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Evaluating Impact of Thermal Heat Units on The Wheat (*Triticum aestivum*) Grain Quality Attributes Under Changing Climate of Central Plain Region of Punjab Pakistan

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Abstract

Wheat plays pivotal role to ensure food security globally, being a staple crop in Pakistan its importance as cereal crop cannot be disregarded. Wheat quality becomes main concern for breeders, agronomists and cereal grain quality researchers. This research was conducted to evaluate the impact of thermal heat units on the quality of wheat grain. The relationship between thermal heat units and wheat quality attributes viz. thousand grain weight, test weight, moisture content, gluten content and starch content were explored. Seven genotypes namely Akbar-19, Subhani-21, Dilkash-20, Arooj-22, V-20337, V-20330 and V-19317 were sown at two different sowing dates (10, November and 01, December) with three replications under split-plot design. Thermal heat units were determined at each growth stage (emergence, tillering, stem elongation, booting, heading, flowering, kernel development, milk development, dough development and ripening). The positive relationship of thermal heat with thousand grain weight and starch content appeared ($\alpha = 0.05$) with p-value 0.034 and 0.045 respectively. While, accumulation of thermal heat units negatively influenced gluten content, moisture content and protein content with significance level ($\alpha = 0.05$) and critical value (p-value) 0.010, 0.000, 0.034 respectively. A very weak non-significant ($p = 0.173$, $\alpha = 0.05$) positive relationship between thermal heat units and test weight was observed. The year wise and sowing date wise variations in

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thermal heat units were significant ($p = 0.002$ @ $\alpha = 0.05$). The findings of this research highlight the critical influence of thermal heat units on key wheat grain quality attributes, that may help to optimize sowing dates and select suitable genotypes to maintain grain quality under changing climatic conditions.

Keywords: Wheat, Quality traits, Thermal heat time, Climate change, Punjab, Pakistan

INTRODUCTION

Wheat (Triticum aestivum L.) is one of the world's most important cereal crop and ensure food security of millions of people around the globe. This golden grain is the staple food of 35% of the world population including Pakistan, and fulfills the major portion of dietary intake including 20% protein. In addition to major nutrition component, wheat protein also determines the elastic properties of dough, especially the gluten (glutenin and gliadin complex) which is essential parameter of wheat grain in baking industries (Bai, Khoddami, Messina, Zhang, & Tan, 2025; Sharma & Kumar Sharma, 2025). Therefore, grain quality, in addition to yield, is a central concern of wheat researcher, as it directly influences nutritional value, grain processing performance, and end-use suitability of the products. Wheat grain quality is determined by protein and its composition, starch, 1000 grain weight, moisture contents and test weight etc. Wheat grain development is largely a physiological phenomenon, in which different nutritional compound accumulate in the grain during grain filling stage, and duration of grain filling is majorly affected by certain environmental anomalies. Plant growth stages and their durations largely depends on genetics, however climatic factors, soil fertility and cultural practices also account for prolong or shortening of plant growth stages. Among the climatic factor temperature is the most crucial that effect the plant phenology (Miller, Lanier, & Brandt, 2001). Spring wheat is a temperate crop best adapted to temperatures below 30 °C, with a threshold of 26 °C during the post-anthesis stage. Exposure to heat stress above 35 °C severely affects both grain yield and quality, particularly during anthesis and grain filling. While extensive research has examined the influence of heat stress on yield-related traits, comparatively fewer studies have addressed its impact on grain quality attributes. Elevated temperatures disrupt grain development by reducing assimilate supply, shortening the grain-filling period, altering the grain-filling rate, and impairing starch biosynthesis and deposition pathways (Wang et al., 2018). A crop needs certain amount of accumulated heat to complete its specific growth stages and life cycle. This accumulated heat unit also termed as thermal time (TT) which refers accumulated

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heat absorbed by plant. Thermal time, generally measured in growing degree days (GDD), which is calculated by averaging the day's maximum and minimum temperatures and subtracting the crop's base temperature, below which the plant growth ceases. (Aslam et al., 2017). Additionally, TT triggers sequential changes in key quality attributes such as thousand grain weight (TGW), test weight (TW), protein content (PC), starch content (SC) and gluten content (Asseng, Foster, & Turner, 2011). The interaction between the quality traits and thermal time is complex, because variations in temperature during critical growth stage may alters the compositional structure of grain thereby manipulating end-use properties (Farooq, Bramley, Palta, & Siddique, 2011).

Among other critical growth stages, grain filling stage is most likely prone to temperature fluctuation. The accumulation of thermal heat units governs the time frame of protein and starch synthesis in developing kernels. A desirable thermal heat unit endorses effective starch biosynthesis, efficient flour yield extraction, improved dough elasticity and baking properties (Hafeez et al., 2023). Excessive heat accumulation, during grain filling stage, quickens the rate of grain maturity imposing reduction in period of nutrient integration, resulting in lowering protein content and damage gluten proteins fraction (Tewolde, 2019). Higher temperature variations of thermal heat units exhibits decline in test weight resulting in lower flour extraction rates and milling efficiency which effects the economic value of wheat grain (C. Zhao et al., 2017).

The effect of temperature stress during reproductive and grain filling growth stage on the quality attributes appears impactful through several physiological mechanisms. As protein synthesis is carried out by enzymatic activity, rising temperatures induces disruption in chemical process leading to compositional alterations in gluten proteins (gliadin and glutenin) which is detrimental to dough strength (Koga et al., 2016). Additionally, longer thermal time prevalence accelerates moisture loss from grains which modifies starch-protein proportion that results in affecting baking quality of flour (Balla et al., 2011).

Several approaches have been executed to mitigate the detrimental effects of excessive thermal time on wheat quality. These strategies includes introducing heat tolerant cultivars through breeding, optimization of sowing dates and improving agronomic and irrigation practices (de Oliveira Silva, Slafer, Alderman, & Carver, 2026). Research on the effects of growing degree days (GDDs) on wheat highlights major gaps, as current cultivars with single-stress tolerance are inadequate against rising temperatures that shorten grain filling, disrupt biomass partitioning, and impair key quality traits. Advancing food security requires region-specific GDD studies alongside integrated approaches such as multi-omics, MAS, CRISPR, AI-driven breeding to develop resilient, high-quality wheat varieties suited to

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Punjab's changing climate (Han, Wang, & Sun, 2025). The current research focused on the estimation of TT at selected critical growth stages. The growth stages were defined as per Zadok's scale. The seven genotypes, comprising widely grown mega varieties and advanced lines, were evaluated under two sowing dates, with November 10 representing the normal recommended sowing and December 01 serving as late sowing to impose terminal heat stress conditions. This approach strengthens the rationale by assessing the performance of promising germplasm for both heat tolerance and grain quality retention under normal and stress-prone environments.

2. Material and Methods

2.1 Experimental location and weather conditions

The experiment was conducted in the field area (latitude: 31.39256 N, longitude: 73.04397 E) of Wheat Research Institute (WRI), AARI, Faisalabad (Figure 1) during 2022-23 and 2023-24 cropping season. Soil samples were taken from the experimental field prior to crop sowing in 2022-23 and analysis was performed in the Soil and Water Testing Laboratory, AARI, Faisalabad. The experimental site had a sandy clay loam texture with the following physico-chemical properties: pH 8.24, electrical conductivity (EC) 0.87 dS m^{-1}, organic matter 1.00%, available phosphorus 16.76 mg kg^{-1}, and available potassium 419 mg kg^{-1}. The soil type of study area is loamy. It falls under semi-arid climatic conditions which undergoes hot summers, mild winters and low to moderate rainfall. The winter temperature usually ranges from 5 °C to 20 °C. While temperature during summer season reaches above 40 °C. Figure 2 represents monthly average climatic data for study period 2022-23 to 2023-24..

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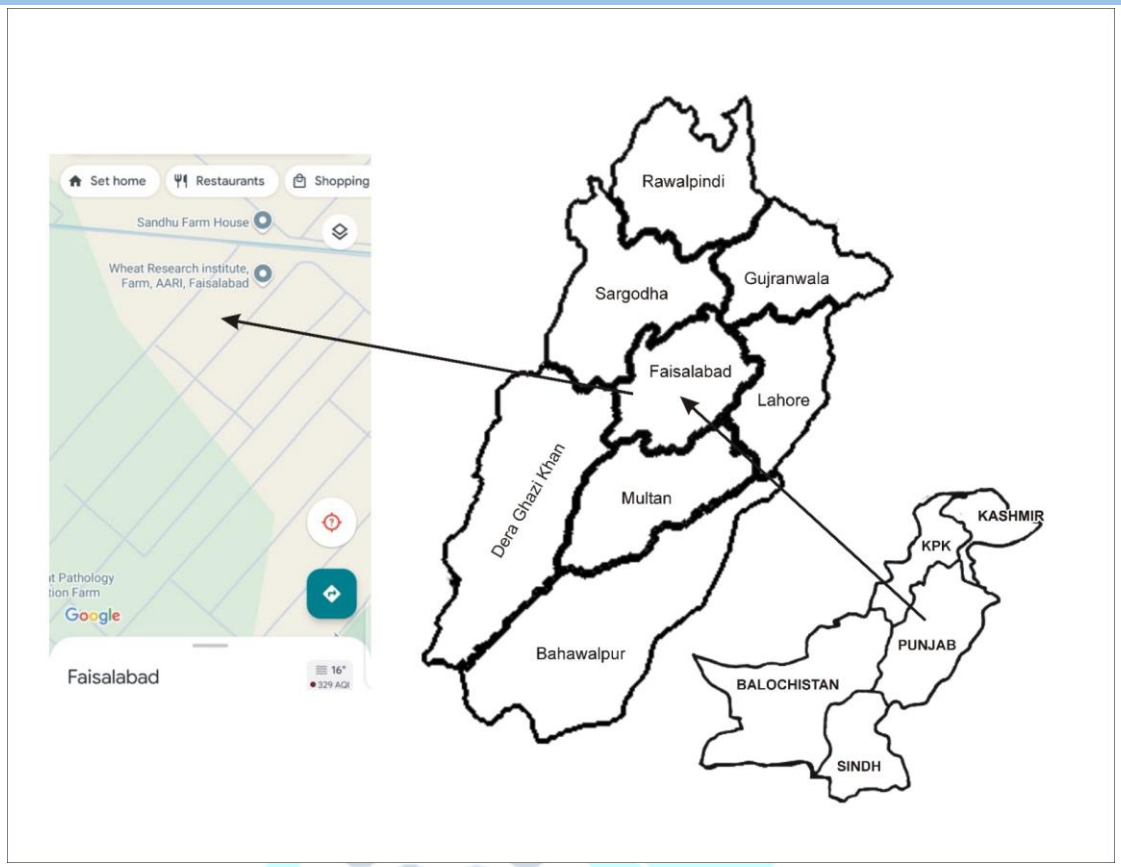


Figure. 1: Geographical map of Wheat Research Farm area (experimental location)

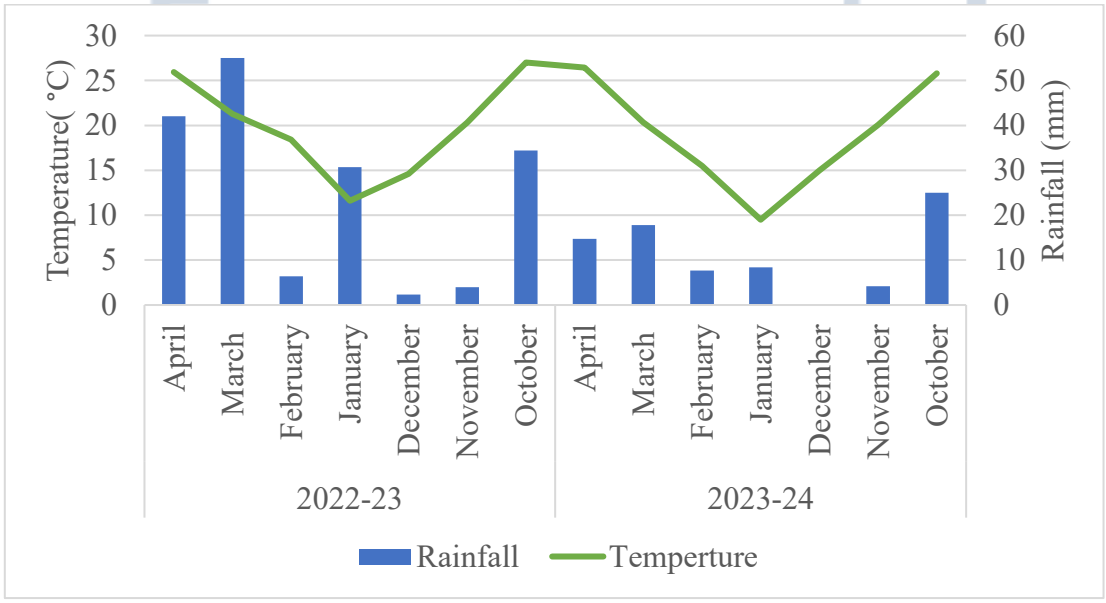


Figure 2. Seasonal Average Temperature and Rainfall Pattern of the Faisalabad region. T (2022-23) and T (2023-24) denotes temperature in centigrade. Rainfall (2022-23) and Rainfall (2023-24) represents precipitation over the crop season. R.H (2022-23) and R.H (2023-24) indicates relative humidity (%).

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2.2 Plant Material and Treatments

Seven genotypes (Akbar-19, Subhani-21, Dilkash-20, Arooj-22, V-20337, V-20330 and V-19317) evaluated during the 2022-23 and 2-23-24 cropping season under two different sowing dates viz. 10 November (D1) and 01 December (D2). Seed of these genotypes were taken from Wheat Research Institute, Faisalabad, the organization that maintained true to type seed purity, multiply it and distribute it to other organization for research purposes. Their purity and true-to-type identity were confirmed through field inspection and morphological comparison with standard descriptors. The layout of experiment was split-plot design with genotype (treatments) as sub-plot and sowing dates (treatments) as main plot factors. The net plot size was 5.0 m × 1.62 m. The parentage and pedigree of genotypes evaluated in experiment is given in Table 1

Table 1. Plant Experimental Material with parentage/pedigree

S. No.	Code	Parentage/Pedigree
1	V-20330	MANKU/BOKOTA CMSS14Y00846S-099Y-099M-099Y-7M-0WGY
2	V-19317	WBLL1//PUB94.15.1.12/WBLL1/3/MUCUY PTSS14Y00345S-0B-099Y-099B-29Y-0B
3	V-20337	VILLA JUAREZ F2009/3/T.DICICCIN P194625/AE.SQUARROSA(372)//3*PASTOR/4/WBLL1*2/BRAMBLING/8/PSN/BOW/SERI/3/MILLA/4/ATTILA/5/KAUZ*2/CHEN//BCN/3/MILAN/5/WBLL1*2/SHAMA/CMS14Y01209T-099TOPM-099M-099Y-6M-0WGY
4	Akbar-19	BECARD/QUAIU#1CMSS07B00230S-099M-099NJ-23WGY-0B
5	Subhani-20	KACHU/SAUL*2/5/SERI.1B//KAUZ/HEVO/3AMAD*2/4/KIRITATIC MSS10B010307-099TOPY-099M-099NJ-WGY-0B
6	Dilkash-20	WBLL*2/4/SNI/TRAP#1/3/KAUZ*2/TRAP//KAUZ/5/PB.96//LU26/HD 2179 PB.35237-0A-0A-5A-0A-0A
7	Urooj-22	SOKOLL/3PASTOR//HXL7573/2*BAU*2/6/OASIS/5*BORL95/5CNDO/R143//ENTE/MEX175/3/AE.SQ/4/2*OCI CMSA10M00159T-050Y-099ZTM-099NJ-5WGY-0B

2.3 Seed bed preparation

Following the harvest of the preceding rice crop, the field was deep-ploughed to break the hardpan, and rice stubbles were incorporated into the soil. Seedbed preparation was carried out using a cultivator (two passes), each followed by planking. In both years, wheat was sown in a well-prepared seedbed on the assigned sowing dates using a Norwegian planter, a special seed metering device designed to plot yield trials in plant breeding (Øyjord, 1968), at a seed rate of 100 kg ha^{-1}. Fertilizers were applied at the rates of 114 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1}. Urea (46% N), diammonium phosphate (18% N, 46%

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P_2O_5), and sulfate of potash (50% K_2O) served as the sources of nitrogen, phosphorus, and potassium, respectively. At sowing, the full doses of phosphorus and potassium, along with one-third of the nitrogen, were applied as a basal dose. The remaining nitrogen was top-dressed in two equal splits with the first and second irrigations. A total of four irrigations (16 acre inch) were applied during the growing season. Experimental trial of 1st season was harvested on April 24, 2023 and of 2nd season on April 24, 2024.

2.4 Data Collection

Determination of Thermal Time (TT) or Growing Degree Days

Thermal time (TT) is the amount of heat accumulated by plant leaf from sowing to maturity, helps to predict rate of growth stage (Kumar et al., 2023). The plant undergoes different growth stages during production phase. The base period of crop was divided in to different growth stages (emergence, tillering, stem elongation, booting, heading, flowering, kernel and milk development, dough development and ripening) as per Zadok's scale. The number of days from sowing to desired growth stage were recorded to calculate thermal heat units.

The thermal time (TT) in relation to growth stages was determined using the eq. 1;

$$Thermal\ time\ (TT) = \left\{\frac{Tmax + Tmin}{2} - Tbase\right\} X\ G.Sdays \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where;

Thermal time (TT) = Thermal time or growing degree days

Tmax = Daily maximum temperature

Tmin = Daily minimum temperature

Tbase = Base temperature taken as 5 °C

G.S days = Number of days for particular growth stage

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The data for other stages were recorded following the procedure as leaf emergence.

2.5 DETERMINATION OF QULAITY TRAITS

The wheat quality parameters were determined after harvesting of crop. The relationship

between thermal time (TT) and grain quality attributes i.e., thousand grain weight (TGW),

test weight (TW), moisture content (MC) gluten content (GC) and starch content (SC) was

evaluated.

2.5.1 Thousand Grain Weight

The seeds of each variety were counted (1000 seeds) on digital seed counter and weighed on digital weight balance apparatus.

2.5.2 Test Weight

Test weight was determined through test weight apparatus. The grains were filled in the measuring cylinder using hopper. The grains were allowed to settle under gravity avoiding any manual tapping. The excessive grains from top edge of cylinder were wiped off by a levelling blade. The filled cylinder was measured using a weight balance. The measured weight was converted into kilogram per hecto liter (kg/hL).

$$Test\ weight\ \left(\frac{kg}{hL}\right) = \{Grain\ weight\ (g)/1000\} * 100 \quad \text{.....(1)}$$

2.5.3 Proximate Analysis

Protein, moisture and starch contents were measured through omeganalyser. It is a sophisticated instrument which makes use of light source omitted from tungsten halogen lamp. The light passes through monochromator and diffracted by optical grating. For different grating angle, specific NIR wavelength is obtained at the exit slit. The NIR radiations collides the sample present in sample shaft. After collision with sample, the reflects leaving the sample shaft. A major proportion of this light is collected by the detector generates a photometric signal. Finally, the absorbance value is calculated from sample reading/reference reading ratio. This value represents the certain quality parameter.

2.5.4 Gluten Quality

Gluten quality was determined through glutomatic system. The wet gluten and gluten index were estimated using eq. 3 & 4. This method is based on the principle of gluten washer and gluten index centrifuge. The gluten separated from wheat flour by the glutomatic was centrifuged by powerful force to separate wet gluten which was collected on specially constructed sieve. The part of gluten remains on

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sieve while some proportion pass through the sieve. The gluten percentage remained on sieve collected as gluten index, while the total weight of gluten is called gluten quantity.

$$Gluten\ Index(\%) = \frac{Gluten\ remained\ on\ sieve\ (g)}{total\ Gluten\ (g)} X\ 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$Wet\ gluten\ content\ (\%) = \frac{Total\ Gluten\ (g)}{10\ (g)} X\ 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

2.6 Statistical Analysis

The data were statistically analyzed through R software for ANOVA and relationship between thermal heat units (CD) and quality attributes. The packages like lmer, lme4, multicompview, emmeans, ggplot2 and dplyr were used for detailed analysis.

3. Results

3.1 Analysis of variance for thermal time (TT): Analysis of variance showed that Thermal time varied significantly against the year (P = 0.002 at α = 5%), sowing date (P = 0.002 at α = 5%) and their interaction (P = 0.002 at α = 5%) (Table 2). Results showed that the significant (p = 0.002 at α = 5%) effect of sowing date on the thermal time accumulation during the both seasons. Similarly, thermal time also was influenced significantly (p = 0.002 at α = 5%) over the years. This effect might be reflected due to protruding temperature differences over the study period (2022-23 to 2023-24).

Table 2. Analysis of Variance (ANOVA) for Thermal Time (TT) across the sowing year

	Sum Sq	Mean Sq	DF	F value	Pr(>F)
Year	24651	24651	1	223.4485	0.002***
Sowing Date	1497865	1497865	1	13577.5	0.002***
Variety	930	155	6	1.4058	0.229
Year x Sowing Date	25915	25915	1	234.9081	0.002***
Year x Variety	930	155	6	1.4058	0.229
Sowing Date x Variety	582	97	6	0.879	0.516
Year x Sowing Date x Variety	582	97	6	0.879	0.516

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

3.2 Multiple comparison of Thermal Time) for year and sowing date: Statistical analysis showed that crop sown on 10th Nov accumulates more thermal heat units more than 1900 as compared to crop sown on 1st Dec which accumulates 1600 thermal heat units

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(Figure 3). The thermal time (TT) remained 60.1 units higher during 2022-23 than the later year 2023-24. Likewise, the crop sown on 10 November (early sowing) accumulates 267 units more thermal time comparing the crop sown on 01 December (Table 3). This difference was highly significant with $p \leq .0001$. The temperature data of both years also revealed that year 2022-23 remained hotter than the year 2023-24 (Table 4). The difference of thermal time was depicted, when comparing between the sowing dates. Additionally, sowing date comparisons revealed thermal time variations, suggesting that both seasonal climate differences and planting time critically influence wheat's heat unit accumulation during the growth periods.

Table 3. Year-wise and sowing date-wise comparison of Thermal Time (TT)

Contrast	Estimate	SE	df	t.ratio	p.value
Year:2022-23 & 2023-24	60.1	5.32	1620	11.313	<.0001
Sowing date:10 November & 01 December	267	2.29	56	116.523	<.0001

Table 4. Month wise Average Temperature During Growing Seasons

	2022-23		**2023-24**	
Month	T_{max}	T_{min}	T_{max}	T_{min}
October	34.07	18.90	32.48	19.08
November	28.22	12.41	26.43	13.74
December	21.82	7.35	22.47	7.58
January	18.41	4.81	13.31	6.02
February	26.12	10.69	22.90	8.09
March	*28.20*	15.39	29.20	16.39
April	33.49	18.38	33.89	19.02
Average	27.19	12.56	25.81	12.84

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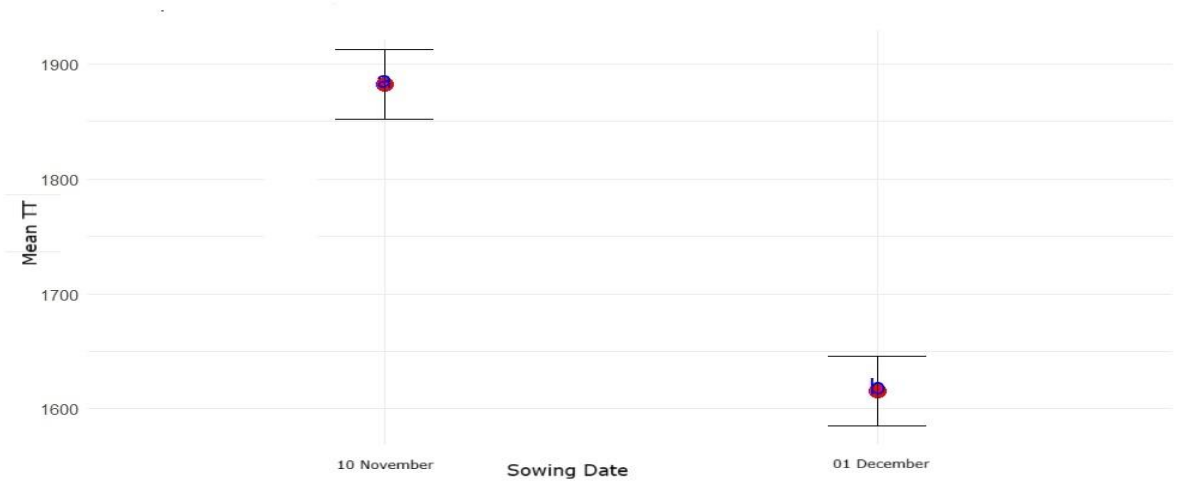


Figure 3. Plot of thermal time (TT) and sowing dates; 1= crop sown on 10 November, 2 = crop sown on 01 December

3.3 Relationship between wheat grain quality traits and thermal time (TT)

Thermal time was found to be significantly correlated with most of wheat grain quality traits (Table 5, Figure 4) in the figure only the traits which are significantly correlated with the TT are shown. Thousand grain weight GW_{1000} is an important parameter of wheat grain indicating seed size, density and grain development. It is a crucial parametric factor that play role in milling yield, flour extraction and end-use quality (Shewry, 2015). The study revealed positive relationship (r = 0.231) of thermal time with GW_{1000} (Figure 3), which appeared statistically significant (p = 0.034) Table 6.

Test Weight (TW) is a crucial quality parameter which is usually expressed in kilograms per hectolitre (kg/hl). It provides an indirect insight into grain density, maturity, representing grain filling and overall milling efficiency (Pagani, Marti, & Bottega, 2014). Table 6 represent a very weak positive relationship (r = 0.150) between TW and TT, it appeared statistically non-significant ($p>0.05$). Study revealed negative (r = -0.320) relationship between protein contents and thermal time (Table 5, Figure 4). The correlation appeared statistically significant ($p<0.05$). This indicates higher increase in protein content with slight decrease in TT.

The study found a moderate negative correlation (r = -0.425, $p<0.001$) indicating that higher variation in TT significantly diminishes moisture contents (Table 5).

Starch is mainly a structural component in wheat grain. It affects dough strength and baking quality (Delcour & Hoseney, 2010). This research revealed a weak positive correlation (r = 0.216, $p<0.05$) between SC and TT (Figure 4). It suggests that slight increase in TT during late hard dough-growth stage enhance starch synthesis which stimulates gelatinization properties.

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Gluten proteins (gliadins and glutenins) play pivotal role in influencing dough viscoelasticity. The results showed highly significant negative relationship (r = -0.277, *p = 0.010*) between gluten content and thermal time (Figure 4). This indicates that higher TT, at kernel hard dough-growth stage, tends to reduced gluten content altering gliadins and glutenins composition.

Table 5. Correlation Coefficient of Thermal Time and Quality Traits

	2022-23 to 2023-2024	
Quality Traits	***r***	***p-value***
GW_{1000}	0.231	0.034*
Test Wt.	0.150	0.173
Protein (%)	-0.230	0.034*
Moisture (%)	-0.425	0.000***
Starch (%)	0.216	0.048*
Gluten (%)	*-0.277*	0.010**

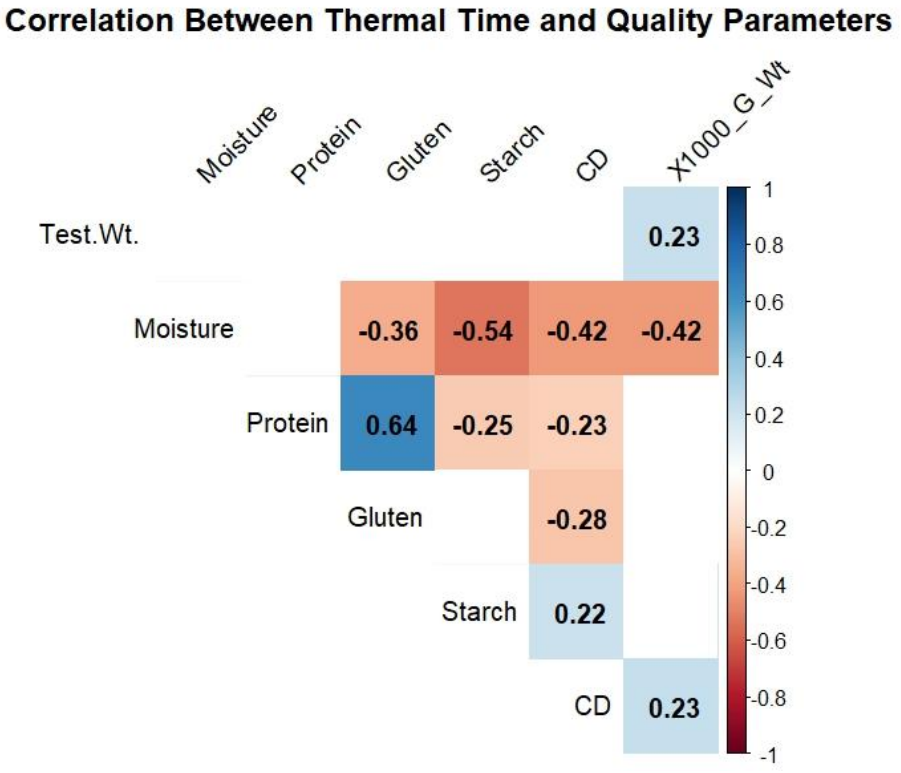


Figure. 4: Correlation between thermal time and grain quality traits

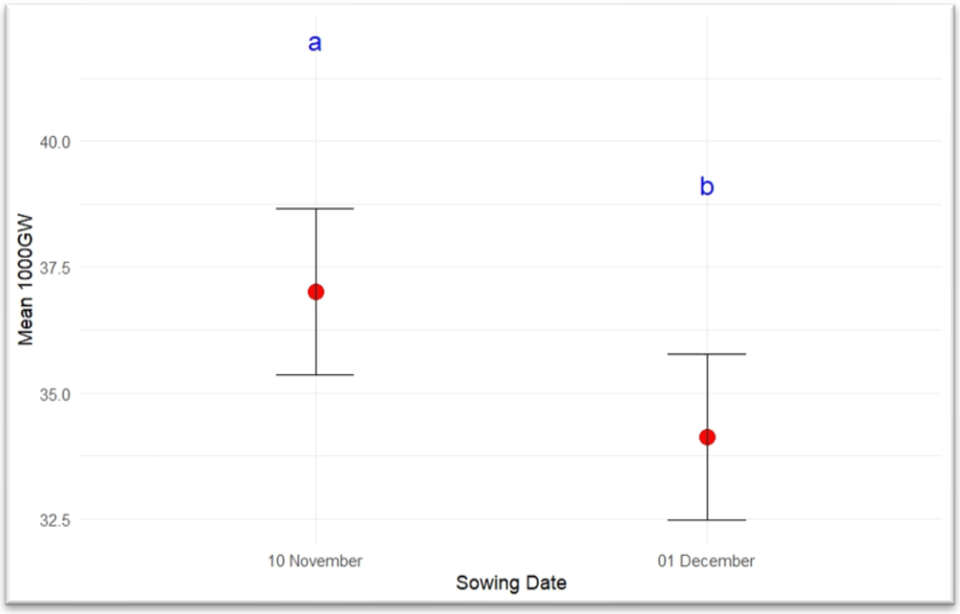
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3.4 Relationship between wheat grain quality traits and sowing dates

Effect of sowing dates on the quality parameters of grain was found to be significant for thousand-grain weight, moisture content, and starch levels. Crop sown on D1 was found to have more 1000 grain weight as compared to D2. Similar trend was observed for the of starch contents, as grain from the harvest of D1 has higher starch accumulation as compared to D2. Variety had no significant effect on any quality trait (P = 0.4665 to 0.9070). None of the interactions (year × sowing date, year × variety, sowing date × variety, or the three-way interaction) was significant for any trait. (Table 6, Figure 5).

Table 6. Analysis of Variance (ANOVA) for Grain Quality Traits across the sowing dates and sowing year

P-vlaue						
Source of Variation	Gluten	Moisture	Protein	Starch	Test Weight	1000G.W
Year	0.0639	0.0001***	0.0857	0.0147*	0.2624	0.7403
Sowing Date	0.0245*	0.0000***	0.0652	0.0015**	0.2239	0.0001***
Variety	0.4692	0.9070	0.7577	0.4665	0.7899	0.5711
Year x Sowing Date	0.9573	0.5193	0.2648	0.2075	0.3832	0.4243
Year x Variety	0.1253	0.2622	0.6505	0.8846	0.3388	0.9550
Sowing Date x Variety	0.4648	0.7387	0.6290	0.3309	0.7375	0.9978
Year x Sowing Date x Variety	0.2888	0.2392	0.6093	0.9362	0.1576	0.9733



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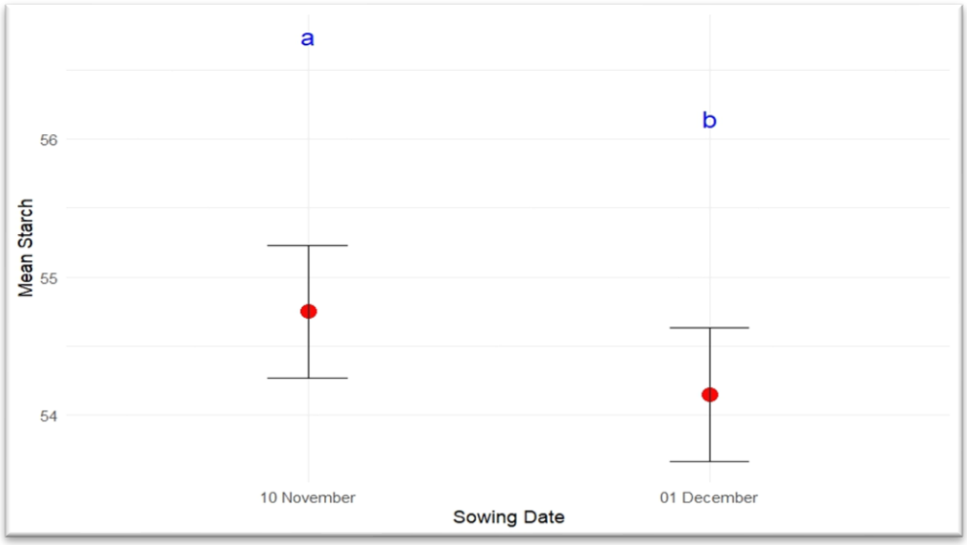


Figure 5. Multiple comparison of GW_{1000} and starch contents against the sowing dates

3.5 Thermal time for different wheat varieties across growth stages: The statistical analysis of the thermal time units required to reach the specific stage of crop growth indicated that sowing dates significantly affected the days to attain specific stage. The Mean thermal time accumulated by each genotype at selected growth stage is represented by figure 6 & 7 for year 2022-23 & 2023-24 respectively. During the cropping season 2022-23, the crop sown on D1 sowing date showed a minute difference in variation of thermal time units required to reach specific growth stage comparing to experimental trial sown on D2 sowing date in figure 6. Akbar-19, Arooj-22 and Dilkash-20 availed less thermal heat unit (1000) as compared to Subhani-21 and advance lines that avail ~1500 (Figure 6). While, during the cropping season 2023-24 slighter variations in accumulation of thermal time exhibits rising temperature during year 2022-23 (Table 4). During year 2023-24, slight change in the behavior of thermal heat units required to complete crop growth stages among the varieties was observed. As this season was relatively cooler than the previous all genotypes sown on D1 accumulate higher heat unit to complete all phenological growth stages as compared to D2 sowing date. At D1 all genotypes accumulate more than 1500 thermal heat units up to their ripening stage as compared to S2 which took less than 1500 thermal heat unit (Figure 7).

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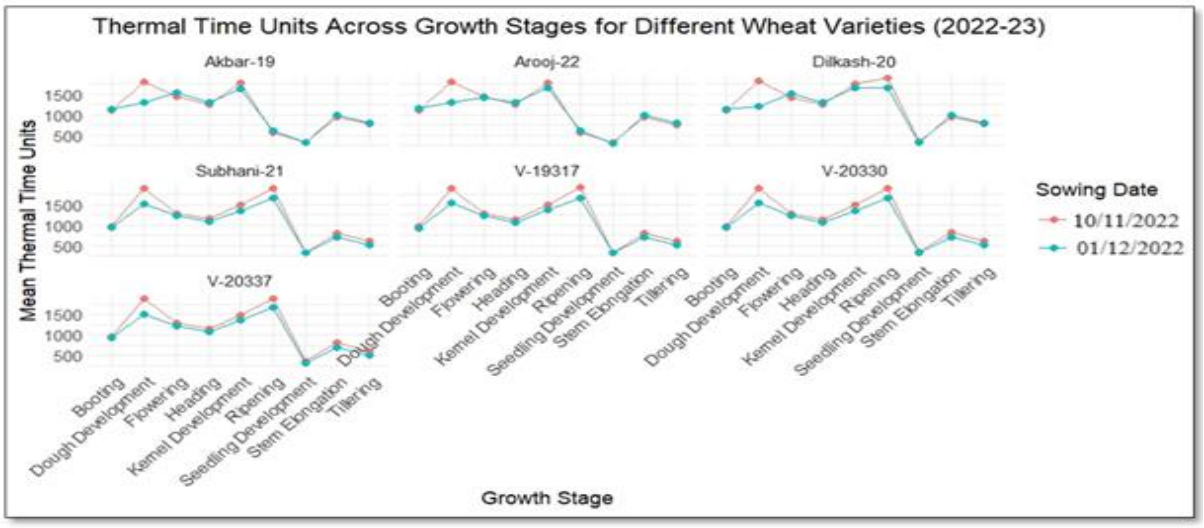


Figure 6. Thermal Heat Units Across Growth Stages for Different Wheat Varieties (2022-23)

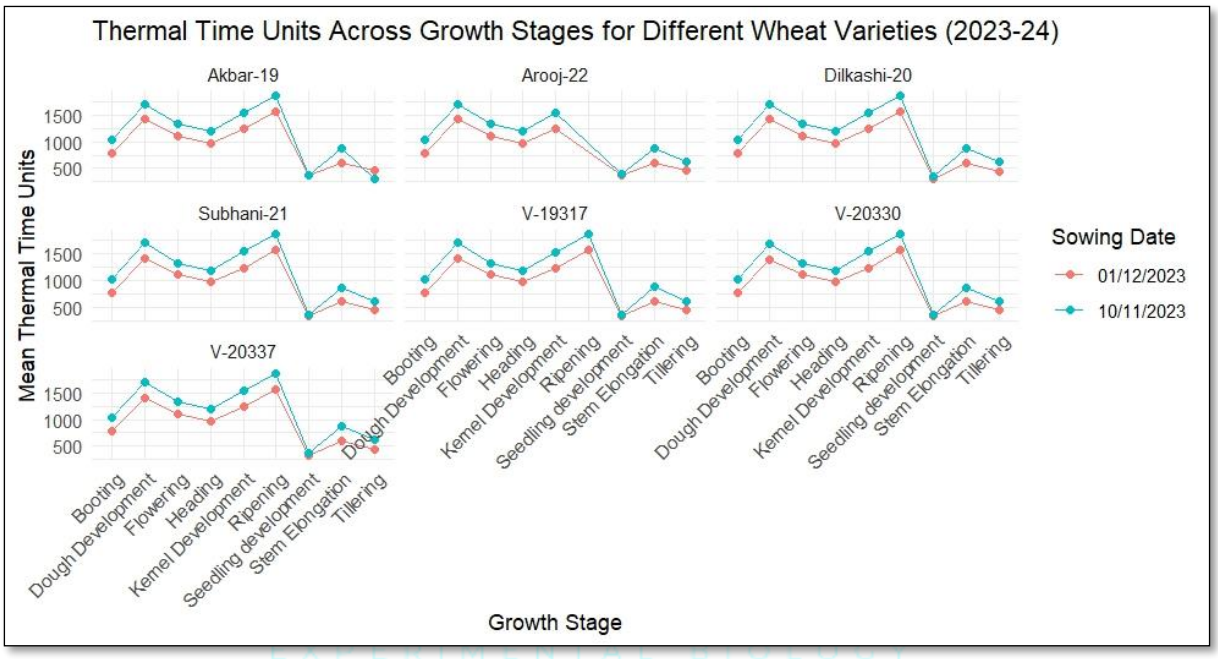


Figure 7. Thermal Heat Units Across Growth Stages for Different Wheat Varieties (2023-24)

4. Discussion

Wheat grain quality is determined by key traits such as GW_{1000}, protein content, starch composition, gluten strength, and test weight, all of which influence milling efficiency, dough properties, and end-product quality (Hassoon, Dziki, Miś, & Biernacka, 2021). The assessment of impact of environmental conditions is vital, making it an important trait in evaluating wheat performance and market value (Hassoon et al., 2021). This study showed that sowing date was the dominant factor that affect the thermal time in accumulating heat units to attain the specific crop growth stage and ultimately the grain produce. Therefore, planting timing strongly influences heat unit requirements in wheat, likely due to varying

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temperature conditions across different sowing dates (Figure 3). The inter-seasonal variation suggested that yearly climatic differences, such as fluctuating temperatures between 2022-23 and 2023-24, further affected thermal time, impacting crop growth and development stages. In a study in china it was observed that over the past four decades, accumulated GDD for winter wheat has risen markedly, with stronger increases in the northern regions than in the south. This warming, driven by climate effects, has reduced the number of colder days and significantly shortened the sowing to jointing duration in northern winter wheat areas (Liu et al., 2025). The crop sown on D1 (10 November) accumulated 267 more thermal heat units than the crop sown on D2 (01 December). This difference remained highly significant (Table 2&3). The thermal heat units accumulated by crop grown on 10 November and 01 December were about 1882 and 1615 respectively (Figure 3). Bisht *et al.* (2019) also observed that mid-November sowing crop avail higher heat units at all stages of crop and with delay in sowing heat unit consumption by the wheat plant decreased significantly.

The positive correlation ($r = 0.231$, $p = 0.034$) between thermal time and GW_{1000} (Figure 4) suggests that higher accumulated heat units during the growing season promote better grain filling, likely by extending the duration for starch and protein deposition, leading to larger, denser grains. This aligns with previous findings (Shewry and Hey 2015), as improved GW_{1000} enhances milling yield and end-use quality, reinforcing the importance of temperature-driven growth conditions in wheat grain development. GW_{1000} is associated with grain uniformity, which is necessary for storage stability and economical processing (Moradi, Tarzi, Farhoodi, & Fallah, 2015). Study found a clear indication of slight increase in GW_{1000} with higher TT values. According to Moradi *et al*. (2015), GW_{1000} is vital for end-use quality, inducing useful impact on flour yield extraction and dough rheology. Test weight influences flour extraction rates, enhanced baking quality and higher economic value in market (Y. Zhao et al., 2023). Weak positive correlation between test weight and TT indicates that variations in TT imparts non meaningful impact on test weight. Similar research by Ni *et al.* (2022) suggested that test weight may not directly affect compositional quality parameters, but it is an gage of kernel density. MC levels are associated with storage quality and enzymatic activity which ultimately affect compositional stability (Hassoon et al., 2021). This highly significant moderately strong relationship suggests that higher thermal time reduces moisture contents in wheat grain. This finding is aligned with the research conducted by Savin *et al*. (1996). MC is critical during the kernel hard-growth stage, as higher TT means increased temperature which influence grain quality, storability and milling performance. Jiang et al. (2025) also reported similar findings. Alternatively, reduced TT means decreased temperature during late hard dough stage, induces prolong grain moisture retention resulting delay in harvesting and enhances chances of sprouting. These findings are

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coherent with observations of Zhao et al. (2022).

Wheat a photosensitive crop which is effected by growing degree days accumulate more starch in grains when sown earlier due to prolonged period of growth cycle as compared to late sown crop (Dhaka, Bangarwa, Pannu, Malik, & Garg, 2006). We have observed similar trends of early sown crop in which grains found to have more starch units as compared late sown crop and resultantly the 1000 grain weight of the late sown crop was less as compared to early sown due to shriveled grain as crop undergo forced maturity due to terminal heat stress. Similar trend was also observed in the study of (Modh & Mor, 2024).

Generally, at high temperatures (37 °C), plants prioritize energy allocation toward stress response over routine metabolic processes. This shift redirects photosynthetic assimilates from regular metabolism to thermal protection and reserve storage, promoting increased storage protein accumulation and stabilizing the dry matter filling rate in grains (Wang et al., 2018). The negative association between protein contents and TT were also observed by Wang *et al*. (2018) representing that higher protein accumulation may influence starch-protein interactions, thereby manipulating TT negatively. The previous findings reported by Zhang *et al*. (2021) are aligned with this study. Several factors have been suggested to explain increased protein content in grains. These include the source-sink dynamics driving leaf-to-grain translocation, the interplay of carbon and nitrogen allocation during grain development and metabolism in both leaves and grains (Bonfil, Abbo, & Svoray, 2015), and the synchronized timing of carbon and nitrogen assimilation in endosperm cells. Moreover, increased TT shortens the period of late hard dough stage resulting higher starch accumulation (Han et al., 2025). But, excessive temperature (above 30 ^{0}C) at this growth stage hinders starch synthesis, resulting reduced starch contents which alters starch structure (Lu et al., 2019). On the contrary, lower TT due to cooler temperature during late hard growth stage may enhance starch accumulation, thus, may reduce yield (K. Zhao et al., 2022).

In case of gluten, negative association was found with TT, Koga *et al*. (2016) also reported that higher growing degree days due to increased temperature is greatly associated with changings in composition of gluten proteins, which ultimately affect the dough elasticity and stability. Furthermore, higher TT as a result of increased temperature during kernel hard growth stage weakens bread dough strength due to compositional changes in the gliadins to glutenins ratio (Tanaka et al., 2021) (Table 5, Figure 4). Under combined heat and drought stress, wheat exhibits notable changes in grain composition, with total protein content and gluten content increasing by 65% and 32%, respectively, compared with control conditions (Sattar et al., 2020). Greenhouse experiments further reveal that heat stress (35 °C day temperature) alters the relative proportions of storage proteins, leading to higher levels of both high and low molecular weight glutenins

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compared to a control environment (K. Zhao et al., 2022).

It was observed that crop sown on D1 accumulate more heat units and days to complete its grain filling period by all the genotypes under study as compared to crop sown on D2 sowing date. Whereas, a slight difference was observed among the genotypes that were sown on D2 sowing dates. The rising temperature might be reason of this slight variation of thermal unit between D1 & D2, as higher temperature triggers the growth stage. There are evidences reporting the shorter crop growth cycle due to increased thermal time period resulting from rising temperatures (Gürkan et al., 2024). Lower temperature than former year, resulted in little longer period of crop growth cycle. Hatfield *et al*. (2011) also revealed that lower temperature induces reduced rate of growth stage. This slower growth rate tends prolonged days to trigger from one growth stage to other growth stage, consequently, prominent difference was observed in thermal time accumulation between sowing date D1 & D2 during year 2023-24 (Figure 5, 6). Environmental temperature strongly influences wheat phenology and yield, as reflected through agrometeorological indices like TT. Similarly, in a study of varying sowing dates, heat unit accumulation ranged from 264 1,960 growing degree days across different growth stages, with the earliest sowing date recording significantly higher accumulated units for all phenological stages compared to later sowings. Variations in thermal indices with sowing environments and cultivars highlight the importance of timely sowing to synchronize crop growth with favorable thermal regimes and maximize the yield potential.

5. Conclusion

This study highlights that accumulated heat thermal units significantly influence wheat grain quality attributes such as protein, starch, gluten, and thousand-grain weight, as well as yield performance across different sowing dates. Early sowing (November 10) allowed for better alignment with optimal thermal regimes, resulting in improved yield and more stable quality parameters compared to late sowing (December 01), which exposed crops to terminal heat stress and reduced quality retention.

The findings are limited to a single location and less cropping season data, and lack integration of molecular studies such as functional gene analysis of genes influencing the targeted grain quality traits. To build on these results, future research should incorporate multi-location, multi-year trials along with molecular and omics-based approaches to better dissect the genetic control of quality traits under heat stress. For breeding programs, focusing on stable grain-quality traits, while optimizing sowing patterns for different ecological zones to avoid terminal heat stress, will be key strategies to sustain both yield and quality in wheat under changing climatic conditions.

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Authors Contribution

Azhar Mehmood (Manuscript write up from own study/research and performed grain quality analysis); **Javed Ahmed** (conceptualization, and supervision); **Razia Sultana** (Helped in field data collection and write up); **Muhammad Abdullah** (Performed grain quality analysis); **Ahmad Kamal** (Field data collection); **Mohammad Owais** (Field data collection); **Majid Nadeem** (Field data collection); **Sadaf Shamim** (Performed grain quality analysis); **M. Usman Khalid** (Writing – Review & Editing).

Conflict of interest

The authors declare no competing interests.

Availability of data and materials

Data will be available through the request from the corresponding author.

Ethical approval

All authors approved the paper for submission.

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