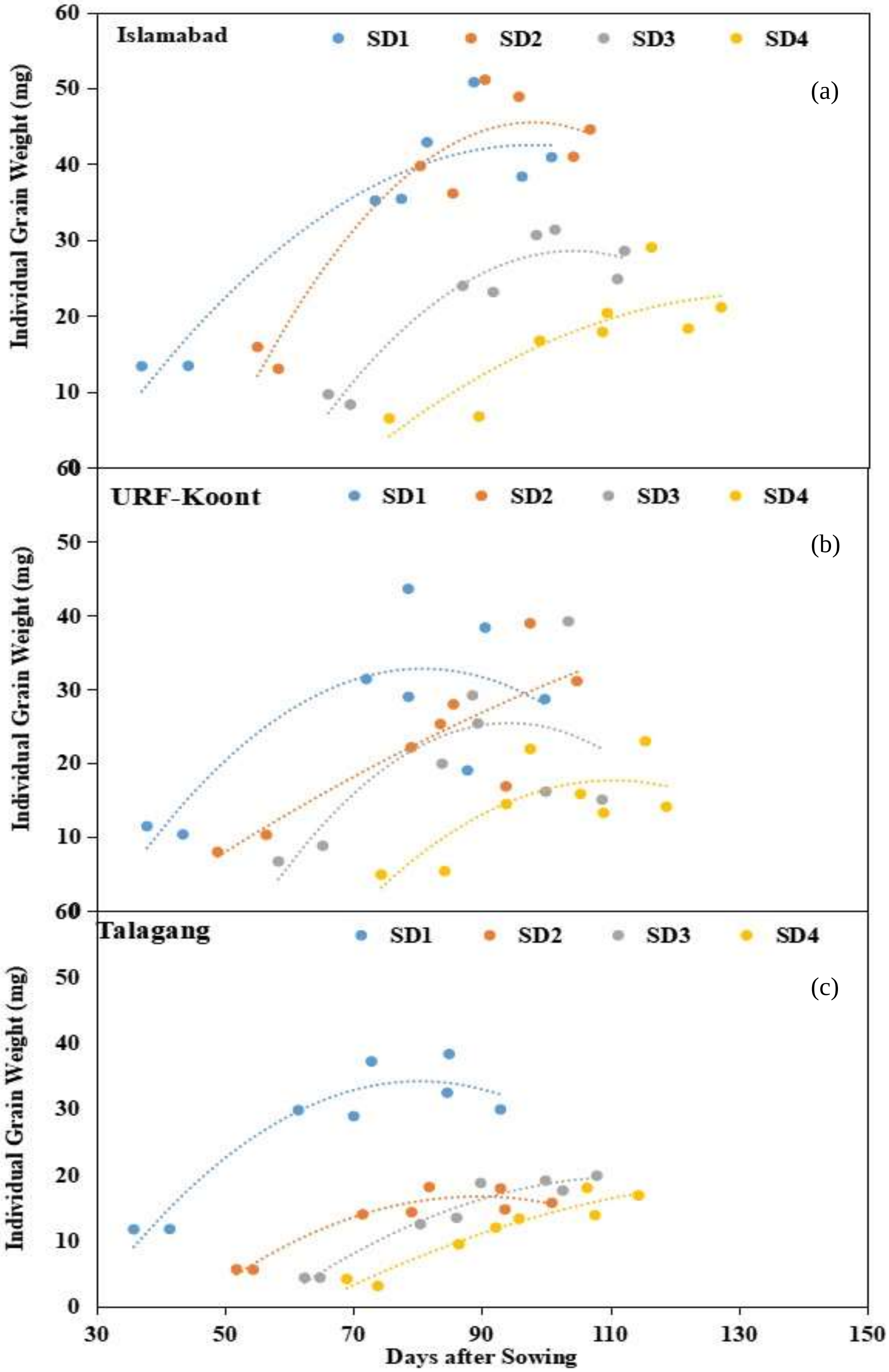

Fig. 1 (a-c). Wheat Grain growth curve under four sowing dates at three locations.

(a)

Table 2. Individual grain weight (mg) at Milky, Soft dough, Hard dough and Maturity stages.

Years	Milky	Soft Dough	Hard Dough	Maturity
2013-14	9.6461A	25.809A	34.794A	29.947A
2014-15	7.2261B	19.849B	27.264B	24.123B
LSD	0.2063	0.4866	0.6612	0.5178
Locations				
Islamabad	10.835A	28.507A	38.115A	32.192A
URF-Koont	8.203B	23.246B	32.431B	29.648B
Talagang	6.27C	16.735C	22.543C	19.264C
LSD	0.2475	0.596	0.8098	0.6341
Sowing dates				
SD1	10.303A	27.86A	38.087A	32.747A
SD2	10.483A	28.222A	38.101A	33.056A
SD3	7.19B	19.496B	26.61B	23.339B
SD4	5.768C	15.739C	21.32C	18.997C
LSD	0.2857	0.6882	0.9351	0.3717
Genotypes				
NARC-2009	8.7569B	23.706C	32.344C	28.28C
AUR-809	9.3111A	25.082B	34.126B	29.627B
Pak-13	9.5556A	26.097A	35.401A	31.04A
Dhurabi	6.9931D	18.843E	25.522E	22.227E
Chakwal-50	7.5639C	20.418D	27.753D	24D
LSD	0.3195	0.7694	1.0454	0.8187

Where: Y= Years; G= Genotypes; L= Locations; SD= Sowing dates

Important insights into the impact of environmental conditions on wheat growth are provided by the examination of grain weight at several stages—milky, soft dough, hard dough, and maturity—across three study sites under varying sowing dates between 2013–14 and 2014–15. Notably, in 2013–14 at Islamabad, the maximum grain weight was reported during the second sowing date (SD2), emphasizing the importance of early sowing to achieve ideal grain development. This result is consistent with research emphasizing how crucial it is to time planting to coincide with ideal weather in order to optimize yield potential. The studies in the Pannonian environment have demonstrated that early sowing prolongs the grain filling phase, which is essential for attaining larger grain weights (Ahmed *et al*., 2014; Zhou *et al*., 2017).

Similar findings were seen at URF-Koont and Talagang: SD2 in 2013–14 produced the highest grain weight, whereas SD4 in 2014–15 produced the lowest grain weight. Increased temperature stress throughout critical growth stages can be the cause of the notable decrease in grain weight under late planting conditions (SD4). According to Jat *et al*. (2018), late sowing exposes wheat plants to greater temperatures during grain filling, which speeds up the process but frequently results in lower grain weight due to shorter filling durations.

Furthermore, the complex interaction between genetic variables and environmental circumstances is further shown by the variance in grain weight among various genotypes throughout varying sowing dates. At the milky stage, SD2 (10.678 mg) had the largest individual grain weight, followed by SD1 (10.5 mg), and SD4 (5.878 mg) had the lowest grain weight. The negative consequences of high temperatures during grain filling are responsible for the 44% reduction in grain weight under late sowing (SD4) compared to early sowing (SD1); these findings are consistent with findings from international studies that have documented similar patterns in wheat genotypes subjected to heat stress (Wu *et al*., 2018).

The grain growth curves exhibited clear variations across locations and sowing dates, reflecting the strong influence of environment and planting time on wheat grain development. Across all sites, grain filling duration and final grain weight consistently declined with delayed sowing, indicating that higher temperatures and moisture stress during late planting curtailed the effective grain growth period. These findings highlight the importance of optimal sowing time and favorable environments for maximizing grain filling and grain weight in wheat under changing climatic conditions.

Effect of genotype and environment on grain growth

The results of this research demonstrated the substantial influence of both genotype and environment on grain growth, as evidenced by the diversity in individual grain weight across the several wheat genotypes at the milky stage. In particular, Pak-13 had the highest grain weight (9.5556 mg), closely followed by AUR-809 (9.3111 mg), NARC-2009 (8.7569 mg) and Chakwal-50 (7.5639 mg). Dhurabi (6.9931 mg) had the lowest grain weight at milky stage. Similar trends were also observed at soft dough, hard dough and maturity stages (Table 2). These variations align with results from earlier investigations that highlight the significance of genotype-environment interactions in influencing grain weight and total yield potential. Genotype-environment interactions significantly influenced grain weight in a study examining 18 wheat genotypes in several contexts. Certain genotypes consistently outperformed others in terms of production across different locales (Eltaher *et al*., 2021; Ahmed *et al*., 2014).

Furthermore, the impact of environmental conditions on wheat development is shown by the reported drop in grain weight during the 2014–15 season compared to the 2013–14 season. The 2014–15 season's 24% decrease in individual grain weight at the milky stage is probably the result of less-than-ideal growing circumstances, including temperature swings or less precipitation, which are known to negatively impact grain filling and final grain weight. Other studies have found similar results, with significant decreases in grain weight and overall yield occurring during the grain filling stage due to unfavorable climatic conditions like heat stress or drought (Bilgin *et al*., 2018; Ahmed *et al*., 2019).

Effect of sowing date on grain growth

According to the study's findings, the sowing date had a substantial impact on grain weight at maturity. The second sowing date (SD2) had the highest grain weight, while the first sowing date (SD1), was closely behind. On the other hand, the late sowing date (SD4) had the lowest grain weight, demonstrating a significant 41% loss in grain weight as a result of delayed sowing. This decrease is in line with studies that show how late planting negatively affects grain weight, mostly as a result of exposure to higher temperatures during the filling phase, which speeds up grain development but shortens the filling time and lowers grain weight overall (Ahmed *at al*., 2010[b];Gyawali *et al*., 2023). Previous research has demonstrated that postponing sowing can lead to notable decreases in both grain weight and yield, highlighting the significance of timely planting in order to maximize yield potential (Tamiru *et al*., 2023). These variations imply that grain weight, which is further impacted by environmental factors, is largely determined by genotype. These results are supported by earlier research, which shows that genotypic variations in wheat can cause substantial diversity in grain weight and yield, with particular genotypes doing better in particular environmental circumstances (Bhagat *et al*., 2023). The study's year-to-year variability, which included a 19% drop in grain weight at maturity in 2014–15 compared to 2013–14, highlights the significance of incorporating environmental and genetic factors into wheat cultivation strategies in order to guarantee stable yields under a range of climatic conditions (Stella *et al*., 2023).

Global analyses have shown that wheat yields decline by approximately 6% for each 1 °C increase in mean temperature, with South Asia identified as a hotspot of vulnerability (Zhao *et al*., 2017). Grain weight itself can decrease by 2.5–3% for each day of heat exposure above 30 °C during the grain-filling period (Asseng *et al*., 2015), which aligns with but also contextualizes the 40–44% reductions observed in our study under late sowing. Mechanistically, heat stress accelerates senescence, reduces starch synthase activity, and shortens endosperm cell division, while drought restricts assimilate flow to developing grains (Farooq *et al*., 2011; Djanaguiraman *et al*., 2020). Although our study did not measure grain quality, previous reports indicate that heat stress often increases grain protein content while reducing carbohydrate accumulation, thereby altering nutritional value (Stone and Nicolas, 1995). Future climate projections suggest a 1.5–2.0 °C rise in Pakistan by mid-century, likely increasing the frequency of terminal heat stress during grain filling (Shaheen, 2020). These findings underscore the urgency of integrating heat- and drought-tolerant traits into breeding programs, such as ‘stay-green’ characteristics and stress-responsive genes (Reynolds *et al*., 2016; Pinto *et al*., 2010), alongside adaptive agronomic practices like optimized sowing windows, conservation tillage, and nutrient sprays to safeguard yield stability.

CONCLSION

By concluding, the current study underscores the importance of understanding grain growth curve dynamics in wheat and highlights the need for climate-resilient varieties and adaptive management practices to safeguard grain yield and food security under changing climate scenarios. The findings clearly suggest that in rainfed Pothwar, timely sowing plays a decisive role, with the optimum window falling between late October and mid-November to ensure prolonged grain filling and higher grain weight. Late sowing beyond December markedly shortened the grain growth duration and reduced yield potential due to exposure to higher temperatures during grain filling. Among the tested genotypes, varieties such as Pak-13 and AUR-809 exhibited superior grain development and should be prioritized under variable environments. Therefore, farmers in rainfed Pothwar are recommended to adopt optimum sowing dates and select climate-resilient genotypes to maximize productivity, while breeding programs should emphasize heat- and drought-tolerant varieties with extended grain-filling capacity to sustain wheat yields under changing climate conditions.

AUTHOR CONTRIBUTIONS

All the authors contributed equally in the manuscript.

COMPETING OF INTEREST

There is no conflict of interest amongst the authors.

REFERENCES

Ahmed, M., F.U. Hassan, G. Qadir, F.A. Shaheen and M.A. Aslam (2017). Response of proline accumulation in bread wheat (*Triticum aestivum* L.) under rainfed conditions. *J. Agric. Meteorol.*, 73(4): 1–9.

Ahmed, M., F.U. Hassan, M. Asim, M.A. Aslam and M.N. Akram (2010). Correlation of photothermal quotient with spring wheat yield. *Afr. J. Biotechnol.*, 9: 7869–7852.

Ahmed, M., F.U. Hassan, M. Aslam, M.N. Akram and M.A. Aslam (2010). Photosynthesis of spring wheat (*Triticum aestivum* L.) in rainfed ecology of Pakistan. *Afr. J. Biotechnol.*, 9: 7495–7503.

Ahmed, M., F.U. Hassan, M.A. Aslam, M.N. Akram and M. Akmal (2011). Regression model to study sole and cumulative effect of temperature and solar radiation on wheat yield. *Afr. J. Biotechnol.*, 10(45): 9114–9121.

Ahmed, M., F.U. Hassan, U. Qadeer and M.A. Aslam (2011). Silicon application and drought tolerance mechanism of sorghum. *Afr. J. Agric. Res.*, 6: 594–607.

Ahmed, M., M.A. Aslam, F.U. Hassan, M. Asif and R. Hayat (2014). Use of APSIM to model nitrogen use efficiency in rainfed wheat. *Int. J. Agric. Biol.*, 16(3): 461–470.

Ahmed, M., M.A. Aslam, F.U. Hassan, R. Hayat and S. Ahmad (2019). Biochemical, physiological and agronomic response of wheat to changing climate of rainfed Pakistan. *Pak. J. Bot.*, 51(2): 1–10.

Ahmed, M., S. Khan, M. Irfan, M.A. Aslam, G. Shabbir and S. Ahmad (2019). Effect of phosphorus on root signaling of wheat under different water regimes. In: *Global Wheat Production*. Intech Publishers, pp. 1–20. DOI: 10.5772/intechopen.75806.

Alam, B., I. Ullah, F. Ullah, I.U. Khan, M.A. Aslam, G. Zahid, S. Begum, A. Errum, F. Amin, R. Akram, M. Murtaza, F. Jabeen, E. Yaseen, G.M. Ali and S.H. Khattak (2025). Morphological and yield characterization of different wheat genotypes. *J. Agric. Vet. Sci.*, 4(2): 151–157.

Aslam, M.A., M. Ahmed, C.O. Stöckle, S.S. Higgins, F.U. Hassan and R. Hayat (2017). Can growing degree days and photoperiod predict spring wheat phenology? *Front. Environ. Sci.*, 5: 57. DOI: 10.3389/fenvs.2017.00057.

Aslam, M.A., M. Ahmed, F.U. Hassan and R. Hayat (2017). Modeling nitrogen use efficiency under changing climate. In: *Quantification of Climate Variability, Adaptation and Mitigation for Agricultural Sustainability* (M. Ahmed and C.O. Stöckle, eds.). Springer International Publishing, Switzerland, pp. 71–90.

Aslam, M.A., M. Ahmed, F.U. Hassan, O. Afzal, M.Z. Mehmood, G. Qadir, M. Asif, S. Komal and T. Hussain (2021). Impact of temperature fluctuations on plant morphological and physiological traits. In: *Building Climate Resilience in Agriculture* (Jatoi *et al*., eds.). Springer, Cham, pp. 25–52. ISBN 978-3-030-79408-8. DOI: 10.1007/978-3-030-79408-8.

Aslam, M.A., M. Ahmed, F.U. Hassan, R. Hayat and S. Ahmad (2018). Quantification of impact of sowing dates on productivity of rainfed wheat. *Sci. Tech. Dev.*, 37(1): 28–35.

Asseng, S., F. Ewert, P. Martre, R. P. Rötter, D. B. Lobell, D. Cammarano, B. A. Kimball, M. J. Ottman, G. W. Wall, J. W. White, M. P. Reynolds, P. D. Alderman, P. V. V. Prasad, P. K. Aggarwal, J. Anothai, B. Basso, C Biernath, A. J. Challinor, G. De Sanctis and J. Doltra (2015). Rising temperatures reduce global wheat production. *Nature Climate Change*, 5: 143–147.

Begum, S., M. A Aslam, M. Saeed, S. H. Khattak, G. Zahid, F. Amin, G. M. Ali and others. (2025). Molecular marker-assisted identification of rust resistance genes in NUWYT wheat (*Triticum aestivum* L.). *Jammu Kashmir Journal of Agriculture*, 5(1): 55–71.

Bhagat, R.K., M. Sahu, D. Narayan and R. Dhurve (2023). Influence of different sowing dates and nutrient management on dry matter accumulation and correlation study for grain yield of wheat (Triticum aestivum L.). *International Journal of Plant & Soil Science*, 35(21): 751–757.

Bilgin, O., A. Balkan, Z. K. Korkut and I. Başer (2018). Multi-environmental evaluation of triticale, wheat and barley genotypes by GGE biplot analysis. *Journal of Life Sciences*, 12: 13–23.

Cetin, O., M. Yildirim, C. Akinci and A. Yarosh (2022). Critical threshold temperatures and rainfall in declining grain yield of durum wheat (Triticum durum Desf.) during crop development stages. *Romanian Agricultural Research*, 39: 1–8.

Curtis, B.C. (2002). Wheat in the world. In: *Bread Wheat Improvement and Production*. Curtis, B.C., Rajaram, S. and Gómez Macpherson, H. (eds.), Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 301–308.

Djanaguiraman, M., S. Narayanan, E. Erdayani and P. V. V. Prasad (2020). Effects of high temperature stress during anthesis and grain filling periods on photosynthesis, lipids and grain yield in wheat. *BMC Plant Biology*, 20: 206.

Eltaher, S., Baenziger, P.S., Belamkar, V., Emara, H.A., Nower, A.A., Salem, K.F., Sallam, A. and others. (2021). GWAS revealed effect of genotype × environment interactions for grain yield of Nebraska winter wheat. *BMC Genomics*, 22: 1–14.

Farooq, M., H. Bramley, J. A. Palta and K. H. M. Siddique (2011). Heat stress in wheat during reproductive and grain-filling phases. *Critical Reviews in Plant Sciences*, 30: 491–507.

Gyawali, P., P. Gyawali, B. B. Adhikari and D. R. Katuwal (2023). Effect of seed rates and sowing dates on productivity of wheat (Triticum aestivum L.). *Turkish Journal of Agriculture-Food Science and Technology*, 11(12): 2347–2355.

Hussain, J., T. Khaliq, M. H. U. Rahman, A. Ullah, I. Ahmed, A. K. Srivastava and A. Ahmad (2021). Effect of temperature on sowing dates of wheat under arid and semi-arid climatic regions and impact quantification of climate change through mechanistic modeling with evidence from field. *Atmosphere*, 12(7): 927.

IPCC. (2007). *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, USA, 996 pp.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jat, R. K., P. Singh, M. L. Jat, M. Dia, H. S. Sidhu, S. L. Jat and S. L. Ridaura (2018). Heat stress and yield stability of wheat genotypes under different sowing dates across agro-ecosystems in India. *Field Crops Research*, 218: 33–50.

Kumar, S., R. Prasad, S. S. Rana, S. Manuja, G. Singh and N. Rana (2022). Impact of sowing dates on different growth attributes and yield of wheat in North Western Himalayas. *Environment Conservation Journal*, 23(3): 303–308.

Li, X., Y. Gao, X. Liu, Y. Tian, Y. Zhu, W. Cao and Q. Cao (2022). Effects of sowing dates, sowing rates, and nitrogen rates on growth and spectral indices in winter wheat. *Acta Agronomica Sinica*, 48: 975–987.

Liu, K., C. Zhang, B. Guan, R. Yang, K. Liu, Z. Wang and X. Wang (2021). The effect of different sowing dates on dry matter and nitrogen dynamics for winter wheat: an experimental simulation study. *PeerJ*, 9: e11700.

Ludwig, F. and S. Asseng (2006). Climate change impacts on wheat production in a Mediterranean environment in Western Australia. *Agricultural Systems*, 90(1–3): 159–179.

Mehmood, M. Z., O. Afzal, M. Ahmed, G. Qadir, A. M. S. Kheir, M. A. Aslam, A. M. U. Din, I. Khan, M. J. Hassan, T. A. Meraj, M. A. Raza and S. Ahmad (2021). Can sulphur improve the nutrient uptake, partitioning, and seed yield of sesame? *Arabian Journal of Geosciences*, 14: 865.

Mehmood, M. Z., M. Ahmed, O. Afzal, M. A. Aslam, R. Z. U. Arfeen, G. Qadir, S. Komal, M. A. Shahid, A. A. Awan, M. A. Awale, A. Sameen, T. Kalsoom, W. Nasim, F. U. Hassan and S. Ahmad (2021). Internet of Things (IoT) and sensors technologies in smart agriculture: Applications, opportunities, and current trends. In: *Building Climate Resilience in Agriculture* (Jatoi *et al*., eds.). Chapter 21. Springer International Publishing, Switzerland. ISBN 978-3-030-79408-8, DOI: 10.1007/978-3-030-79408-8.

Mehmood, M. Z., G. Qadir, O. Afzal, A. M. Din, M. A. Raza, I. Khan, M. J. Hassan, S. A. Awan, S. Ahmad, M. Ansar, M. A. Aslam and M. Ahmed (2021). Paclobutrazol improves sesame yield by increasing dry matter accumulation and reducing seed shattering under rainfed conditions. *International Journal of Plant Production*, 15: 337–349.

Nishio, Z., O. Uchikawa, Y. Hideshima, H. Nishioka, M. Mihara, K. Nakamura and K. Yamaguchi (2019). Influence of precipitation and sunshine hours on yield of paddy field grown wheat (Triticum aestivum L.) in Northern Kyushu, Japan. *Plant Production Science*, 22(4): 479–489.

Parry, M., C. Rosenzweig and M. Livermore (2005). Climate change, global food supply and risk of hunger. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360(1463): 2125–2138.

Pinto, R. S., M. P. Reynolds, K. L. Mathews, C. L. McIntyre, J. J. Olivares-Villegas and S. C. Chapman (2010). Heat and drought adaptive QTL in a wheat population designed to minimize confounding agronomic effects. *Functional Plant Biology*, 37: 255–268.

Ren, A., M. Sun, L. Xue, Y. Deng, P. Wang, M. Lei and Z. Gao (2019). Spatio-temporal dynamics in soil water storage reveals effects of nitrogen inputs on soil water consumption at different growth stages of winter wheat. *Agricultural Water Management*, 216: 379–389.

Reynolds, M. P., P. Langridge and M. Reynolds (2016). Physiological breeding. *Current Opinion in Plant Biology*, 31: 162–171.

Sereyrorth, O., B. Yan, K. Chunpanha, P. Lybun and P. Linvolak (2020). Study on the effects of extreme precipitation for seven growth stages of winter wheat in Northern Weihe Loess Plateau, China. *Journal of Water Resource and Protection*, 12(4): 358–380.

Shaheen, N. (2020). Future changes in growing degree days of wheat in Pakistan: A regional analysis. *APN Science Bulletin*, 10: 45–56.

Sial, M. A., M. A. Arain, S. Khanzada, M. H. Naqvi, M. U. Dahot and N. A. Nizamani (2005). Yield and quality parameters of wheat genotypes as affected by sowing dates and high temperature stress. *Pakistan Journal of Botany*, 37(3): 575–584.

Stella, T., H. Webber, E. Eyshi Rezaei, S. Asseng, P. Martre, S. Dueri and F. Ewert (2023). Wheat crop traits conferring high yield potential may also improve yield stability under climate change. *in silico Plants*, 5(2): diad013.

Stone, P.J. and M. E. Nicolas (1995). Effect of timing of heat stress during grain filling on two wheat varieties differing in heat tolerance. I. Grain growth. *Australian Journal of Plant Physiology*, 22: 927–934.

Tamiru, T., G. Gemedi, B. Debelu and H. Tesfaye (2023). Phenology and yield response of wheat varieties as influenced by sowing dates at Gonde and Ardayita seed production farm, Ethiopia. *Research in Agriculture, Livestock and Fisheries*, 10(2): 133–145.

Thornton, P. K., P. J. Ericksen, M. Herrero and A. J. Challinor (2014). Climate variability and vulnerability to climate change: a review. *Global Change Biology*, 20(11): 3313–3328.

Ullah, S., S. M. Arif, M. A. Aslam, S. H. Khattak, S. Begum, G. M. Ali, M. Murtaza and M. Jamil (2025). Assessment of various herbicides for weed management and their impact on wheat yield components in rice-wheat cropping system in Punjab, Pakistan. *Plant Protection*, 9(1): 173–179.

USEPA. (2011). Office of Solid Waste and Emergency Response. U.S. Environmental Protection Agency, Washington, DC. EPA530-R-99-009.

Wu, X., Y. Tang, C. Li and C. Wu (2018). Characterization of the rate and duration of grain filling in wheat in southwestern China. *Plant Production Science*, 21(4): 358–369.

Zeleke, K. (2021). Simulating agronomic adaptation strategies to mitigate the impacts of climate change on wheat yield in south-eastern Australia. *Agronomy*, 11(2): 337.

Zhao, C., B. Liu, S. Piao, X. Wang, B. D. Lobell, Y. Huang, M. Huang, Y. Yao, S. Bassu, P. Ciais, J. L. Durand, J. Elliott, F. Ewert, I. A. Janssens, T. Li, E. Lin, Q. Liu, P. Martre, C. Müller and S. Asseng (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Nature Communications*, 8: 157.

Zhou, B., Y. Yue, X. Sun, Z. Ding, W. Ma and M. Zhao (2017). Maize kernel weight responses to sowing date-associated variation in weather conditions. *The Crop Journal*, 5(1): 43–51.