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Seasonal Variability in Thermal Indices and Heat Use Efficiency of Maize under Varietal and Nutrient Management in *Tarai* Region of Uttarakhand, India

Anurag Tripathi [a++], Neha Chand [a++], Chinmaya Kumar Sahu [a#], Rajeev Ranjan [a,b†*], Ravi Kiran [a‡], Ajeet Pratap Singh [c‡] and Subhash Chandra [d‡]

[a] *Department of Agrometeorology, College of Agriculture, GBPUA&T, Pantnagar, Uttarakhand, India.*
[b] *ICAR-Central Marine Fisheries Research Institute, Kochi, Kerala, India.*
[c] *Department of Soil Science, College of Agriculture, GBPUA&T, Pantnagar, Uttarakhand, India.*
[d] *Department of Agronomy, College of Agriculture, GBPUA&T, Pantnagar, Uttarakhand, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Original Research Article

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Abstract

Maize (*Zea mays* L.) growth and productivity are strongly influenced by temperature and seasonal climatic conditions that regulate crop phenology and thermal energy utilization. However, limited information is available on seasonal variability of thermal indices and heat use efficiency of maize under different varieties and nutrient management practices in the Tarai region of Uttarakhand. Therefore, a field experiment was conducted at the N.E. Borlaug Crop Research Centre, Pantnagar during the winter (November 2024-April

[++] *Research Scholar;* [#] *Junior Agrometeorologist;* [†] *Assistant Professor & Senior Scientist;* [‡] *Professor;*
**Corresponding author: E-mail: drrajeev.ranjan@icar.org.in;*

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2025) and spring (February-June 2025) seasons to evaluate seasonal effects on thermal indices, phenology and heat use efficiency of maize. The experiment was laid out in a split-plot design with three maize varieties (PCM-04, DKC-9081 and DKC-9188) as main plot treatments and four nutrient management levels as subplots: T1-control (no fertilizer), T2-vermicompost (80:20), T3-poultry manure (80:20) and T4-recommended dose of inorganic fertilizers (RDF). Temperature-based indices including Growing Degree Days (GDD), Heliothermal Units (HTU), Photothermal Units (PTU) and Heat Use Efficiency (HUE) were computed. Spring maize accumulated higher thermal units (GDD 1691.45 °C Day, HTU 14327.25 and PTU 21830.23) and recorded higher grain yield (9373.04 kg ha^{-1}) than winter maize (GDD 1303.38 °C Day, HTU 9824.29, PTU 14733.81; yield 7305.00 kg ha^{-1}). Spring maize also matured earlier (92-110 days) compared to winter maize (132-151 days). The treatment V_3F_4 (DKC-9188 with RDF) recorded the highest grain yield and heat use efficiency in both seasons. The results indicate that improved varieties combined with optimum nutrient management enhance thermal resource utilization and maize productivity under different seasonal environments.

Keywords: Agrometeorological indices; growing degree days; heat use efficiency; seasonal variability and maize yield.

1. Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops cultivated across a wide range of Agro-climatic regions of the world. It belongs to the family Poaceae (Gramineae) and genus Zea and originated from Central and South America. Owing to its highest genetic yield potential among cereals, maize is commonly referred to as the "Queen of Cereals" (Choudhari and Channappagouda, 2015). Its wide adaptability allows cultivation under diverse soil types, climatic conditions and management practices and it is currently grown in about 160 countries worldwide.

With the global population projected to reach nearly 9 billion by 2050, food demand is expected to increase by about 85%, requiring a substantial rise in crop productivity to ensure food security (Raza *et al.,* 2019; Janni *et al.,* 2024). However, ongoing climate change has intensified the frequency and severity of extreme weather events such as drought, heat stress and strong winds, posing serious challenges to agricultural sustainability and food production (Wang *et al.*, 2018; Edreira *et al.,* 2013).

Grain yield in maize is determined by the interactive effects of genetic potential, climatic factors such as solar radiation, temperature and precipitation (Feng *et al.*, 2021; Yang *et al.*, 2020) and agronomic practices including planting density, sowing time, row spacing and fertilization strategies (Zhang Ming *et al.,* 2018; Yang *et al.*, 2010).

In India, maize cultivation has expanded steadily over the last decade, highlighting its growing importance in national agriculture. During 2023-24, maize was cultivated on about 10.89 million hectares in India, an increase from 10.52 million hectares recorded in the previous year. A major share of maize cultivation occurred during the *Kharif* season, accounting for nearly 78.8% (8.58 million hectares) of the total maize area, while about 2.31 million hectares were grown during the *Rabi* season. Compared to the previous year, the *Kharif* maize area increased by 3.8%, while the *Rabi* maize area increased by 2.1%. The major *Kharif* maize-growing states include Madhya Pradesh, Karnataka, Rajasthan and Maharashtra, whereas Bihar, Maharashtra and Tamil Nadu are the leading states for *Rabi* maize cultivation (Acharya N. G. Ranga Agricultural University, 2024).

Rabi maize is increasingly gaining importance in India due to its higher yield potential under irrigated conditions. Unlike *Kharif* maize, the crop experiences lower pest pressure and more favorable radiation conditions during winter. The longer crop duration (150-170 days) and availability of controlled irrigation allow better utilization of solar radiation and thermal time, which often results in higher productivity compared to *Kharif* maize. Because of these advantages, *Rabi* maize is increasingly promoted in eastern and southern India to strengthen food and feed security and to improve farm income (Agrawal *et al.,* 2019).

Spring maize, which is sown in late winter and harvested during late spring or early summer, has also expanded in irrigated regions of northern India, including parts of Punjab, Haryana and western Uttar Pradesh. This expansion is mainly driven by cropping system intensification and the use of residual soil moisture or irrigation after wheat harvest. Research indicates that improved planting methods, appropriate variety selection and efficient irrigation management significantly enhance the productivity and profitability of spring maize under irrigated conditions (Singh and Vashist, 2016). However, the expansion of spring maize in regions facing groundwater stress highlights the need for careful water management to ensure sustainability. Overall, the increasing contribution of *Rabi* and spring maize has strengthened India's maize production system by diversifying cropping seasons, improving yield stability and ensuring a continuous supply of maize for food, feed and industrial uses beyond the monsoon period.

Several temperature-based agrometeorological indices are used to assess crop phenology, growth and yield, including growing degree days, heliothermal units, photothermal units and heat use efficiency (Choudhary *et al.*, 2018). Crop biomass accumulation and developmental changes during the growing season are largely governed by climatic factors, particularly temperature. Each crop has specific thermal requirements for attaining different phenophases and the duration between successive growth stages depends on the accumulation of heat units or GDD at each stage (Bhat *et al.*, 2015; Wani *et al.*, 2023).

Growing degree days and their derived indices provide valuable information for understanding crop phenology and identifying suitable sowing windows for different crops and varieties (Sreenivas *et al.*, 2010). They are widely used to describe crop developmental behaviour under different environmental conditions (Fealy and Fealy, 2008; Matzarakis *et al.*, 2007; Soler *et al.*, 2005). In maize, temperature and photoperiod are the two major environmental factors regulating crop development. The response of maize to temperature is characterized by critical thresholds such as base temperature and optimum temperature, which determine the minimum and maximum rates of crop development (Jamsheed *et al.,* 2023). These thermal relationships are also widely used in crop simulation models to predict crop growth and phenological events.

Overall, maize growth and yield are influenced by the interaction between environmental conditions and crop management practices (Porter, 2005; Wahid *et al.*, 2007). Accurate estimation of accumulated growing degree days enables prediction of crop developmental stages and phenological events, thereby supporting timely and effective crop management decisions (Parthasarathi *et al.*, 2013). Although several studies have examined the influence of temperature on maize phenology, limited information is available regarding seasonal variation in thermal indices and their interaction with varietal performance and nutrient management under the *Tarai* conditions of Uttarakhand. Understanding these relationships is important for optimizing crop management strategies and improving heat use efficiency under varying seasonal environments. Therefore, the present study was undertaken to evaluate the seasonal variability in thermal indices and heat use efficiency of maize under different varieties and nutrient management levels.

2. Materials and Methods

2.1 Site Description

The study was conducted at the N.E. Borlaug Crop Research Centre of G.B. Pant University of Agriculture and Technology, Pantnagar, situated in the *Tarai* belt at the foothills of the Shivalik range of the Himalayas in the Kumaon division at 29°3′ N latitude and 79°31′ E longitude, with an average altitude of 243m (Fig. 1). Pantnagar, located in Udham Singh Nagar district, serves as the primary food-producing region of Uttarakhand State, experiencing two major cropping seasons, namely *Kharif* and *Rabi.* The predominant crops in the region include rice, wheat, sugarcane, mustard and soybean.

Udham Singh Nagar district exhibits a climate characterized by sub-tropical humid and sub-humid conditions, featuring three distinct seasons: summer, monsoon and winter. Summer temperatures can reach up to 42°C, while winter temperatures range between 3°C and 6°C. The annual total rainfall in the district is approximately 1300 mm, with 80-85% of it occurring during the monsoon season and the remainder distributed across the non-monsoon period.

2.2 Experimental Details

The experiment was conducted in a split-plot design with two factors. Factor A consisted of three maize varieties, namely PCM-04 (V_1), DKC-9081 (V_2) and DKC-9188 (V_3), which were assigned to the main plots. Factor B comprised four nutrient management levels allocated to the subplots: T1-control (no fertilizer), T2-

vermicompost (80:20), T3-poultry manure (80:20) and T4-recommended dose of inorganic fertilizers (RDF). The interaction between varieties and nutrient management levels resulted in twelve treatment combinations (3 × 4), namely V_1T_1, V_1T_2, V_1T_3, V_1T_4, V_2T_1, V_2T_2, V_2T_3, V_2T_4, V_3T_1, V_3T_2, V_3T_3 and V_3T_4. The recommended package of practices for maize cultivation in the region was followed throughout the experimental period.

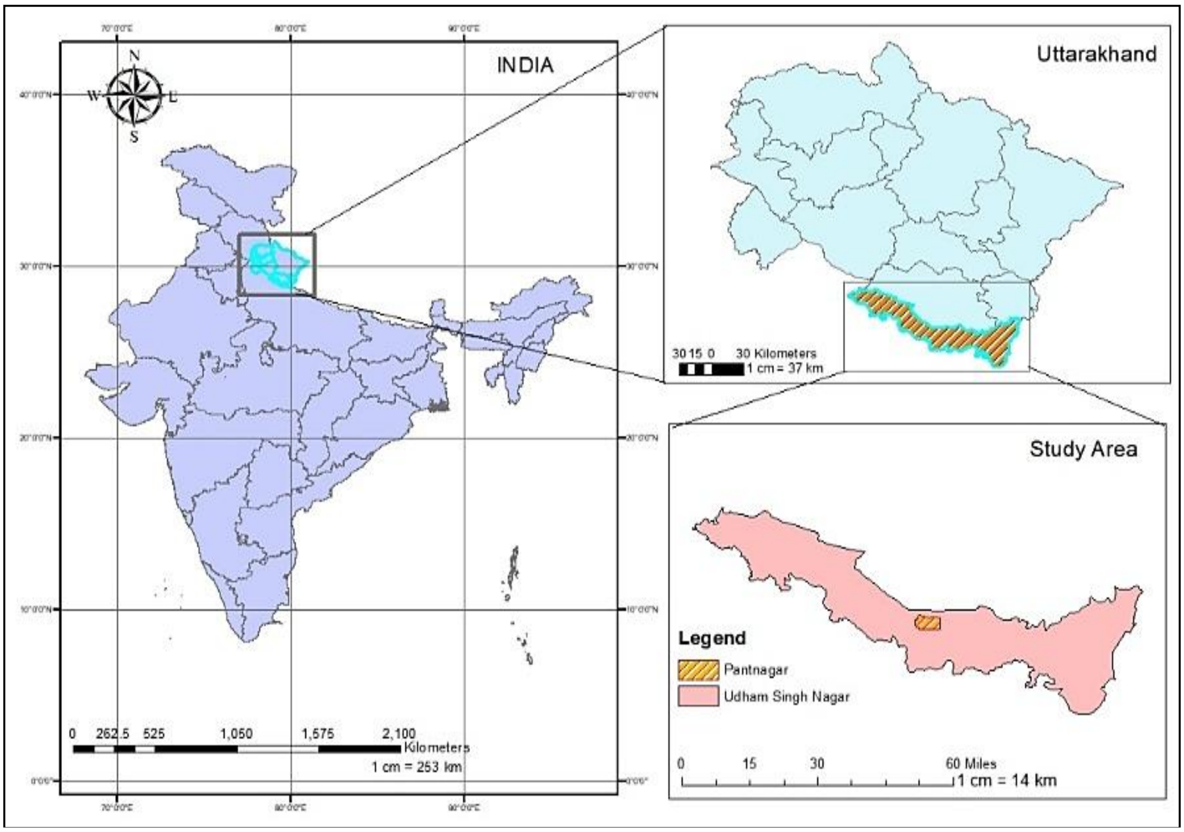

Fig. 1. Location map of the experimental site

2.3 Details of Experiment

Table 1. Schedule of cultural operations in maize crop during 2024-25

S. No.	Operations	Date	
		Winter 2024-25	**Spring 2025**
1.	Pre-sowing irrigation	08.11.2024	02.02.2025
2.	Harrowing and levelling	18.11.2024	18.02.2025
3.	Layout	19.11.2024	19.02.2025
4.	Basal N, P and K fertilizer application	20.11.2024	20.02.2025
5.	Sowing	20.11.2024	20.02.2025
6.	First irrigation	27.12.2024	22.03.2025
7.	First top dressing of urea	22.01.2025	28.03.2025
8.	Chemical weed control	10.01.2025	02.04.2025
9.	Harvesting	20.04.2025	12.06.2025
10.	Threshing	30.05.2025	06.07.2025

2.4 Temperature-Based Indices

2.4.1 Growing Degree Days (GDD)

Cumulative growing degree days were calculated by adding the daily mean temperature above base temperature, expressed in °C by using the following formula:

$$GDD = \frac{Tmax + Tmin}{2} - Tb$$

Where, Tmax = Daily maximum temperature (°C), Tmin = Daily minimum temperature (°C), Tb = Minimum threshold/base temp. (For maize Tbase = 8°C) (Kiniry and Ritchie, 1983).

2.4.2 Photothermal units (PTU)

Photothermal units are calculated as the product of daily growing degree days and maximum possible sunshine hours, which are then summed up for the crop season as follows:
PTU = GDD × Day length (°C day hours) Jondhale *et al.*, (2018).

2.4.3 Heliothermal units (HTU)

These are calculated as the product of daily growing degree days and actual bright sunshine hours, which are then summed up for the crop season as follows:
HTU = GDD × Actual bright sunshine hours (°C day hours) (Jondhale *et al.*, 2018).

2.4.4 Heat Use Efficiency (HUE)

It measures the amount of yield produced per unit of heat accumulated during the growing season. A higher HUE value indicates that the crop is more efficient in utilizing thermal energy, while a lower value suggests less efficient use of heat for biomass or yield production.

$$HUE = \frac{Grain\ Yield}{Accumulated\ GDD}$$

Where, HUE = Heat Use Efficiency, Grain yield = Yield (kg ha^{-1}) and Accumulated GDD = Accumulated Growing Degree Days during the crop growth period (°C Day) (Kumar *et al.,* 2023).

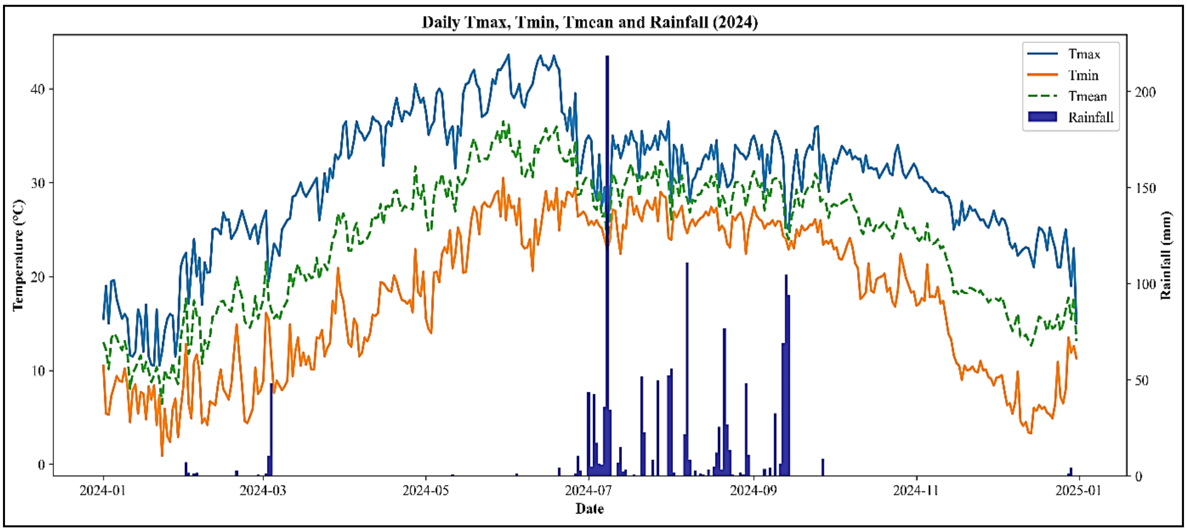

Fig. 2. Weather conditions at the experimental site 2024

2.5 Weather Conditions during the Growing Seasons (2024-25) at Pantnagar

The meteorological conditions prevailing at the experimental site during the maize growing seasons of 2024 and 2025 are shown in Figs. 2 and 3, respectively. The figures depict the temporal variation in important weather parameters such as maximum temperature, minimum temperature, rainfall and sunshine hours throughout the crop growth period.

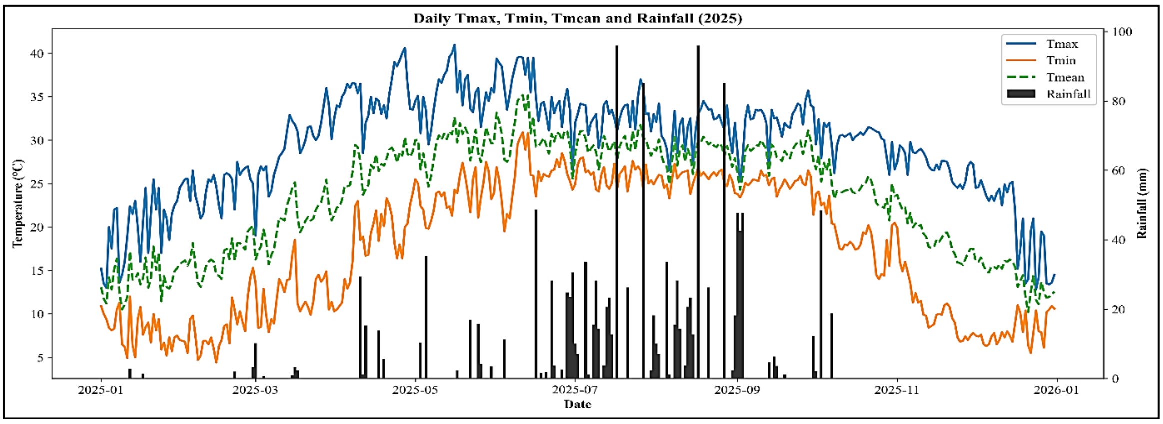

Fig. 3. Weather conditions at the experimental site 2025

3. Results and Discussion

3.1 Phenological Development of Maize under Different Treatments

The number of days taken to attain different phenophases in winter maize as shown in Table 2 and Fig. 4 varied among the treatment combinations from V1T1 to V3T4, indicating that treatments significantly influenced crop growth and development. The emergence stage occurred within 9 to 13 days after sowing, where the longest duration was recorded under V1T1 and V3T1 (13 days), while the earliest emergence was observed under V3T3 and V3T4 (9 days), which may be attributed to favorable soil temperature and moisture conditions that enhanced rapid germination and seedling establishment. The knee-high stage was attained between 50 - 63 days after sowing, with the earliest occurrence in V2T1 (50 days) and the longest duration in V3T4 (63 days), reflecting variation in vegetative growth among treatments. Tasseling occurred between 82 - 99 days, where V2T1 recorded the earliest tasseling (82 days) while V3T4 took the longest time (99 days), indicating differences in reproductive development influenced by environmental conditions. Similarly, the silking stage occurred between 93 - 109 days, whereas the milking and dough stages were attained between 111-125 days and 121-136 days, respectively. Physiological maturity was reached between 132 - 151 days after sowing, where the earliest maturity was recorded in V2T1 (132 days) and the longest duration were taken by V3T4 (151 days). These variations in phenological stages among treatments may be attributed to differences in temperature regime, moisture availability and management practices that regulate crop development and accumulation of thermal units during the crop growth period. Similar findings regarding variation in maize phenology due to environmental conditions and crop management practices have also been reported by Vanaja *et al.* (2017), Dadapeer *et al.* (2020) and Sreenivas *et al.* (2010), who reported that temperature and crop growing environment significantly influence the duration of vegetative and reproductive stages in maize.

The number of days taken to attain different phenophases in spring maize shown in Table 3 and Fig. 5 varied among the treatment combinations from V1T1 to V3T4, indicating that treatments significantly influenced crop growth and development. The emergence stage occurred within 8 to 11 days after sowing, where the earliest emergence was recorded in V2T4 and V3T4 (8 days), while the longest duration was observed in V1T1, V2T1 and V3T1 (11 days), which may be attributed to variations in soil temperature and moisture conditions affecting germination and early seedling establishment. The knee-high stage was attained between 33 - 42 days after sowing, with the earliest occurrence in V1T1 (33 days) and the longest duration in V3T4 (42 days), indicating differences in vegetative growth rate among treatments. Tasseling occurred between 47 - 60 days after sowing, where the earliest tasseling was observed in V1T1 (47 days) while V3T4 required the longest duration (60 days).

Similarly, the silking stage appeared between 54 - 69 days, followed by the milking and dough stages which were attained between 66-81 days and 76-92 days, respectively. Physiological maturity occurred between 92 - 110 days after sowing, with the earliest maturity recorded under V1T1 (92 days) and the longest duration under V3T4 (110 days). The variations in phenological stages among treatments may be attributed to differences in temperature regime, thermal unit accumulation and crop management practices that regulate maize growth and development. Similar findings have been reported in recent studies on spring maize which indicated that sowing date and temperature significantly influence the duration of vegetative and reproductive phases, phenology and yield formation of maize crops (Tsimba *et al.*, 2013; Cao *et al.*, 2024 and Bamboriya *et al.*, 2025).

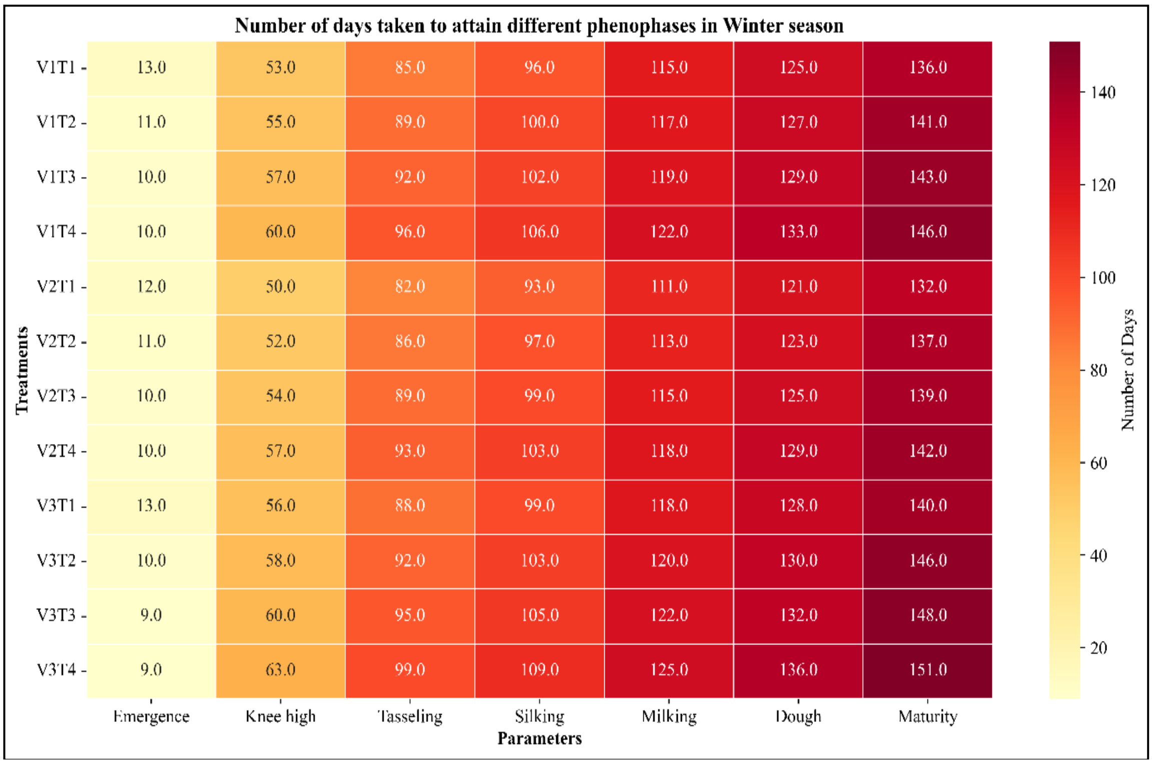

Fig. 4. Heatmap showing the number of days taken to attain different phenological stages of winter maize under different variety-fertilizer combinations

3.2 Accumulation of Thermal Indices in Maize

The heatmap of Growing Degree Days accumulation across treatments and phenophases in winter maize (Fig. 6) shows a clear increasing trend of thermal time from emergence to maturity. The accumulated GDD ranged from about 93.7-132.0 °C days at emergence and gradually increased through vegetative and reproductive stages, reaching 1146.1-1472.2 °C days at physiological maturity. Early phenological stages such as emergence and knee-high required comparatively lower heat units, while later stages such as tasseling, silking, milking and maturity required progressively higher GDD values. Among the treatments, treatment 12 (V3T4) showed the highest thermal accumulation at maturity (1472.2 °C days), followed by treatments 11 and 4, indicating that these treatments required greater thermal time to complete their growth cycle. In contrast, treatment 5 (V2T1) recorded the lowest GDD accumulation at maturity (1146.1 °C days), suggesting a comparatively shorter crop duration. The gradual increase in GDD from vegetative to reproductive phases indicates that maize development is strongly regulated by thermal time, where each phenological stage requires a specific amount of accumulated heat units to progress to the next stage. Variations in accumulation of GDD among treatments may be attributed to differences in crop management practices, micro-climatic conditions and cultivar characteristics that influence temperature utilization and crop development. Similar findings have been reported in several studies where maize phenology and crop duration were closely associated with accumulated growing degree days and thermal conditions during the growing season (Jamsheed *et al.*, 2023 and Ge *et al.*, 2022).

Table 2. Number of days taken to attain different phenophases in Winter Maize

	V1T1	V1T2	V1T3	V1T4	V2T1	V2T2	V2T3	V2T4	V3T1	V3T2	V3T3	V3T4
Emergence	13	11	10	10	12	11	10	10	13	10	9	9
Knee high	53	55	57	60	50	52	54	57	56	58	60	63
Tasseling	85	89	92	96	82	86	89	93	88	92	95	99
Silking	96	100	102	106	93	97	99	103	99	103	105	109
Milking	115	117	119	122	111	113	115	118	118	120	122	125
Dough	125	127	129	133	121	123	125	129	128	130	132	136
Maturity	136	141	143	146	132	137	139	142	140	146	148	151

Table 3. Number of days taken to attain different phenophases in Spring Maize

	V1T1	V1T2	V1T3	V1T4	V2T1	V2T2	V2T3	V2T4	V3T1	V3T2	V3T3	V3T4
Emergence	11	10	10	9	11	10	9	8	11	10	9	8
Knee high	33	34	36	38	35	36	38	40	37	38	40	42
Tasseling	47	50	53	55	50	53	56	58	52	55	58	60
Silking	54	57	60	64	57	60	63	67	59	62	65	69
Milking	66	69	72	76	69	72	75	79	71	74	77	81
Dough	76	79	82	86	79	82	85	89	81	84	87	92
Maturity	92	95	99	103	96	99	103	107	100	102	106	110

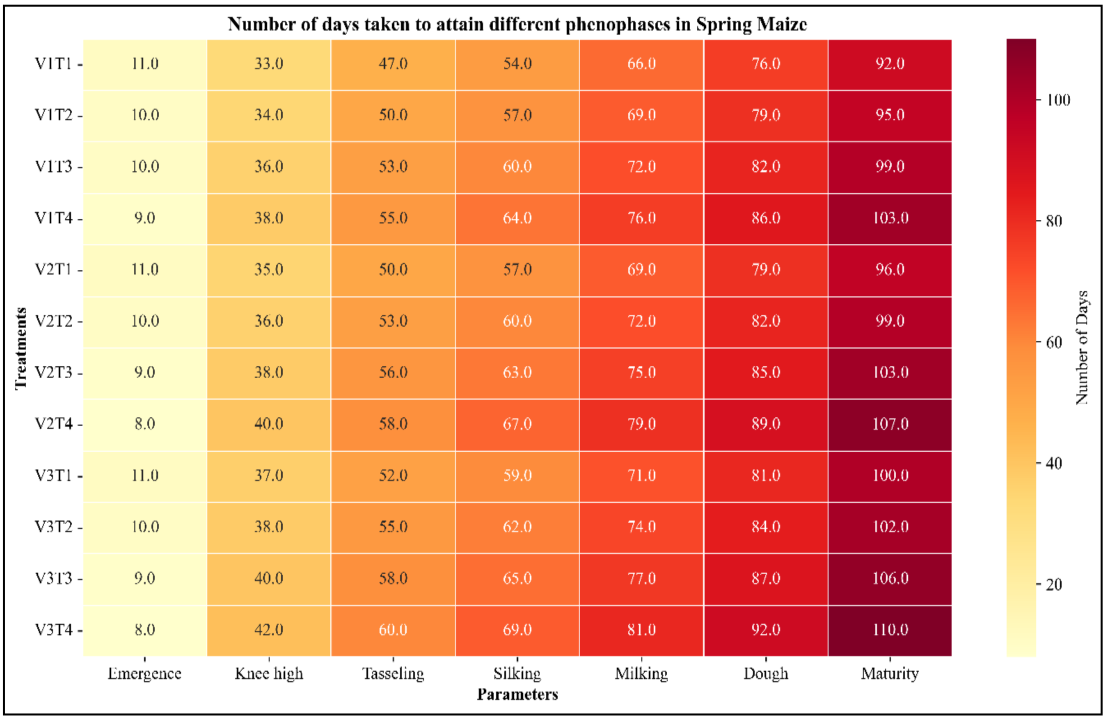

Fig. 5. Heatmap showing the number of days taken to attain different phenological stages of spring maize under different variety-fertilizer combinations

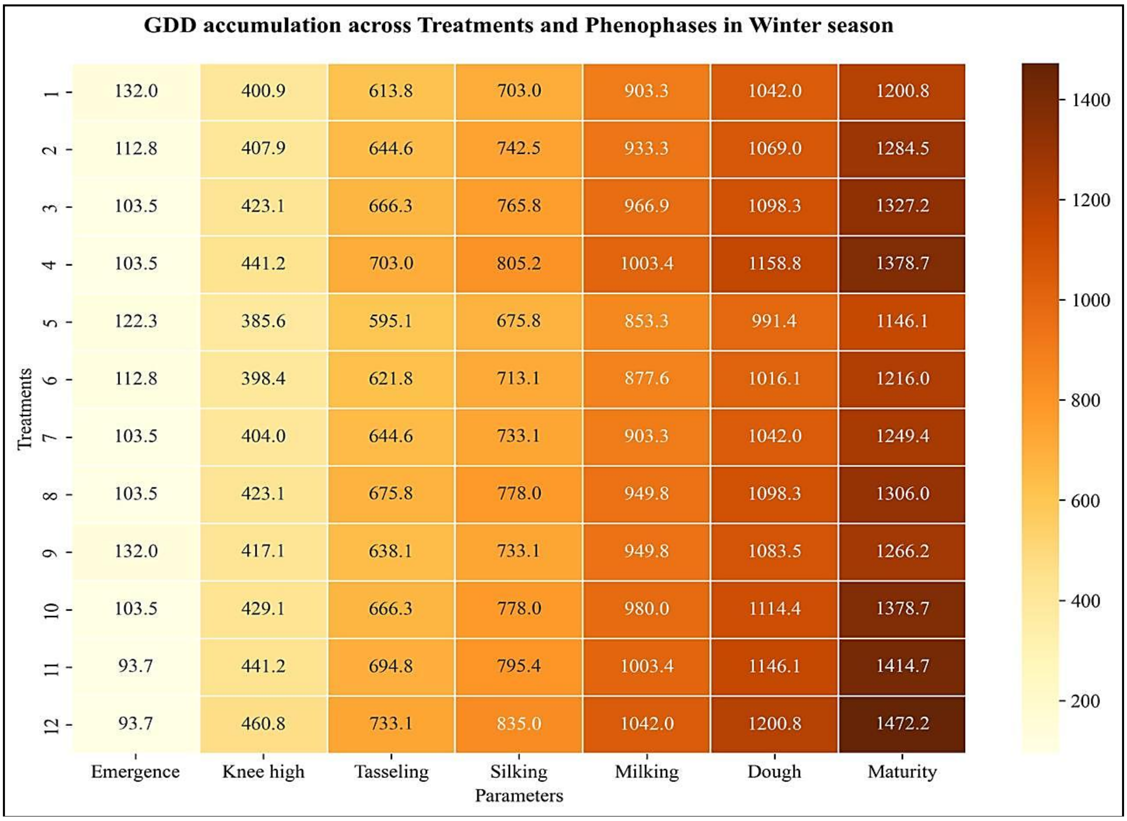

Fig. 6. Heatmap of GDD accumulation across treatments and phenophases in winter maize

The heatmap of GDD accumulation across treatments and phenophases in spring maize in Fig. 7 shows a gradual increase in thermal time from emergence to physiological maturity across all treatments. The accumulated GDD ranged from 76.2 - 111.7 °C days at emergence, increased to 375.8 - 506.0 °C days at the knee-high stage and further to 583.2 - 825.2 °C days at tasseling and 712.5 - 1009.4 °C days at silking, indicating progressive thermal requirements for vegetative and reproductive development. During grain filling stages, GDD accumulation increased to 946.3 - 1248.4 °C days at milking and 1153.8 - 1500.0 °C days at dough stage, while the highest values were observed at physiological maturity (1500.0 - 1848.7 °C days). Among the treatments, T12 (1848.7 °C days) and T8 (1829.2 °C days) recorded the highest heat unit accumulation at maturity, whereas T1 (1500.0 °C days) showed the lowest accumulation, indicating variation in crop duration and thermal requirements among treatments. The progressive increase in GDD across phenophases indicates that maize growth and development are strongly governed by accumulated thermal units above the base temperature and each developmental stage requires a specific amount of heat units for completion, which has been widely reported in maize phenology studies (Kumudini *et al.*, 2014).

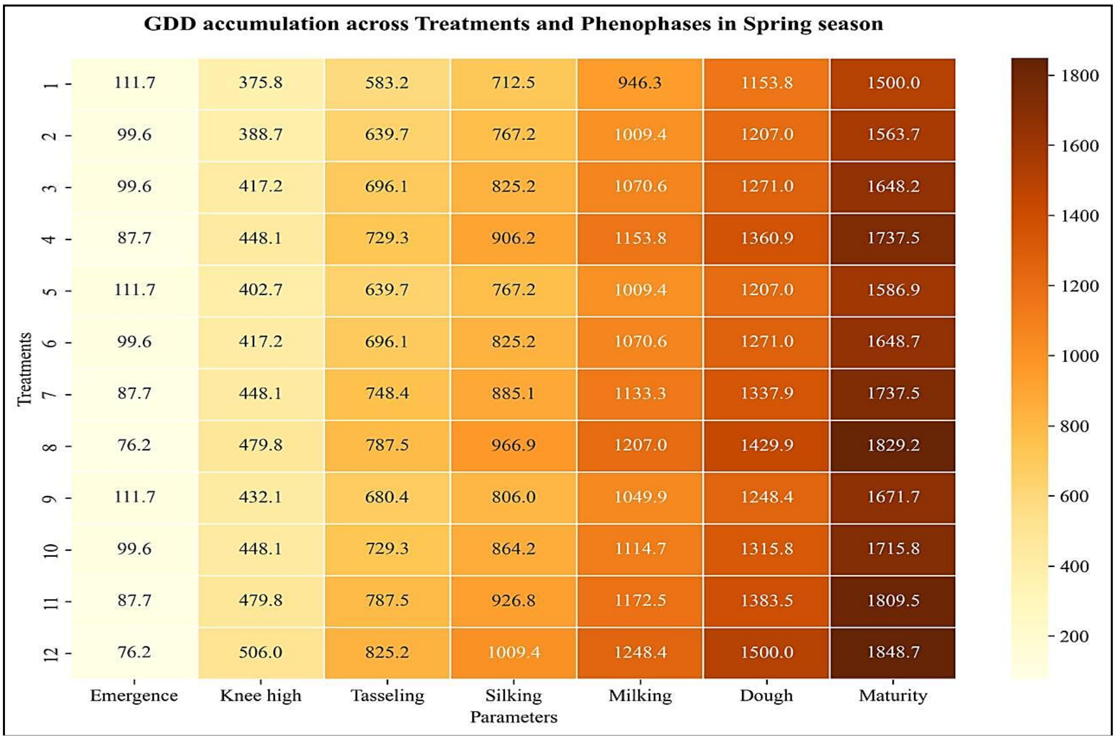

Fig. 7. Heatmap of GDD accumulation across treatments and phenophases in spring maize

The heatmap of Heliothermal Unit (HTU) accumulation across treatments and phenophases in winter maize as shown in Fig. 8 indicates a steady rise in HTU values as the crop progresses from emergence to physiological maturity. The HTU values were comparatively lower during the emergence stage (636.5 - 928.4), reflecting the lower combined influence of temperature and sunshine hours during early crop establishment. As the crop entered the knee-high stage, HTU increased to 2351.9 - 2704.4, indicating higher energy requirements for vegetative growth. A further increase in HTU was observed during tasseling (3642.2 - 4751.5) and silking (4312.6 - 5400.1) stages, suggesting that reproductive development requires greater thermal and radiative energy. During the grain development stages, HTU accumulation increased markedly, ranging from 5558.0 - 7319.8 at milking and 6798.8 - 8893.9 at dough stage. The maximum HTU accumulation occurred at physiological maturity (8319.5 - 11363.1), where Treatment 12 (V3T4) recorded the highest value (11363.1) followed by Treatment 11 (10868.9), indicating longer crop duration and greater utilization of thermal and solar energy, whereas Treatment 5 showed the lowest HTU (8319.5) suggesting comparatively earlier maturity. The increasing trend of HTU across phenophases highlights the importance of combined temperature and sunshine hours in regulating maize growth and development, which determine crop phenology and energy use efficiency under different growing environments (Kumudini *et al.*, 2014).

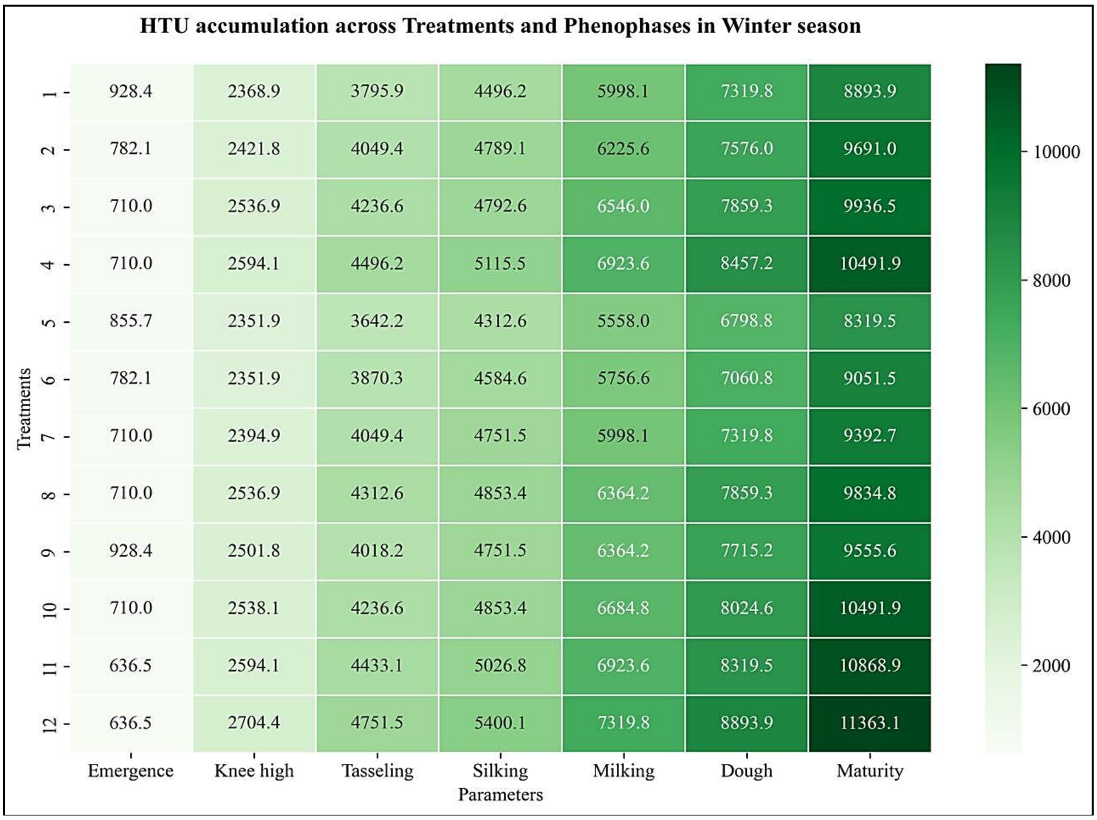

Fig. 8. Heatmap of HTU accumulation across treatments and phenophases in winter maize

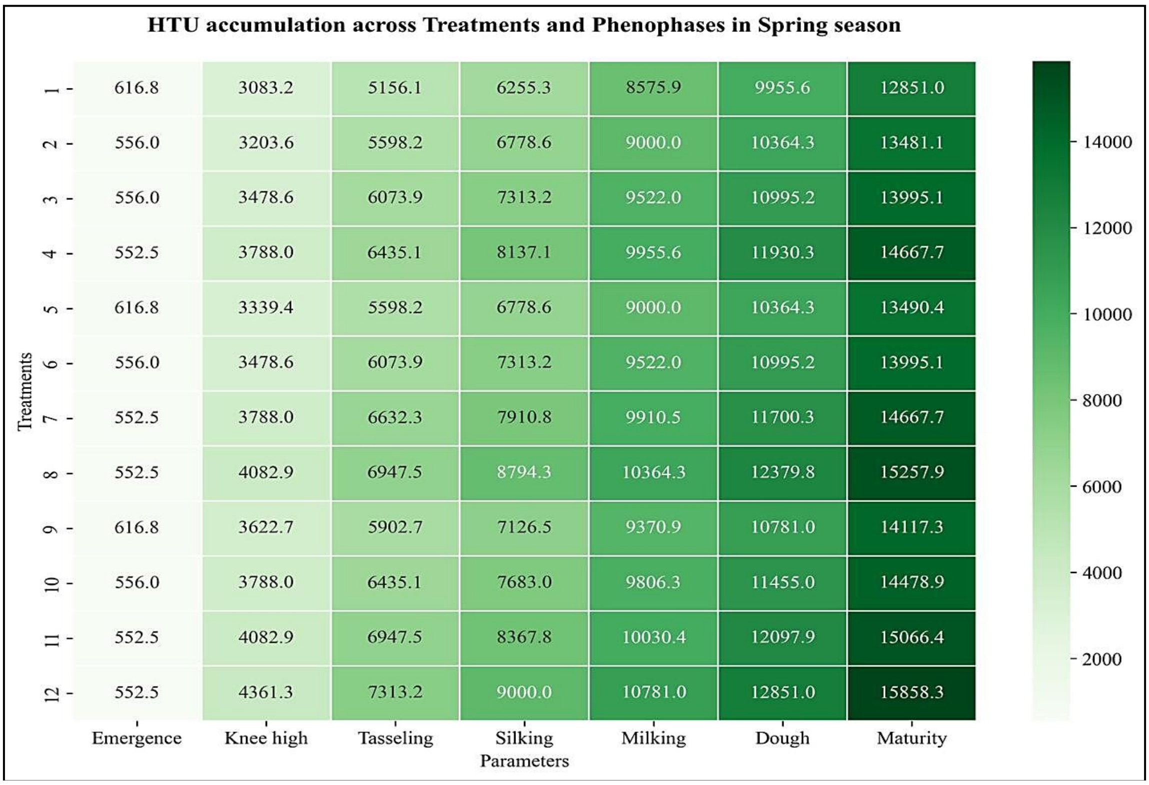

Fig. 9. Heatmap of HTU accumulation across treatments and phenophases in spring maize

The heatmap of Heliothermal Units accumulation across treatments and phenophases in spring maize in Fig. 9 shows a consistent increase in HTU from emergence to physiological maturity across all treatments. HTU values were lowest at emergence (552.5 - 616.8) and increased at the knee-high stage (3083.2 - 4361.3) due to higher energy demand for vegetative growth. Further increases were observed during tasseling (5156.1 - 7313.2) and silking (6255.3-9000.0) stages, indicating greater thermal and solar radiation requirements during reproductive development. The milking (8575.9 - 10781.0) and dough stages (9955.6 - 12851.0) recorded higher HTU values due to active grain filling. The highest HTU accumulation occurred at physiological maturity (12851.0 - 15858.3), with treatment 12 (V3T4) recording the maximum value, indicating greater HTU requirement and longer crop duration, while Treatment 1 recorded the lowest HTU suggesting earlier maturity. This trend indicates that maize phenological development is strongly influenced by the combined effects of temperature and sunshine hours (Kumudini *et al.*, 2014).

The heatmap of Photothermal Units (PTU) accumulation across treatments and phenophases in winter maize in Fig. 10 indicates a continuous increase in PTU values as the crop progresses through successive growth stages. The lowest PTU accumulation was observed at the emergence stage (987.4 - 1387.1), reflecting the lower photothermal requirement during early crop establishment. As the crop advanced to the knee-high stage, PTU values increased to 4006.1 - 4794.8, indicating greater utilization of temperature and day length during vegetative growth. A further rise in PTU was recorded during the tasseling (6244.8 - 7798.4) and silking (7145.8 - 8982.0) stages, showing increased photothermal energy requirement during the reproductive phase. During grain development, PTU accumulation increased markedly to 9197.1 - 11465.7 at milking and 10850.1 - 13432.2 at dough stage. The highest PTU accumulation occurred at physiological maturity (12748.6 - 16894.5), where treatment 12 (V3T4) recorded the maximum PTU (16894.5) followed by Treatment 11 (16151.0), indicating higher photothermal energy utilization and longer crop duration, whereas Treatment 5 recorded the lowest PTU (12748.6) suggesting comparatively earlier maturity. This progressive increase in PTU across phenophases demonstrates that maize phenological development is strongly influenced by the combined effects of temperature and photoperiod during the crop growth period, which regulate crop development and growth rate (Kumudini *et al.*, 2014).

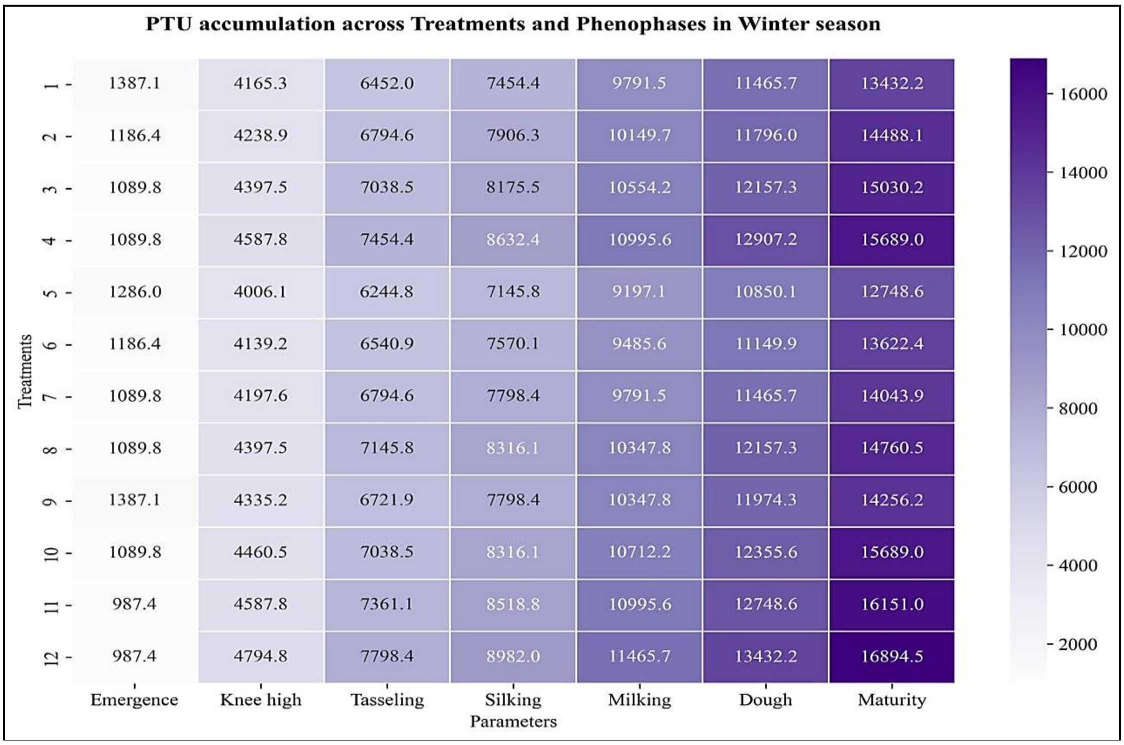

Fig. 10. Heatmap of PTU accumulation across treatments and phenophases in winter maize

The heatmap of Photothermal Units (PTU) accumulation across treatments and phenophases in spring maize as shown in Fig.11 indicates a steady increase in PTU values as the crop advances from emergence to physiological maturity, indicating the combined influence of temperature and day length on crop growth. PTU accumulation was lowest at the emergence stage (867.8 - 1277.6) and increased markedly by the knee-high stage (4427.2 - 6035.8) due to greater photothermal energy requirement during vegetative growth. As the crop progressed to the reproductive phase, PTU values further increased during tasseling (7005.4 - 10105.8) and silking (8650.5 - 12519.3) stages. Higher PTU accumulation was observed during grain development stages, ranging from 11687.5 - 15713.5 at milking and 14440.6 - 19138.1 at dough stage. The maximum PTU values were recorded at physiological maturity (19138.1 - 24554.4), where Treatment 12 (V3T4) showed the highest accumulation, indicating greater photothermal requirement and longer crop duration, while Treatment 1 recorded comparatively lower PTU, suggesting earlier maturity. The increasing PTU trend across phenophases highlights the importance of combined temperature and photoperiod in regulating maize phenology and crop development under spring growing conditions (Andrade *et al.*, 2005).

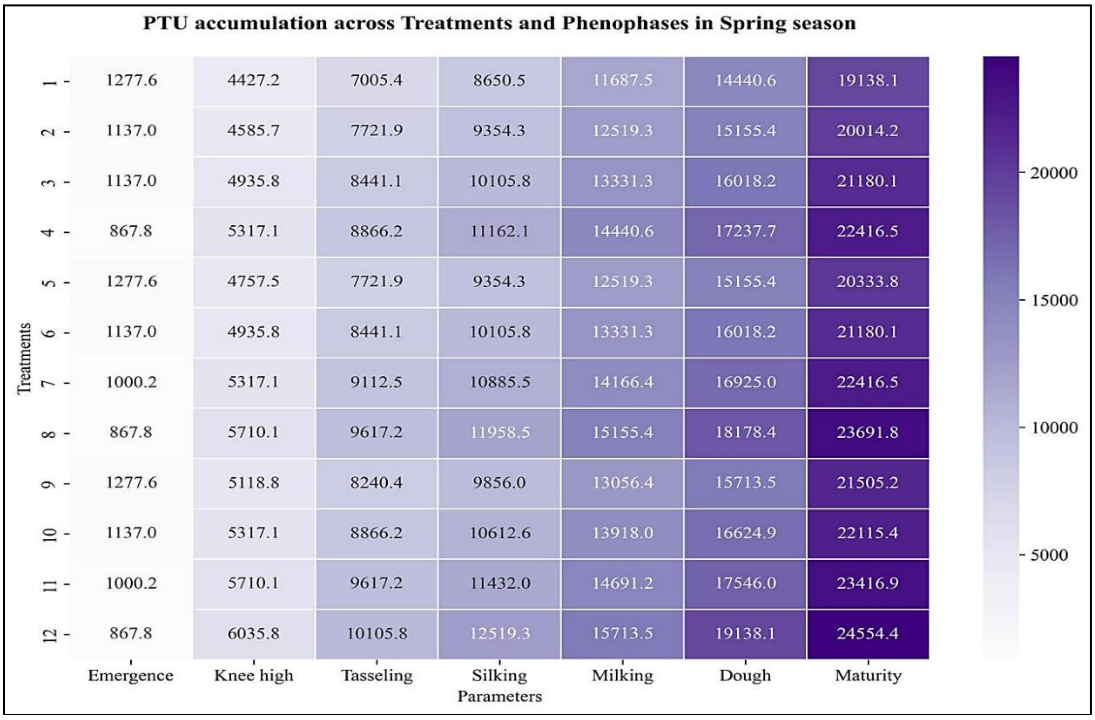

Fig. 11. Heatmap of PTU accumulation across treatments and phenophases in spring maize

3.3 Thermal Use Efficiency of Maize under Different Varieties and Nutrient management levels

The Table 4 and Fig. 12 shows the thermal use efficiency of winter and spring maize in terms of Heat Use Efficiency (HUE), Heliothermal Use Efficiency (HTUE) and Photothermal Use Efficiency (PTUE) under different varieties and nutrient management levels. Among the varieties, V3 recorded the highest HUE, HTUE and PTUE in winter maize (5.79, 0.76 and 0.51 kg ha^{-1} °C Day^{-1}, respectively) as well as in spring maize (6.21, 0.74 and 0.48 kg ha^{-1} °C Day^{-1}), whereas V1 recorded the lowest values, indicating better utilization of accumulated thermal units by V3 for biomass and yield production. The differences among varieties were statistically significant, with CD ($P = 0.05$) values of 0.47, 0.06 and 0.04 for HUE, HTUE and PTUE, respectively, in winter maize and 0.38, 0.05 and 0.03 in spring maize. Under nutrient management levels, the highest HUE, HTUE and PTUE was recorded with F4 in winter maize (6.87, 0.90 and 0.60 kg ha^{-1} °C Day^{-1} respectively) and also for spring maize highest HUE, HTUE and PTUE (6.15, 0.72 and 0.48 kg ha^{-1} °C Day^{-1} respectively) were observed at F4 nutrient management level, while F1 recorded the lowest efficiency. The differences among nutrient management treatments were statistically significant with CD ($P = 0.05$) values of 0.60, 0.08 and 0.05 for HUE, HTUE and PTUE, respectively, in winter maize and 0.426, 0.05 and 0.03 in spring maize. This indicates that higher nutrient management levels improved the ability of crop to convert accumulated heat units into grain yield. Similar results regarding higher thermal use efficiency under improved nutrient management and superior cultivars have also been reported in maize and other crops (Sreenivas *et al.*, 2010; Kumudini *et al.*, 2014).

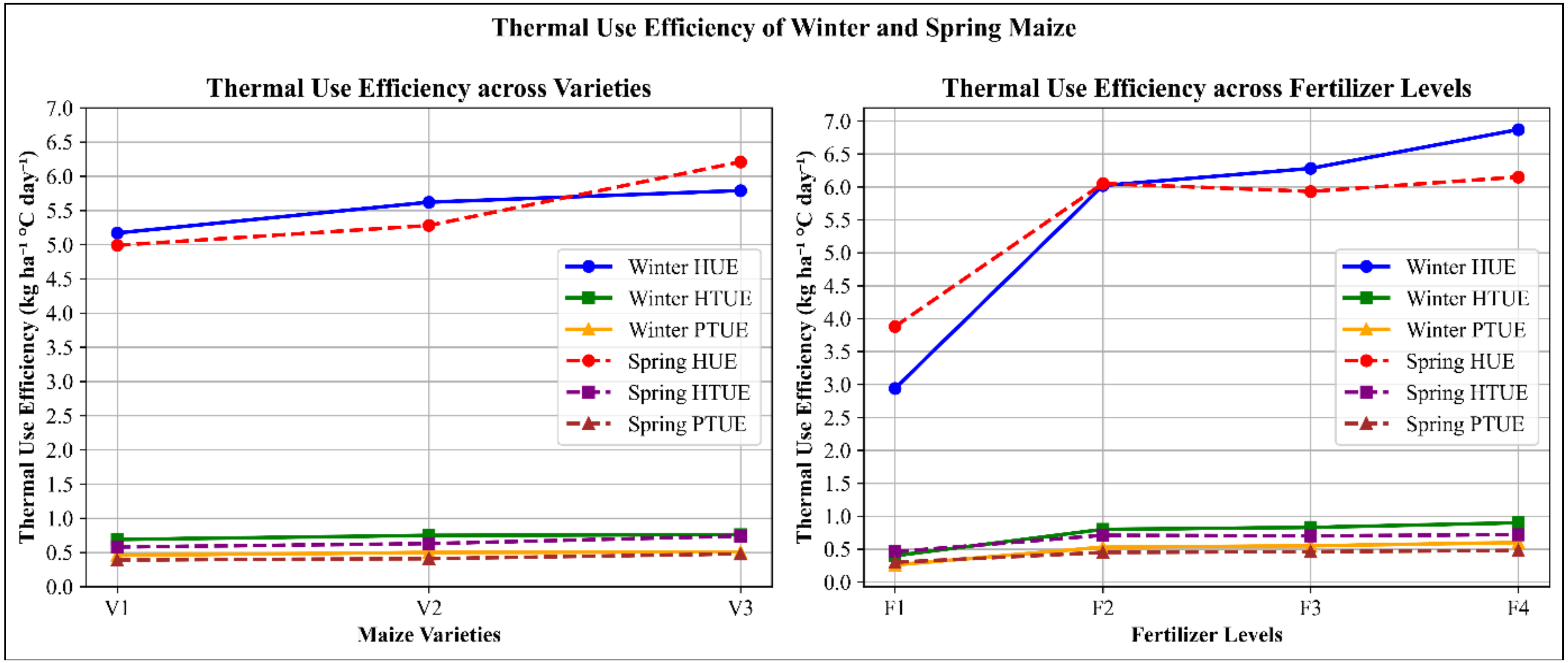

Fig. 12. Thermal Use Efficiency of Maize under Different Varieties and Nutrient management levels in Winter and Spring Seasons

Table 4. Thermal use efficiency

	Winter Maize			Spring Maize		
Treatments	**HUE (kg/ha/°C Day)**	**HTUE (kg/ha/°C Day)**	**PTUE (kg/ha/°C Day)**	**HUE (kg/ha/°C Day)**	**HTUE (kg/ha/°C Day)**	**PTUE (kg/ha/°C Day)**
				Varieties		
V1	5.17	0.69	0.46	4.99	0.58	0.39
V2	5.62	0.75	0.50	5.28	0.63	0.41
V3	5.79	0.76	0.51	6.21	0.74	0.48
SEm+	0.12	0.02	0.01	0.10	0.01	0.01
CD at p-0.05	0.47	0.06	0.04	0.38	0.05	0.03
				Fertilizer		
F1	2.94	0.40	0.26	3.88	0.46	0.30
F2	6.02	0.80	0.53	6.05	0.71	0.45
F3	6.28	0.83	0.55	5.93	0.70	0.46
F4	6.87	0.90	0.60	6.15	0.72	0.48
SEm+	0.20	0.03	0.02	0.143	0.017	0.01
CD at p-0.05	0.6	0.08	0.05	0.426	0.05	0.03

Table 5. Relationship between yield and thermal indices of winter and spring maize

	Winter Maize				Spring Maize			
Treatment	**Yield (kg/ha)**	**GDD (°C Day)**	**HTU**	**PTU**	**Yield (kg/ha)**	**GDD (°C Day)**	**HTU**	**PTU**
V1F1	4023.30	1200.8	8893.92	13432.2	4845.45	1500.0	12851.0	19138.1
V1F2	7512.77	1284.5	9691.05	14488.1	8949.00	1563.7	13481.1	20014.2
V1F3	7113.47	1327.2	9936.52	15030.2	8991.67	1648.2	13995.1	21180.1
V1F4	8446.67	1378.7	10491.9	15689.0	9617.00	1737.5	14667.7	22416.5
V2F1	3123.00	1146.1	8319.54	12748.6	6496.67	1586.9	13490.4	20333.8
V2F2	6996.67	1216.0	9051.48	13622.4	9456.67	1648.7	13995.1	21180.1
V2F3	8358.27	1249.4	9392.67	14043.9	9606.00	1737.5	14667.7	22416.5
V2F4	9572.33	1306.0	9834.76	14760.5	10526.00	1829.2	15257.9	23691.8
V3F1	3471.00	1266.2	9555.63	14256.2	7210.00	1671.7	14117.3	21505.2
V3F2	8913.13	1378.7	10491.9	15689.0	12003.33	1715.8	14478.9	22115.4
V3F3	9616.00	1414.7	10868.9	16151.1	12318.00	1809.5	15066.4	23416.9
V3F4	10513.33	1472.2	11363.1	16894.5	12456.67	1848.7	15858.3	24554.4

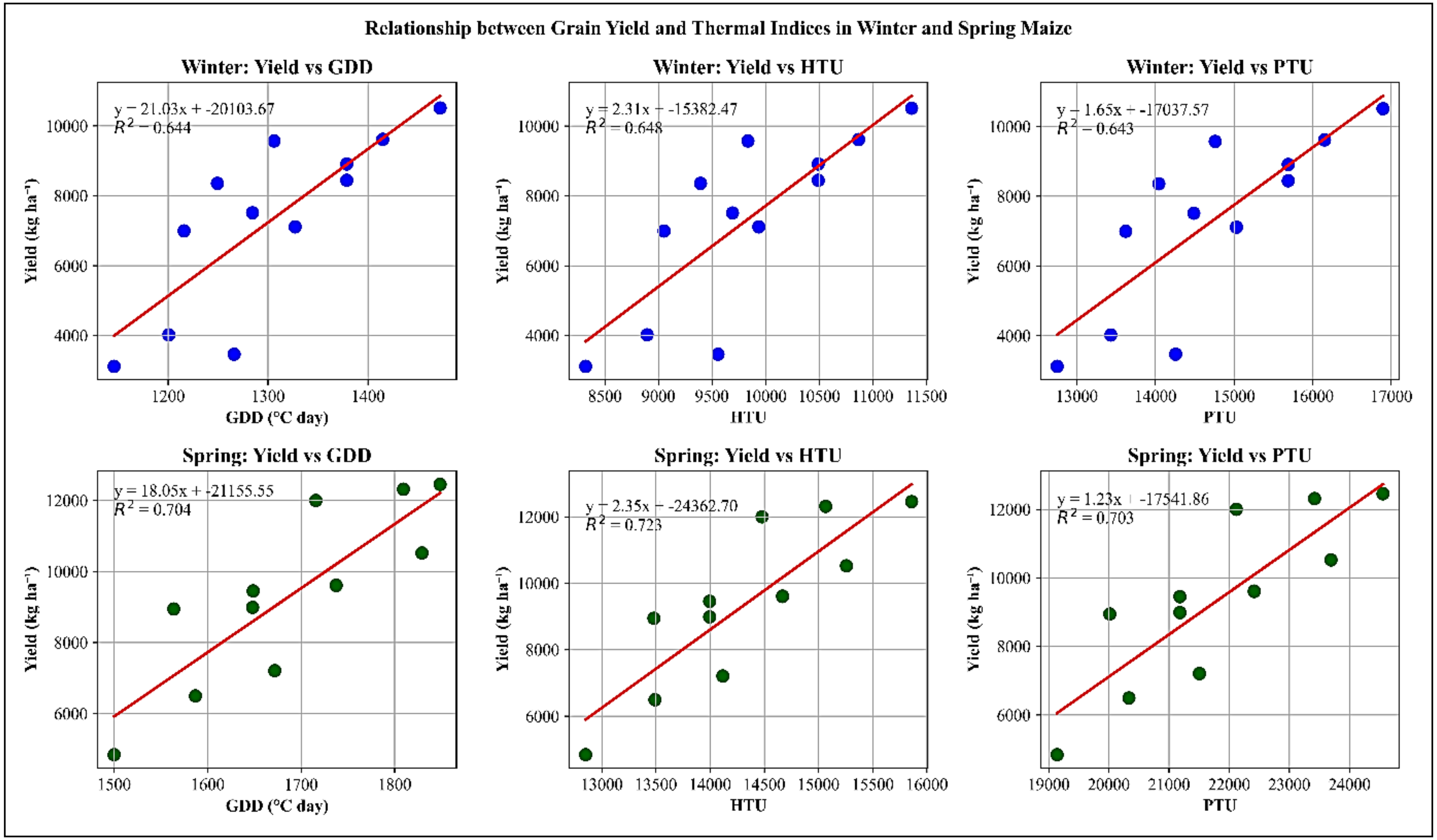

Fig. 13. Relationship between grain yield and thermal indices (GDD, HTU and PTU) in winter and spring maize based on regression analysis

3.4 Relationship between Grain Yield and Thermal Indices (GDD, HTU and PTU) of Winter and Spring Maize

The Table 5 represents the relationship between grain yield and thermal indices (GDD, HTU and PTU) of winter and spring maize. In general, spring maize recorded higher values of yield and thermal indices compared to winter maize, indicating greater thermal accumulation during the spring season. Among the treatments, V3F4 recorded the highest grain yield in both seasons (10,513.33 kg ha^{-1} in winter and 12,456.67 kg ha^{-1} in spring) along with the highest accumulated GDD, HTU and PTU, whereas V2F1 recorded the lowest yield in winter (3,123.00 kg ha^{-1}) and V1F1 recorded the lowest yield in spring (4,845.45 kg ha^{-1}). The results indicate that higher nutrient management levels combined with improved varieties enhanced thermal accumulation and grain yield, suggesting better utilization of available heat units for crop growth and development. Overall, the V3F4 treatment showed superior performance in both seasons, reflecting the combined effect of improved variety and higher nutrient level on maize productivity and thermal index accumulation.

The Fig. 13 illustrates the relationship between grain yield and thermal indices (GDD, HTU and PTU) in winter and spring maize using regression analysis. In both seasons, grain yield showed a positive linear relationship with the accumulated thermal indices, indicating that higher thermal accumulation during the crop growth period contributed to increased maize productivity. In winter maize, yield was moderately correlated with GDD (R^2 = 0.64), HTU (R^2 = 0.65) and PTU (R^2 = 0.64), suggesting that about 64% of the variation in yield could be explained by these thermal indices. In spring maize, the relationships were slightly stronger, with R^2 values of 0.70 for GDD, 0.72 for HTU and 0.70 for PTU, indicating a stronger influence of thermal conditions on yield during the spring season. The higher coefficient of determination in spring maize suggests that temperature and solar radiation played a more significant role in determining crop yield during the spring growing season compared to winter. Overall, the results indicate that grain yield increases with increasing accumulation of thermal units and HTU showed the strongest association with yield among the thermal indices, highlighting the importance of combined temperature and sunshine hours in maize productivity.

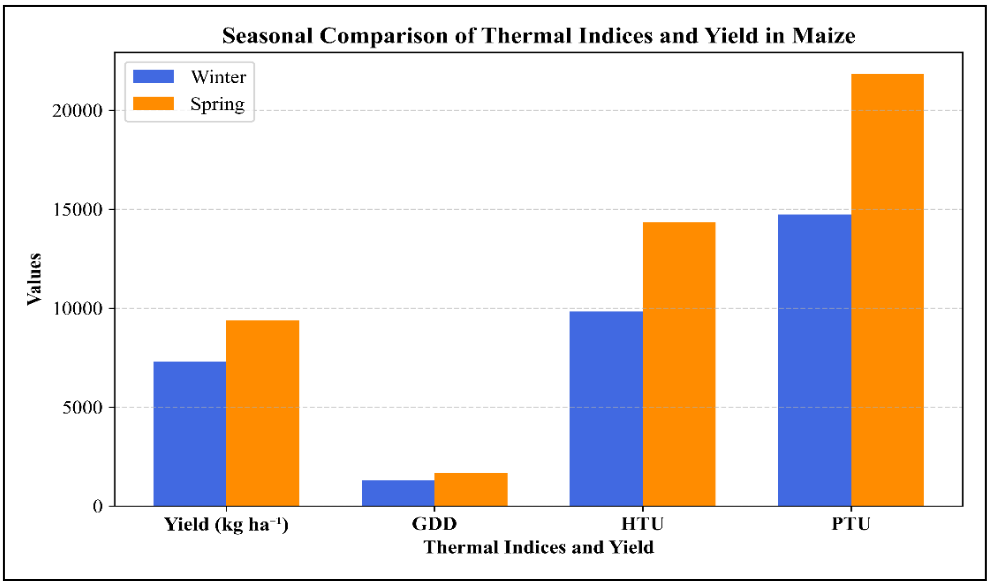

Fig. 14. Seasonal comparison of grain yield and accumulated thermal indices (GDD, HTU and PTU) in winter and spring maize

3.5 Seasonal Comparison of Grain Yield and Accumulated Thermal Indices in Winter and Spring Maize

The seasonal comparison indicates that spring maize recorded higher grain yield (9,373.04 kg ha^{-1}) and greater accumulation of thermal indices (GDD, HTU and PTU) compared to winter maize. The higher GDD (1691.45 °C Day), HTU (14327.25) and PTU (21830.23) observed in the spring season suggest that maize experienced greater thermal energy, solar radiation and longer day length, which enhanced crop growth, dry matter accumulation and ultimately grain yield. In contrast, the relatively lower values of these indices in winter maize indicate reduced thermal accumulation due to lower temperature and shorter sunshine duration, resulting in comparatively lower yield. Similar results have been reported by Shingne *et al.* (2020) who observed that higher accumulation of agrometeorological indices such as GDD, HTU and PTU significantly improved maize growth and productivity. Likewise, Jamsheed *et al.* (2023) reported a positive relationship between thermal indices and maize grain yield, indicating that higher thermal accumulation enhances crop development and yield formation. These findings support the present results, suggesting that spring maize, which accumulated greater thermal units and solar radiation, produced higher grain yield compared to winter maize.

Table 6. Comparison of thermal indices and grain yield between winter and spring maize

	Winter Maize	Spring Maize
Yield (Kg/ha)	7305.00	9373.04
Mean Growing Degree Day (GDD)	1303.38	1691.45
Mean Heliothermal Unit (HTU)	9824.29	14327.25
Mean Photothermal Unit (PTU)	14733.81	21830.23

4. Conclusion

The study demonstrated that maize growth, phenology and yield are strongly influenced by the accumulation of thermal indices such as GDD, HTU and PTU. Spring maize recorded higher thermal accumulation with mean values of 1691.45 °C Day (GDD), 14327.25 (HTU) and 21830.23 (PTU) and produced higher grain yield (9373.04 kg ha^{-1}) compared to winter maize, which accumulated 1303.38 °C Day (GDD), 9824.29 (HTU) and 14733.81 (PTU) with a yield of 7305.00 kg ha^{-1}. Among the treatment combinations, V_3F_4 (DKC-9188 with recommended dose of fertilizer) recorded the highest grain yield of 10513.33 kg ha^{-1} in winter and 12456.67 kg ha^{-1} in spring, along with higher thermal accumulation and thermal use efficiency. The highest heat use efficiency was also observed under the F_4 nutrient management level, indicating improved conversion of accumulated heat units into grain yield. These findings suggest that the adoption of improved maize varieties along with optimum nutrient management can enhance thermal resource utilization and significantly improve maize productivity under different seasonal environments.

Disclaimer (Artificial Intelligence)

The authors declare that no generative artificial intelligence tools, including large language models (e.g., ChatGPT, Copilot) or text-to-image generators, were used in the writing, analysis, or preparation of this manuscript.

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Competing Interests

Authors have declared that no competing interests exist.

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