

International Journal of Plant & Soil Science

Volume 38, Issue 11, Page 162-181, 2026; Article no.IJPSS.169112
ISSN: 2320-7035

Weather and Agrometeorological Indices in Relation to Phenology, Growth and Yield of Rainfed Pearl Millet under Different Growing Environments

Yogesh Rajrana [a*], Chander Shekhar [a], Anil Kumar [a], Ambika [a], Ankit Phougat [a], Muskan Yadav [b], Renu [a] and Rahul Punia [a]

[a] Department of Agricultural Meteorology, Chaudhary Charan Singh Haryana Agricultural University, Hisar-125004, Haryana, India.
[b] Department of Agronomy, Chaudhary Charan Singh Haryana Agricultural University, Hisar-125004, Haryana, India.

Authors' contributions

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

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i116412

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/169112

Original Research Article

Received: 24/08/2026
Accepted: 24/10/2026
Published: 06/11/2026

Abstract

Agrometeorological assessment of crop phenology and productivity helps to understand crop–weather relationships and the effects of thermal and radiation resources on crop performance. In rainfed areas, where crop development is strongly influenced by prevailing weather conditions, thermal indices are useful for assessing phenological development, resource-use efficiency and yield. A field experiment was conducted during the *Kharif* season of 2022 at the Research Farm Area, Department of Agricultural Meteorology, CCS Haryana Agricultural University, Hisar, to study the effect of sowing dates and varieties on phenology, thermal indices, heat use efficiency and yield of rainfed pearl millet under semi-arid conditions. The experiment was laid out in a factorial randomised block design with three sowing dates (24th June, 18th July and 10th August) and three varieties (GHB 558, HHB 67 Improved and HHB 197), with four replications. Growing degree days, heliothermal units, photothermal units and heat use efficiency were calculated to assess the thermal and radiation conditions during crop growth. Heavy rainfall of 190.8 mm during

**Corresponding author: E-mail: yogeshrajrana51@gmail.com;*

Cite as: *Rajrana, Y., Shekhar, C., Kumar, A., Ambika, Phougat, A., Yadav, M., … Punia, R. (2026). Weather and Agrometeorological Indices in Relation to Phenology, Growth and Yield of Rainfed Pearl Millet under Different Growing Environments. International Journal of Plant & Soil Science, 38(11), 162–181. https://doi.org/10.9734/ijpss/2026/v38i116412*

Standard Meteorological Weeks 38th–39th caused prolonged waterlogging in the 10th August sown crop, severely damaging it before physiological maturity. The 24th June sown crop recorded greater accumulation of growing degree days, heliothermal units and photothermal units, a longer crop duration and a higher grain yield (3974.5 kg ha^{-1}) than the 18th July sowing (2976.3 kg ha^{-1}). It also recorded higher heat use efficiency (2.49 kg ha^{-1} °Cday^{-1}) than the 18th July sowing (2.06 kg ha^{-1} °Cday^{-1}). Among varieties, GHB 558 recorded the highest grain yield (4026.0 kg ha^{-1}), 1000-grain weight (9.98 g), biological yield (14531.3 kg ha^{-1}) and heat use efficiency (2.58 kg ha^{-1} °Cday^{-1}). Delayed sowing reduced the accumulation of thermal indices and shortened the crop growing period. Grain yield showed significant positive relationships with growing degree days (r = 0.72**), heliothermal units (r = 0.73**) and photothermal units (r = 0.71**), while bright sunshine hours showed a strong positive relationship (r = 0.96**) and evening relative humidity showed a negative relationship (r = −0.84*). Regression analysis showed strong relationships between thermal indices and phenological development (R^2 = 0.97–0.99), whereas the combined model incorporating growing degree days, heliothermal units and photothermal units explained 54.2 per cent of the variation in grain yield (R^2 = 0.542, p = 0.001). The study indicated that timely sowing during late June, particularly with GHB 558, resulted in better utilisation of thermal resources and higher productivity of rainfed pearl millet, while delayed sowing increased the risk of yield reduction due to unfavourable weather conditions.

Keywords: *Rainfed pearl millet; sowing date; agrometeorological indices; growing degree days; Heliothermal units; photothermal units; crop phenology; heat use efficiency; grain yield.*

1. Introduction

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is an important cereal crop grown widely in the arid and semi-arid regions of Asia and Africa. In India, it is the fourth most important cereal crop after rice, wheat and sorghum. It is a drought-tolerant C_4 crop that can give satisfactory yields even under low rainfall conditions (200–250 mm) and can withstand high temperature and moisture stress, making it well suited to rainfed farming (Khajuria *et al.*, 2018). In India, pearl millet is cultivated on about 7.38 million ha, with a production of 10.72 million tonnes and an average productivity of 1,453 kg ha^{-1} (Department of Agriculture & Farmers Welfare, 2024). It is mainly grown during the *Kharif* season in Rajasthan, Gujarat, Haryana and Maharashtra, and provides grain for food, as well as fodder, feed and raw materials for various industries. Since the crop is mainly grown under rainfed conditions, its growth, development and yield are greatly affected by prevailing weather conditions, particularly temperature, sunshine hours, relative humidity and rainfall distribution. Sowing time is an important factor determining crop growth and yield, as it influences the duration of vegetative, reproductive and maturity phases (Sattar *et al.*, 2023). The optimum sowing time of pearl millet varies according to the variety and region because of differences in agro-ecological conditions. Timely sowing helps synchronise the major growth stages of the crop with favourable weather conditions, thereby improving the chances of achieving higher yield. Pearl millet has a base temperature of about 10°C and optimum temperatures around 30–35°C. Temperature plays an important role in determining crop duration, particularly the grain-filling period, and higher temperatures during this stage can shorten the grain-filling duration and reduce yield (White & Reynolds, 2003).

Recent work on pearl millet has documented genotypic variation in phenological responses to temperature and photoperiod (Carcedo *et al.*, 2024). Field evidence from Rajasthan has also identified differences in grain yield among sowing dates and hybrids under semi-arid conditions (Reager *et al.*, 2023). A field-based modelling study in Tamil Nadu assessed the sensitivity of pearl millet productivity to temperature and rainfall under different management conditions (Ramanjineyulu *et al.*, 2024).

Agrometeorological indices such as growing degree days (GDD), heliothermal units (HTU), photothermal units (PTU) and heat use efficiency (HUE) are useful for quantifying the thermal requirements of crops and evaluating the efficiency of heat utilisation. These indices help in predicting crop development, scheduling agricultural operations and identifying stress periods during crop growth (Salack *et al.*, 2015). Additionally, thermal use efficiency (TUE) is a key measure that indicates how efficiently a plant utilises the absorbed thermal energy to produce dry matter and yield (Balagond *et al.*, 2020; Kumar *et al.*, 2024). These efficiencies vary depending on the cultivar, environmental conditions and sowing time. Since each phenological stage has a specific temperature requirement, understanding the duration and thermal requirements of these stages under different growing conditions is important for assessing crop performance (Halder *et al.*, 2023). The relationship between weather conditions, agrometeorological indices, phenology, growth and yield is therefore important for identifying suitable sowing dates and varieties under particular agroclimatic conditions and for making better use of prevailing weather conditions to achieve optimum productivity.

A field assessment of pearl millet hybrids across sowing environments in Rajasthan identified variation in yield-related performance among genotypes and environments (Jat *et al.*, 2025). A rainfed experiment in Uttar Pradesh likewise reported differences in pearl millet growth and grain yield across sowing dates and cultivars (Maya *et al.*, 2026). Accordingly, a site-specific assessment is needed to examine sowing-date and varietal differences in phenological development, thermal-time accumulation, heat use efficiency and yield of rainfed pearl millet under the semi-arid conditions of Hisar.

Therefore, the present study was undertaken to quantify the effect of sowing dates and varieties on phenological development, thermal-time accumulation and heat use efficiency of rainfed pearl millet, and to assess the relationships between weather variables, agrometeorological indices, growth and yield. The study also aimed to develop regression models relating grain yield and phenological development with thermal indices.

2. Materials and Methods

2.1 Experimental Site

The field experiment was conducted at the Research Farm, Department of Agricultural Meteorology, CCS HAU, Hisar (Haryana), India (Fig. 1). It is situated at 29° 10'N latitude and 75° 46' E longitude with an elevation of 215.2 metres above mean sea level.

Hisar is situated in the subtropical, semi-arid climatic zone of India. The station lies under the Eastern Agroclimatic Zone of Haryana. The experiment comprised three sowing dates (24th June, 18th July and 10th August) and three varieties (GHB 558, HHB 67 Improved and HHB 197) and was laid out in a factorial randomised block design with four replications (Fig. 2). Daily weather data were recorded in the agrometeorological observatory (Annexure 1).

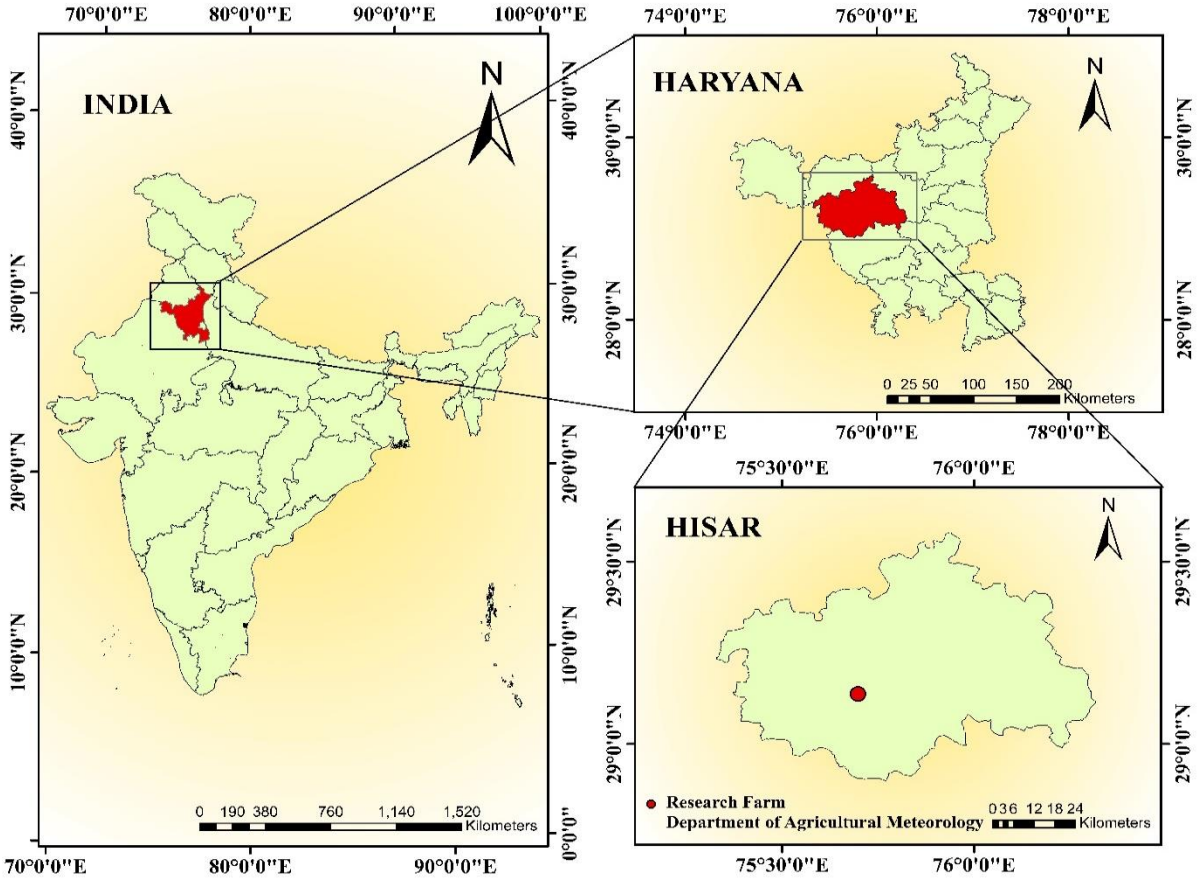


Fig. 1. Location of study area

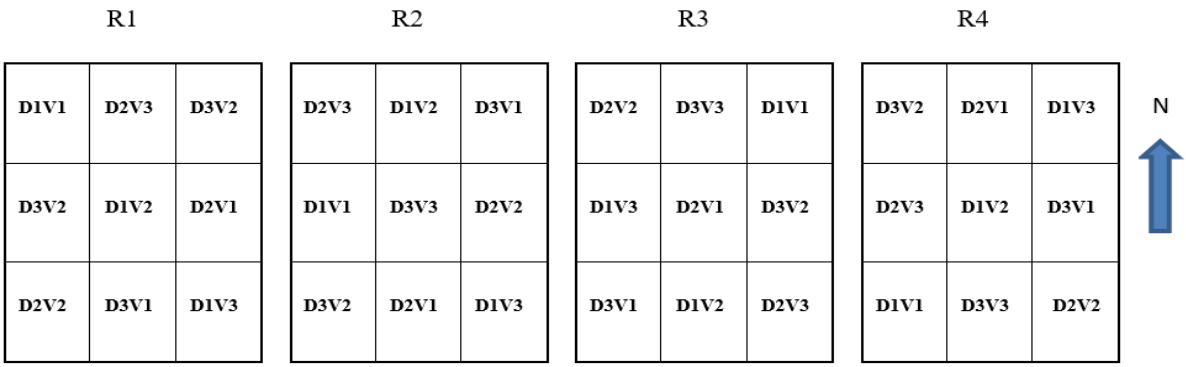


Fig. 2. Layout of Experiment conducted

2.2 Phenological Observations

The number of days taken to reach emergence, five-leaf stage, tillering, booting, 50% flowering, milk stage, dough stage and physiological maturity were recorded for each treatment combination as days after sowing (DAS).

2.3 Agrometeorological Indices

Growing degree days (GDD), heliothermal units (HTU) and photothermal units (PTU) were computed daily using standard agrometeorological formulae and accumulated up to each phenological stage.

$$\text{Growing degree days (°C days)} = \Sigma \{(T_{max} + T_{min}) / 2\} - T_b$$

Where,

T_{max} = Daily maximum temperature (°C)
T_{min} = Daily minimum temperature (°C)

T_b = Minimum threshold / base temperature, taken as 10°C-(ICAR)

$$\text{Helio thermal units (°C days hrs)} = \Sigma \{GDD \times BSS (n)\}$$

Where,

GDD = growing degree days
BSS = Bright sun shine hours (hrs)

$$\text{Photothermal units (°C days hrs)} = \Sigma (GDD * N)$$

Where,

GDD = Growing degree days,
N = Maximum possible sunshine hours (hrs)

$$\text{Heat use efficiency (kg/ha/°C days)} = \text{Grain Yield/AGDD}$$

Where,

AGDD = Accumulated growing degree days (°C days)

2.4 Yield Attributes and Yield

2.4.1 Total Number of Tillers/Plant

Three plants were randomly selected from each plot, and the total number of tillers at harvest was recorded and averaged to obtain the number of tillers per plant.

2.4.2 Effective Tillers/Plant

The total number of ear-bearing tillers on three tagged plants was counted at harvest in each plot, and the average number of effective tillers per plant was calculated.

2.4.3 Test Weight (g)

One thousand grains were counted from each sample of winnowed and cleaned produce from each plot, and their weight was recorded using an electronic balance.

2.4.4 Grain Yield (kg/ha)

The total biomass harvested from each net plot was threshed, cleaned and dried. The resulting grains were weighed in kg per plot and converted to kg/ha.

2.4.5 Stover Yield (kg/ha)

Stover yield per plot was calculated by subtracting grain yield from biological yield and was then expressed in kg/ha.

2.4.6 Biological Yield (kg/ha)

After the harvested material had been thoroughly sun-dried, its weight was recorded to determine biological yield per plot and then converted to kg/ha.

2.4.7 Harvest Index

$$\text{Harvest index} = \frac{\text{Economic yield}}{\text{Biological yield}} * 100$$

2.5 Statistical Analysis

The observations recorded for phenology, agrometeorological indices, growth parameters and yield were subjected to analysis of variance for a factorial randomised block design, as suggested by Fisher (1950). To assess significant differences between treatment means, the critical difference (CD) was calculated at the 5% level of significance by the following formula:

$$\text{CD} = \sqrt{\left(\frac{2EMS}{n}\right)} \times t$$

Where,

C.D. = critical difference
EMS = error mean sum of square
n = number of observations
t = value of t-distribution at 5% level of significance

2.6 Correlation and Regression Analysis

To assess the relationships among weather variables, agrometeorological indices and crop performance, and to develop a regression model relating grain yield and phenological development to GDD, HTU and PTU, simple correlation coefficients (r) and regression equations were calculated following the method of Snedecor and Cochran (1968).

3. Results and Discussion

3.1 Weather Conditions during the Crop Season

Weekly weather parameters were derived from the daily meteorological observations recorded at the agrometeorological observatory of the Department of Agricultural Meteorology, located near the experimental site, throughout the crop growing period. The weekly weather data are presented in Fig. 3 and Fig. 4. Weather conditions varied among the three growing environments, particularly in terms of temperature and rainfall distribution. The crop sown on 24th June (D_1) recorded the highest mean maximum temperature (35.1 °C), followed by the 10th August (34.4 °C) and 18th July (D_2) (33.9 °C) sowings. Similarly, the mean minimum temperature was highest in the 24th June sowing (26.7 °C), followed by the 18th July (26.2 °C) and 10th August (D_3) (25.9 °C) sowings. Rainfall distribution also differed among the growing environments. The cumulative rainfall during the crop season was 356.1 mm, 479.6 mm and 247.0 mm for the 24th June, 18th July and 10th August sowings, respectively. Although D2 received the highest total rainfall, both D2 and D3 received heavy rainfall during the later reproductive period. A total of 190.8 mm rainfall was received between 21 and 25 September 2022. The intense rainfall during this period resulted in waterlogging and unfavourable field conditions, which adversely affected crop growth and development. The effect was more severe in the D3 sowing, as the heavy rainfall coincided with its critical reproductive stage and ultimately led to crop damage.

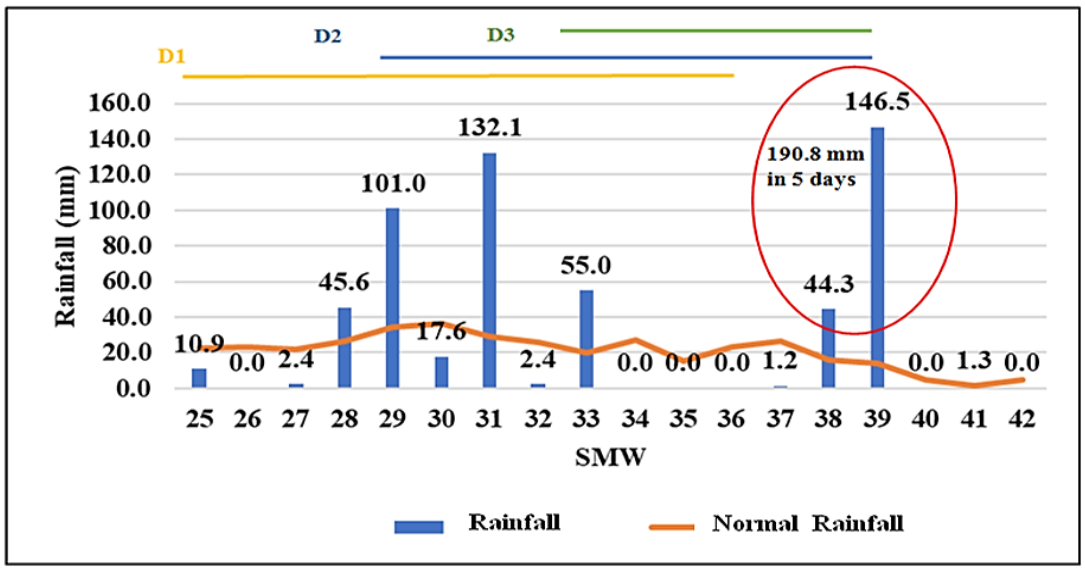


Fig. 3. Mean weekly values of Rainfall during *Kharif* 2022

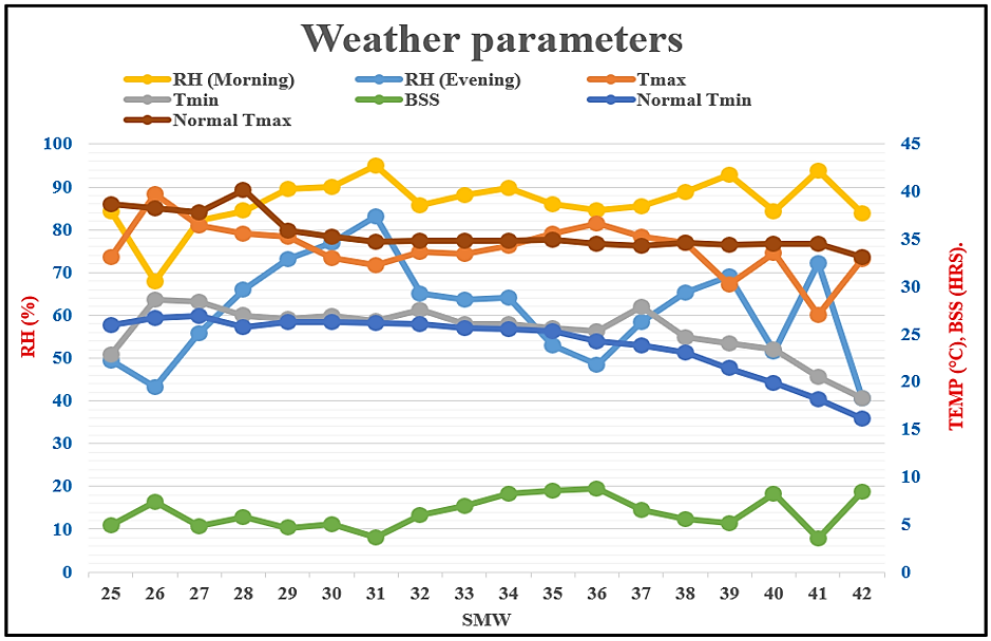


Fig. 4. Mean weekly values of important weather parameters during *Kharif* 2022

3.2 Phenological Development

Phenological observations were recorded daily and the results are presented in Table 1. Dates of sowing significantly influenced phenological development. The 24th June sown crop took the longest time to reach physiological maturity (75.2 days), followed by 18th July (70.5 days). This may have been due to the longer photoperiod during the early growth period of the June sown crop, which delayed flowering and consequently prolonged the reproductive and maturity phases (Ort *et al.*, 2022). In contrast, the shorter duration to physiological maturity under delayed sowing may be due to faster crop development under relatively higher temperatures, which accelerated heat-unit accumulation and shortened the overall duration of the phenological stages (Bhagat *et al.*, 2023; Cao *et al.*, 2024). The 10th August sown crop reached 50% flowering earliest (46.2 DAS) and showed faster development, possibly due to relatively warm conditions during its early growth. However, it was completely damaged after 47 DAS because of heavy rainfall and prolonged water stagnation. Among the varieties, GHB 558 took the longest to reach physiological maturity (74.8 days), followed by HHB 197 (72.9 days) and HHB 67 Improved (70.9 days), indicating varietal differences in crop duration. Lizaso *et al.* (2018) also supported the result and concluded that each degree rise in temperature decreases the length of the developmental period by a few days.

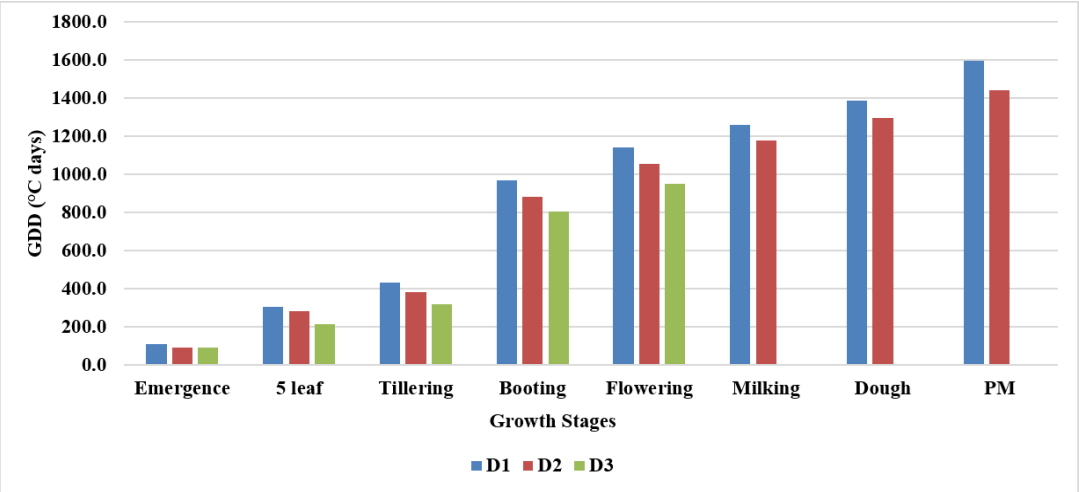
Table 1. Effect of different growing environments on Phenophase development (Days taken) of rainfed pearl millet varieties during crop season 2022

	DAS							
Stage / Treatment	Emergence	Five leaf stage	Tillering stage	Boot stage	50% flowering	Milk stage	Dough stage	PM
Factor A (Sowing dates)								
24th June	4.3	13.1	18.7	45.5	53.9	59.8	66.4	75.2
18th July	4.3	14.3	19.5	44.0	52.3	57.7	63.7	70.5
10th Aug	4.1	10.5	15.7	39.0	46.2	Damaged		
SE(m)	0.12	0.10	0.11	0.06	0.09	0.11	0.13	0.12
CD at 5%	NS	0.28	0.33	0.16	0.26	0.33	0.38	0.36
Factor B (Varieties)								
GHB 558	4.5	13.1	18.5	44.2	52.2	60.5	66.1	74.8
HHB 67 Improved	3.8	12.0	17.1	41.7	49.6	57.4	63.4	70.9
HHB 197	4.4	12.8	18.3	42.7	50.6	58.4	65.6	72.9
SE(m)	0.12	0.10	0.11	0.06	0.09	0.13	0.15	0.14
CD at 5%	0.34	0.28	0.33	0.16	0.26	0.41	0.46	0.44

3.3 Agrometeorological Indices

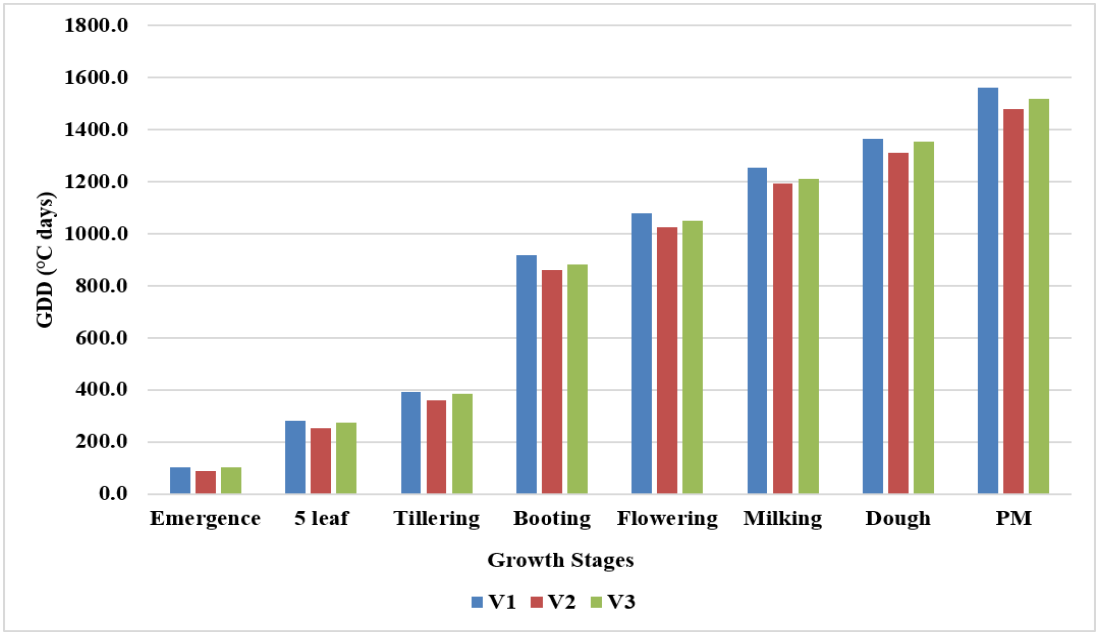
The accumulated GDD, HTU and PTU increased continuously from emergence to maturity (Figs. 5–10). Among sowing dates, the 24th June sowing recorded the highest accumulation, with GDD (1597.1°C Day), HTU (10,295.1°C Day hr) and PTU (20,705.5°C Day hr), followed by the 18th July sowing, which accumulated GDD (1443.6°C Day), HTU (9200.3°C Day hr) and PTU (18,172.9°C Day hr). HTU accumulation was generally higher in D_1 during the vegetative phase and at maturity, but this pattern

changed during the reproductive period, when D_2 and D_3 recorded relatively higher HTU (Fig. 7). Despite the lower GDD under delayed sowing, the higher HTU during these stages may be attributed to greater sunshine duration, which balanced the effect of lower thermal accumulation. The 10th August sowing accumulated the least because of its shorter crop duration and terminal stress caused by waterlogging. Among varieties, GHB 558 recorded the highest cumulative GDD (1562.5°C Day), HTU (10,079.4°C Day hr) and PTU (19,945.0°C Day hr), followed by HHB 197 with 1518.8°C Day, 9733.3°C Day hr and 19,424.3°C Day hr, respectively, while HHB 67 Improved recorded the lowest values of 1479.8°C Day, 9430.3°C Day hr and 18,948.4°C Day hr. The higher GDD in D_1 was explained by its longer crop duration, which provided more time for heat-unit accumulation. The crop experienced favourable temperatures during the early and middle growth stages, supporting steady accumulation of thermal time (Banerjee *et al.*, 2021). Thus, the variation in GDD was mainly due to the combined effect of crop duration and the temperature pattern. Higher HTU under early sowing was due to the combined effect of higher GDD and better sunshine conditions during the crop growth period. Similarly, the higher PTU was mainly associated with greater GDD accumulation and longer day length during the early part of crop growth (Halder *et al.*, 2023). With delayed sowing, the crop had a shorter growth period and encountered progressively shorter days and less favourable sunshine conditions, resulting in lower accumulation of GDD, HTU and PTU (Pathania *et al.*, 2019).



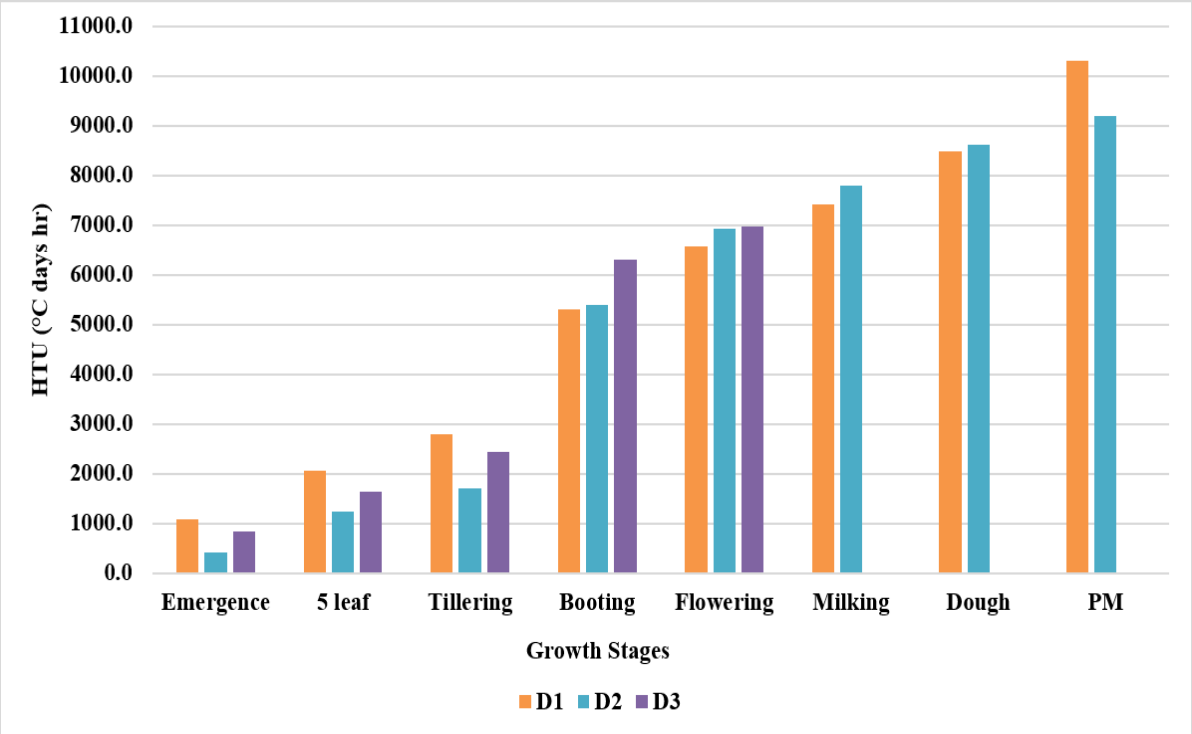
D_1- 24th June, D_2- 18th July, D_3- 10th August

Fig. 5. Growing degree days {GDD (°C days)} accumulation of rainfed pearl millet under different growing environments at different growth stages



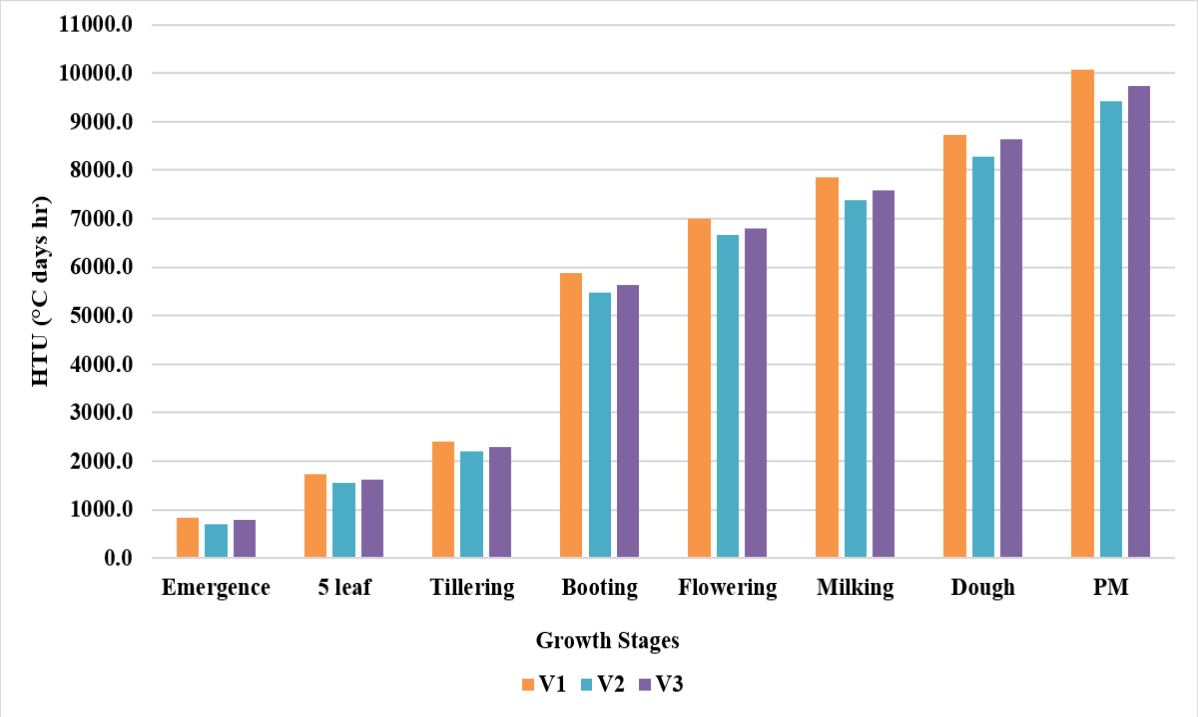
V_1- GHB 558, V_2- HHB 67 Improved, V_3- HHB 197

Fig. 6. Growing degree days {GDD (°C days)} accumulation of different rainfed pearl millet varieties at different growth stages



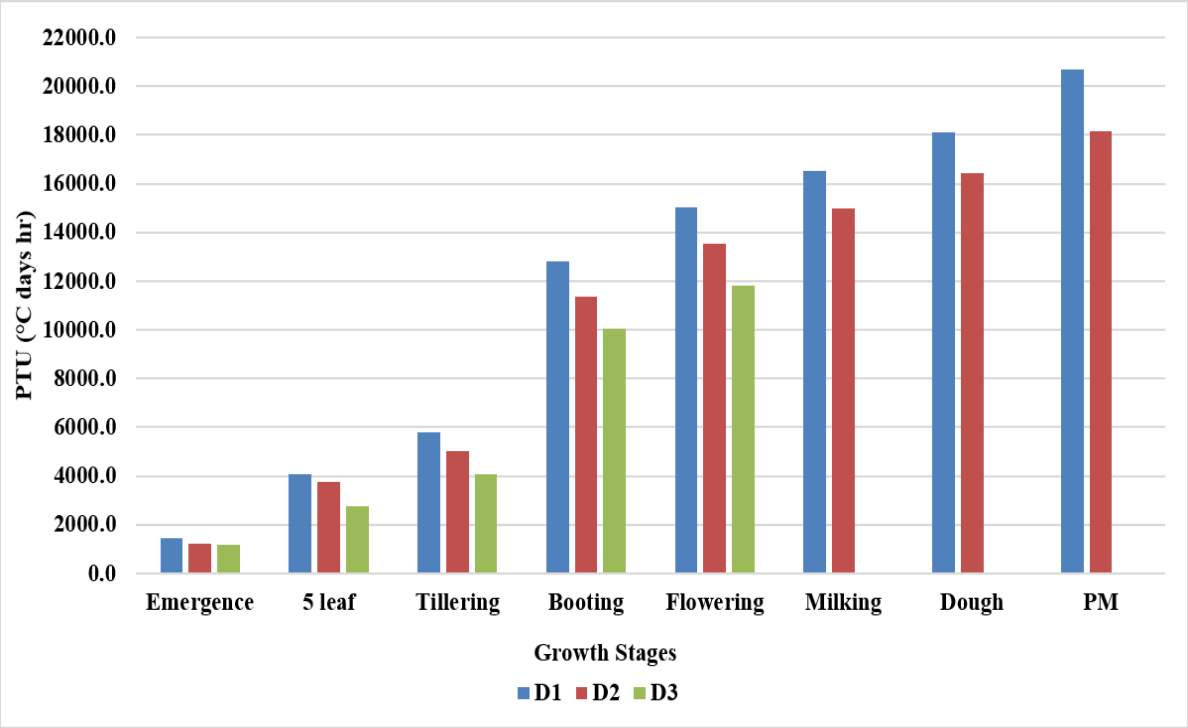
D_1- 24th June, D_2- 18th July, D_3- 10th August

Fig. 7. Heliothermal units {HTU (°C days hr)} accumulation of rainfed pearl millet under different growing environments at different growth stages



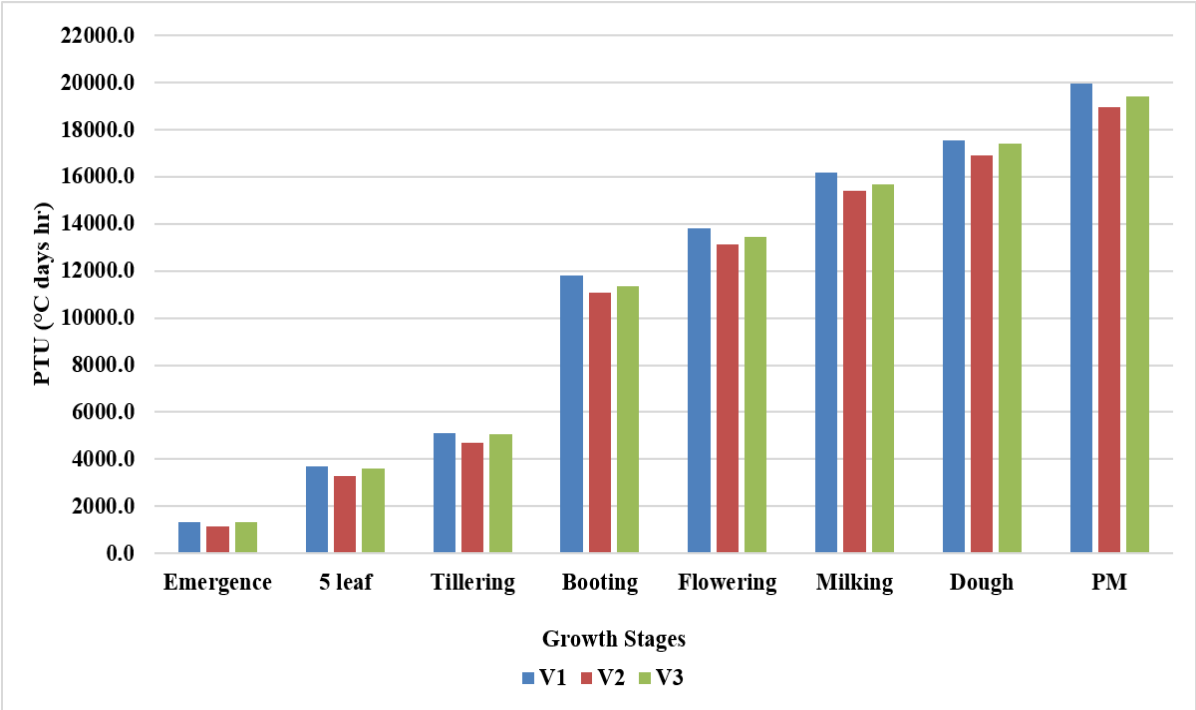
V_1- GHB 558, V_2- HHB 67 Improved, V_3- HHB 197

Fig. 8. Heliothermal units {HTU (°C days hr)} accumulation of different rainfed pearl millet varieties at different growth stages



D_1- 24th June, D_2- 18th July, D_3- 10th August

Fig. 9. Photo thermal units {PTU (°C days hr)} accumulation of rainfed pearl millet under different growing environments at different growth stages



V_1- GHB 558, V_2- HHB 67 Improved, V_3- HHB 197

Fig. 10. Photo thermal units {PTU (°C days hr)} accumulation of different rainfed pearl millet varieties at different growth stages

Heat use efficiency (HUE) was higher under D_1 (2.49 kg/ha/°C days) than D_2 (2.06 kg/ha/°C days), indicating better utilisation of accumulated heat under early sowing (Fig. 11). Among varieties, GHB 558 recorded the highest HUE (2.58 kg/ha/°C days), followed by HHB 197 (kg/ha/°C days) and HHB 67 Improved (2.07 kg/ha/°C days) (Fig. 12). The higher HUE of GHB 558 was consistent with its higher grain and biological yield. Higher HUE under early sowing indicated better conversion of accumulated heat into biomass and grain yield. Favourable temperature and thermal conditions during the reproductive and grain-filling stages also supported better crop growth and yield formation. In delayed sowing, less favourable conditions during these critical stages reduced the efficiency of heat utilisation (Mudassir *et al.*, 2022; El-Ashmouny *et al.*, 2026).

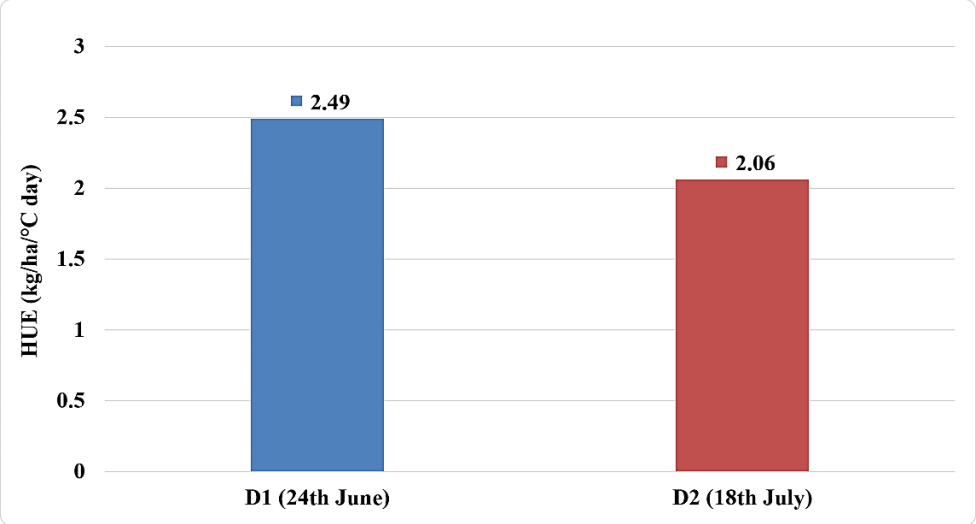


Fig. 11. Heat use efficiency {HUE (kg/ha/°C days)} of rainfed pearl millet under different sowing dates

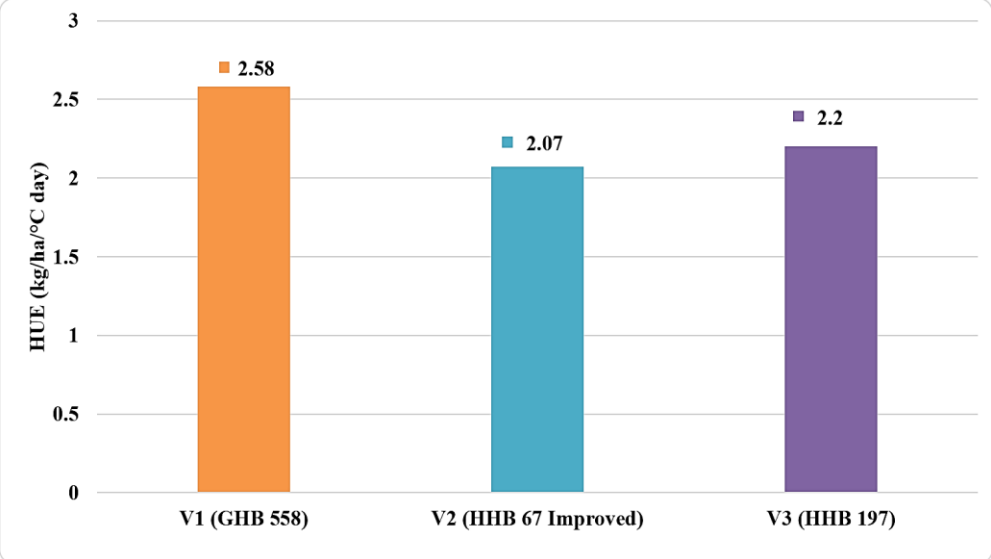


Fig. 12. Heat use efficiency {HUE (kg/ha/°C days)} of different pearl millet varieties under rainfed conditions

3.4 Yield and Yield Attributes

Yield and yield attributes were recorded at maturity. As the crop sown on 10th August was completely damaged after 43 DAS due to heavy rainfall, these observations were analysed only for the 24th June and 18th July sowing dates (Table 2). Sowing date significantly influenced the number of total and effective tillers per plant. The 24th June sown crop recorded higher total (5.75) and effective tillers (5.14) than the 18th July sown crop (5.39 and 4.81, respectively). The varieties did not differ significantly in tiller production; however, HHB 67 Improved recorded the highest total (5.67) and effective tillers (5.13), followed by GHB 558 and HHB 197. The greater tillering under early sowing may be due to a longer favourable growth period and better environmental conditions, whereas lower temperature and shortened growth duration under delayed sowing restricted tiller production (Toyota & Morokuma, 2021; Liu *et al.*, 2019; Joshi *et al.*, 2016). Sowing date did not significantly affect 1000-grain weight, but it was higher under D_1 (9.79 g) than D_2 (9.64 g). Early sowing provided a longer growing period and favourable moisture and temperature

conditions, supporting better grain development and assimilate translocation (G. Singh *et al.*, 2024; Zhiipao *et al.*, 2023; Wu *et al.*, 2024). Delayed sowing exposed the crop to unfavourable moisture conditions during grain filling, resulting in slightly lower test weight (Bonelli *et al.*, 2016; Cheng *et al.*, 2026). Varieties significantly differed in 1000-grain weight, with GHB 558 recording the highest value (9.98 g), followed by HHB 197 (9.67 g) and HHB 67 Improved (9.48 g). Sowing dates and varieties significantly influenced grain, stover and biological yields. The D1-sown crop recorded higher grain (3974.5 kg ha^{-1}), stover (10656.3 kg ha^{-1}) and biological yield (14630.8 kg ha^{-1}) than D_2 (2976.3, 8468.2 and 11444.4 kg ha^{-1}, respectively). Thus, timely sowing resulted in about 34% higher grain yield. This advantage may be attributed to longer crop duration, favourable hydrothermal conditions and better soil moisture availability, which promoted biomass accumulation and grain filling (Reddy *et al.*, 2019; Susmita *et al.*, 2025; Subbulakshmi, 2022). Delayed sowing shortened the growth period and exposed the crop to excess moisture and unfavourable weather during reproductive and grain-filling stages, reducing biomass and grain production (Bisht *et al.*, 2019; Maurya *et al.*, 2016; Detroja *et al.*, 2018). Among the varieties, GHB 558 produced the highest grain (4026.0 kg ha^{-1}), stover (10505.2 kg ha^{-1}) and biological yield (14531.3 kg ha^{-1}), followed by HHB 197 and HHB 67 Improved. The better performance of GHB 558 indicated its better biomass production and assimilate partitioning under rainfed conditions. Harvest index was not significantly affected by sowing dates and varieties, indicating that yield differences were mainly associated with biomass production rather than partitioning efficiency. The highest harvest index was recorded under D_1 sown crop (26.98%) and in GHB 558 (27.49%). Better photosynthetic activity and greater assimilate accumulation may have contributed to improved source–sink relationships and higher yield (Divya *et al.*, 2017; Joshi *et al.*, 2003).

Table 2. Yield and yield attributes at maturity in different varieties of rainfed pearl millet under different growing environments

Yield and yield attributes	Total no. of tillers/plant	No. of effective tillers/plant	1000-grain weight (g)	Grain yield (Kg/ha)	Stover yield (Kg/ha)	Biological yield (Kg/ha)	Harvest index (%)
Factor A (Sowing dates)							
24th June	5.75	5.14	9.79	3974.5	10656.3	14630.8	26.98
18th July	5.39	4.81	9.64	2976.3	8468.2	11444.4	25.93
SE(m)	0.10	0.11	0.09	111.84	172.27	268.72	0.42
CD at 5%	0.31	0.32	NS	340.20	524.02	817.40	NS
Factor B (Varieties)							
GHB 558	5.54	5.00	9.98	4026.0	10505.2	14531.3	27.49
HHB 67 Improved	5.67	5.13	9.48	3057.3	8625.9	11683.2	26.14
HHB 197	5.50	4.79	9.67	3342.9	9555.6	12898.4	25.73
SE(m)	0.12	0.13	0.11	136.98	210.99	329.12	0.52
CD at 5%	NS	NS	0.34	416.66	641.79	1001.11	NS

3.5 Relationship of Growth Parameters with Grain Yield

The correlation between grain yield and different growth parameters at different intervals is presented in Table 3. Grain yield showed a significant positive correlation with LAI at 43 DAS (0.85*), 50 DAS (0.86*) and 57 DAS (0.86*), indicating that better leaf area development during the reproductive period helped the crop intercept more sunshine and maintain photosynthesis, resulting in greater assimilation for grain formation, which contributed to higher grain yield (Liu *et al.*, 2023; Joshi *et al.*, 2003). In contrast, LAI at 29 DAS showed a significant negative correlation (-0.86*), suggesting that higher leaf area at the early stage did not contribute to grain yield (Capo *et al.*, 2023) and may have been associated with excessive early vegetative growth. Total dry matter showed a positive and significant correlation with grain yield from 29 DAS to maturity, with values of 0.90* at 29 DAS, 0.99** at 36 DAS, 0.87* at 43 DAS, 0.81* at 50 DAS, 0.85* at 57 DAS, 0.90* at 64 DAS and 0.90* at PM. This indicated that higher dry matter production throughout the crop period was closely associated with higher grain yield, probably because more biomass provided greater assimilates for grain development (Liu *et al.*, 2020; Patel *et al.*, 2025). Plant height also showed a significant positive correlation from 50 DAS onwards, with values of 0.87* at 50 DAS, 0.95** at 57 DAS, 0.89* at 64 DAS and 0.88* at maturity. This indicated that better plant growth during the later stages was associated with higher grain yield (Amanullah *et al.*, 2021). Overall, LAI during the development stage, total dry matter throughout the crop period and plant height during the later stages showed a strong relationship with grain yield.

Table 3. Correlation coefficients between grain yield and different growth parameters during crop season

Parameters	DAS								
	15	22	29	36	43	50	57	64	PM
LAI	0.37	0.47	-0.86*	0.04	0.85*	0.86*	0.86*	0.77	0.75
Plant Height	0.28	0.41	0.55	0.37	0.46	0.87*	0.95**	0.89*	0.88*
Total Dry Matter	0.71	0.55	0.90*	0.99**	0.87*	0.81*	0.85*	0.90*	0.90*

**Significant at 0.05 p level, ** Significant at 0.01p level, DAS = Days after sowing*

3.6 Relationship of Growth Parameters with Weather Variables

The correlation between growth parameters and weather variables at different intervals (Table 4) indicated that the influence of weather conditions varied across developmental phases. At 22 DAS, plant height was positively correlated with maximum

temperature (0.69*) and minimum temperature (0.84**), while morning relative humidity showed a negative correlation (−0.67*), indicating that warmer conditions supported early vegetative growth by increasing its relative growth rate and net assimilation rate (Ashraf & Hafeez, 2004). During 29–36 DAS, LAI was positively related to minimum temperature (0.86** and 0.84**) and rainfall (0.88** and 0.74*), whereas sunshine hours showed strong negative correlations (−0.99** and −0.93**). These results indicated that adequate soil moisture supported better leaf development, whereas clear and sunny conditions were associated with comparatively lower canopy development, possibly due to higher evaporative demand (Gao *et al.*, 2026; Moseki *et al.*, 2025). TDM at 36 DAS also showed a strong positive relationship with minimum temperature (0.90**). At 43 DAS, LAI, plant height and TDM were positively related to minimum temperature, evening relative humidity and rainfall, while sunshine hours showed negative relationships with these growth parameters. This indicated that adequate moisture and suitable temperature during the active growth period enhanced leaf development and dry matter accumulation (Andrade & Abreu, 2007; Shao *et al.*, 2024). The negative relationship with sunshine hours may be related to the monsoon period, when lower sunshine was accompanied by higher rainfall and moisture availability. At physiological maturity, however, sunshine hours showed significant positive correlations with LAI (0.84*), plant height (0.88*) and TDM (0.95**), suggesting that better sunshine availability during the grain filling stage supported photosynthesis and biomass accumulation (Singh *et al.*, 2017; Yang *et al.*, 2022). Overall, temperature and moisture were more important during the vegetative phase, whereas sunshine became more important during the later stage of crop growth.

Table 4. Correlation coefficients between different growth parameters and weather parameters

DAS	Growth parameters	Weathers paramters					
		Tmax (°C)	Tmin (°C)	RHm (%)	RHe (%)	SSH (hr)	Rainfall (mm)
15 DAS	**LAI**	0.19	0.35	-0.16	0.02	-0.47	0.18
	PLANT HT	0.18	0.26	-0.17	-0.08	-0.18	0.01
	TDM	0.45	0.64	-0.43	-0.19	-0.47	0.03
22 DAS	**LAI**	0.05	0.63	-0.02	0.31	-0.83**	0.54
	PLANT HT	0.69*	0.84**	-0.67*	-0.44	-0.20	-0.22
	TDM	0.27	0.58	-0.25	-0.02	-0.44	0.16
29 DAS	**LAI**	-0.08	0.86**	0.04	0.62	-0.99**	0.88**
	PLANT HT	0.16	0.66	-0.19	0.23	-0.62	0.47
	TDM	0.41	0.58	-0.43	-0.10	-0.36	0.15
36 DAS	**LAI**	0.04	0.84**	-0.09	0.62	-0.93**	0.74*
	PLANT HT	0.06	0.55	-0.03	0.44	-0.64	0.52
	TDM	0.44	0.90**	-0.54	0.14	-0.65	0.30
43 DAS	**LAI**	0.21	0.88**	0.04	0.85**	-0.99**	0.99**
	PLANT HT	-0.17	0.75*	0.03	0.72*	-0.83**	0.83**
	TDM	-0.05	0.87**	-0.11	0.69*	-0.91**	0.87**
PM	**LAI**	0.24	0.14	-0.24	-0.37	0.84*	-0.27
	PLANT HT	0.45	0.32	-0.44	-0.58	0.88*	-0.46
	TDM	0.61	0.53	-0.61	-0.71	0.95**	-0.64

**Significant at 0.05 p level, ** Significant at 0.01p level, TDM = Total dry matter, LAI = leaf area index, HT = Height, DAS = Days after sowing*

3.7 Relationship of Yield with Weather Variables

The correlation between grain yield and different weather variables at different intervals is presented in Table 5. Grain, stover and biological yield showed a significant positive relationship with bright sunshine hours (0.96**, 0.89* and 0.92**), respectively. This indicated that better sunshine availability supported photosynthesis, dry matter accumulation and grain development (Singh *et al.*, 2017). In contrast, evening relative humidity was negatively correlated with grain yield (−0.84*), stover yield (−0.84*) and biological yield (−0.85*), suggesting that prolonged humid conditions were unfavourable for crop growth and may also have increased the risk of disease and lodging (Murria *et al.*, 2022). Total tillers per plant were positively correlated with maximum temperature (0.92*), minimum temperature (0.95*) and rainfall (0.93*) but had a negative correlation with morning (−0.94*) and evening relative humidity (−0.88*). These results suggested that optimum temperature conditions along with adequate moisture enhanced tiller formation (Singh *et al.*, 1998; Londhe *et al.*, 2020), while highly humid conditions were not favourable for tiller development (Kumar *et al.*, 2024). Overall, better sunshine, optimum temperature and adequate moisture favoured crop growth and yield formation.

Table 5. Correlation coefficients between yield and weather parameters

Yield	Weather parameters					
	Tmax (°C)	Tmin (°C)	RHm (%)	RHe (%)	SSH (hr)	RAINFALL (mm)
Grain	0.76	0.64	0.75	-0.84*	0.96**	0.76
Stover	0.77	0.66	0.76	-0.84*	0.89*	0.78
Biological	0.77	0.66	0.76	-0.85*	0.92**	0.78
Total no of Tillers/plant	0.92*	0.95*	-0.94*	-0.88*	0.61	0.93*

**Significant at 0.05 p level, ** Significant at 0.01p level*

3.8 Relationship of Agrometeorological Indices with Grain and biological Yield

The correlation analysis showed positive and highly significant relationships ($p \leq 0.01$) between GDD, HTU and PTU and both grain and biological yield, as shown in Table 6. HTU showed the highest correlation with grain yield (r = 0.73**), while GDD had the strongest relationship with biological yield (r = 0.79**). The positive relationship indicated that greater thermal accumulation, along with favourable sunshine and photoperiod, supported leaf growth, biomass production and grain development. Thus, suitable temperature and radiation conditions during crop growth contributed to better dry matter accumulation and ultimately higher yield (Balagond *et al.*, 2020; McIntyre *et al.*, 1993). The significant correlations indicated that the existing temperature and radiation environment during crop development played an important role in determining yield under different sowing dates and varieties.

Table 6. Correlation coefficients between thermal indices and yield of rainfed pearl millet

Thermal indices	Grain Yield	Biological Yield
GDD	0.72**	0.79**
HTU	0.73**	0.78**
PTU	0.71**	0.77**

*** Significant at 0.01p level. GDD - Growing Degree Days; HTU - Heliothermal Units; PTU - Photothermal Units*

3.9 Regression Model for Yield Prediction and Phenological Development

The regression analysis showed a close linear relationship between accumulated thermal indices and phenological development of rainfed pearl millet (Figs. 13–15). The relationship was strongest with GDD ($R^2 = 0.9981$; $y = 0.0486x - 1.234$), followed by PTU ($R^2 = 0.9945$; $y = 0.0038x - 1.301$) and HTU ($R^2 = 0.9726$; $y = 0.0075x - 0.665$). The very high R^2 values indicated that thermal-time accumulation was closely associated with the rate of phenological development at successive growth stages (G. Singh *et al.*, 2024; P. N. Singh *et al.*, 2025).

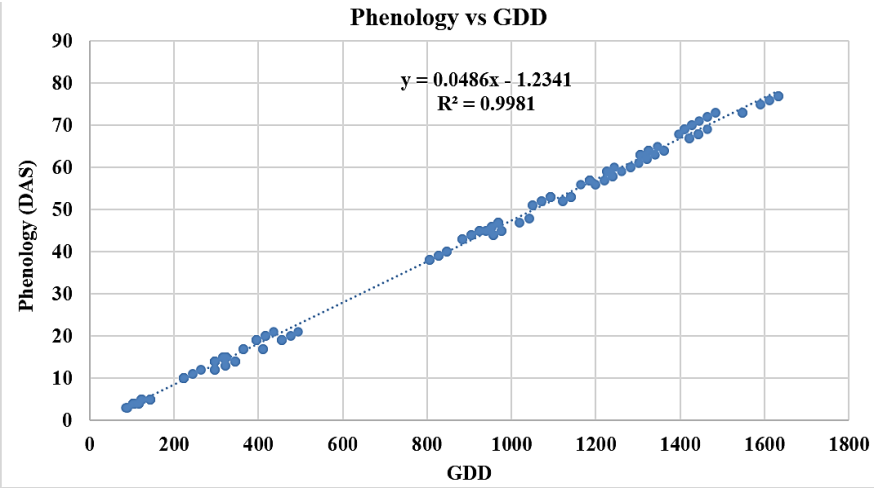


Fig. 13. Relationship between accumulated growing degree days (GDD) and phenological development of rainfed pearl millet

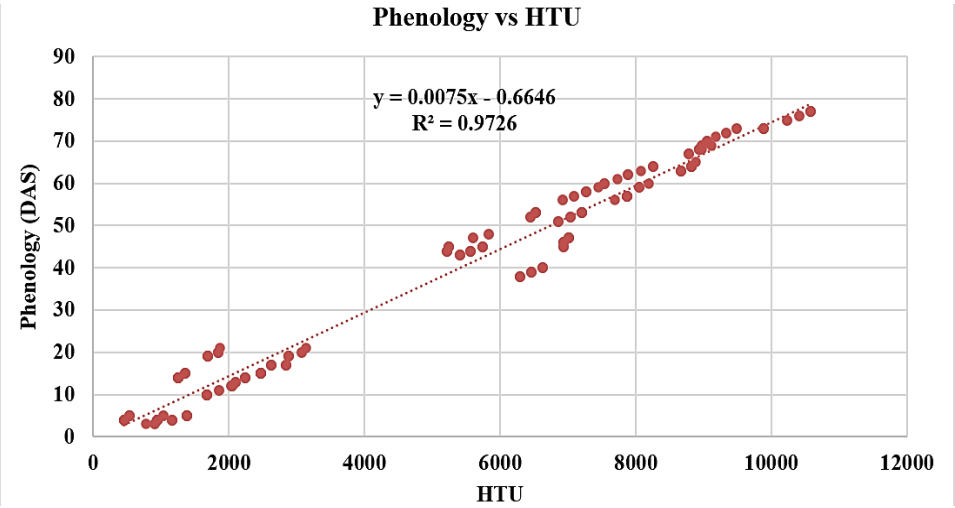


Fig. 14. Relationship between accumulated Helio thermal unit (HTU) and phenological development of rainfed pearl millet

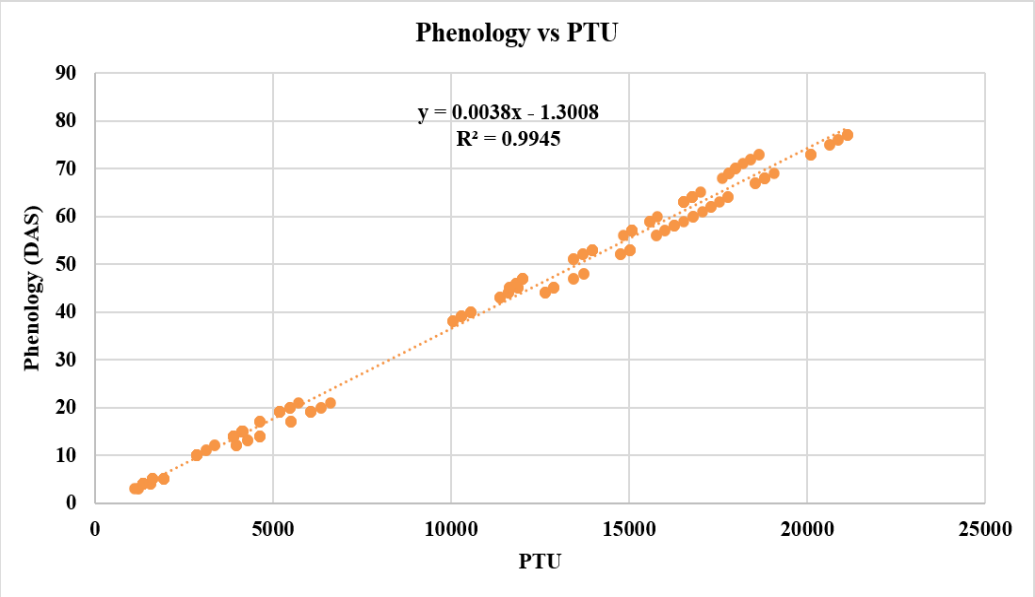


Fig. 15. Relationship between accumulated photo thermal unit (PTU) and phenological development of rainfed pearl millet

The relationship with grain yield was comparatively weaker, as shown in Figs. 16–18. Grain yield showed a positive relationship with GDD (R^2 = 0.524), HTU (R^2 = 0.531) and PTU (R^2 = 0.503), which was also supported by their significant positive correlations (r = 0.724**, 0.729** and 0.709**, respectively). The correlations with biological yield were slightly higher (r = 0.787**, 0.782** and 0.774**, respectively). This shows that thermal accumulation had a considerable impact on crop development and yield, but grain production also depended on other factors such as moisture availability, sunshine, humidity and temperature conditions during the critical growth stages. The combined effect of the three indices was also examined through multiple regression (Fig. 19). The model explained 54.2 per cent of the variation in grain yield (R^2 = 0.54; adjusted R^2 = 0.47) and was highly significant. The positive coefficients for GDD and HTU indicated their contribution to yield, while the negative coefficient for PTU, when GDD and HTU were included in the model, may be due to the close relationship among these indices. Overall, the results suggested that thermal indices were highly useful for explaining phenological development, but thermal indices alone did not account for the variation observed in grain yield as it was also influenced by other environmental factors (Alsaber *et al.*, 2025).

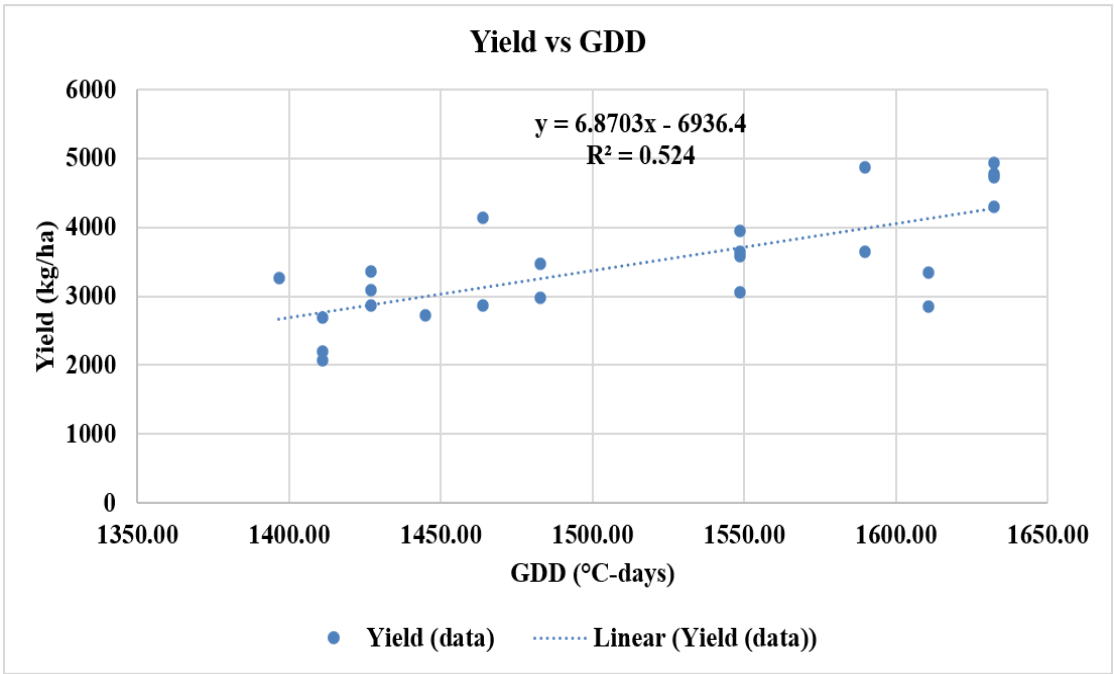


Fig. 16. Relationship between accumulated growing degree days (GDD) and grain yield of rainfed pearl millet

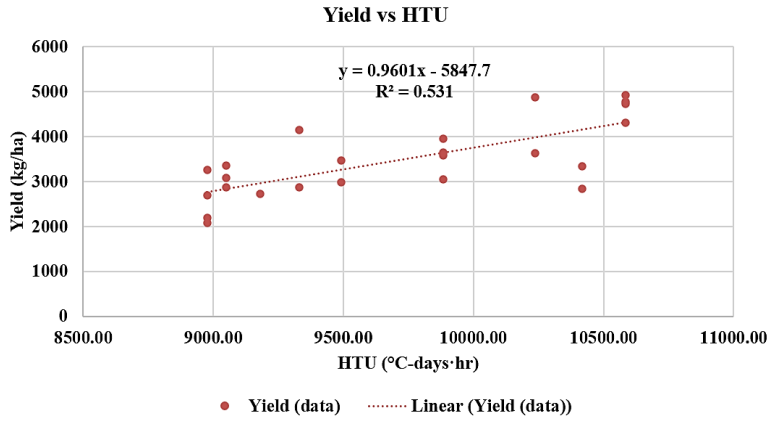


Fig. 17. Relationship between accumulated Helio thermal unit (HTU) and grain yield of rainfed pearl millet

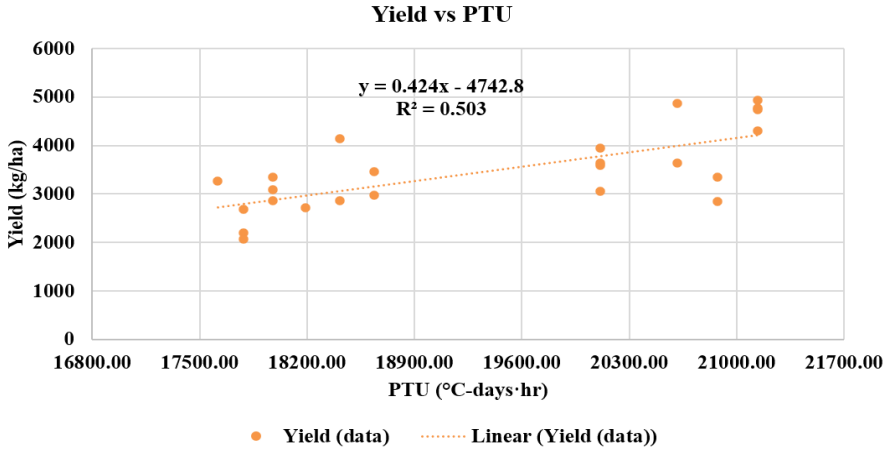


Fig. 18. Relationship between accumulated photo thermal unit (PTU) and grain yield of rainfed pearl millet

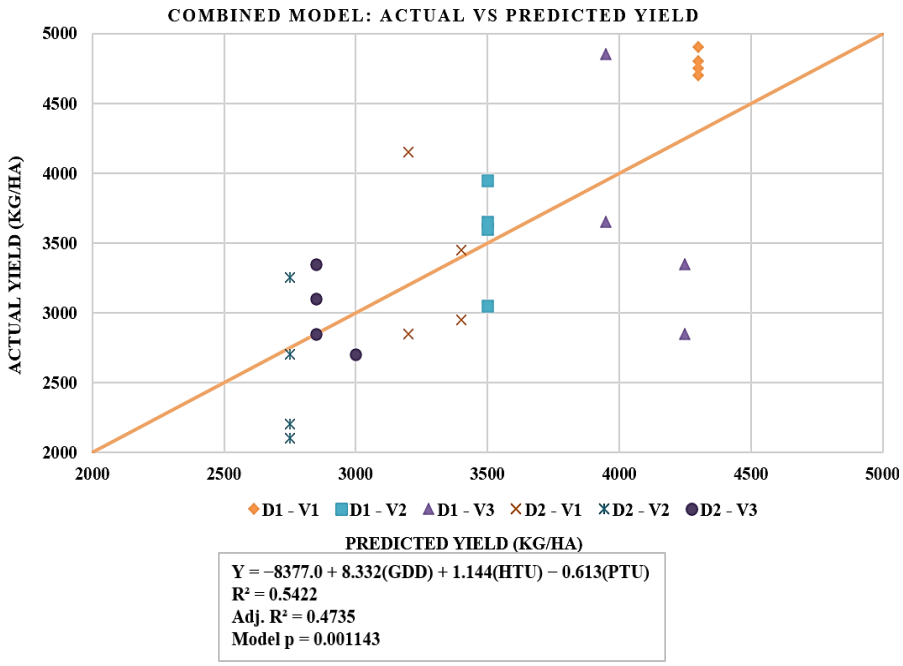


Fig. 19. Actual versus predicted grain yield from the combined regression model (grain yield as a function of GDD, HTU and PTU)

4. Conclusion

The present investigation established that sowing time and variety influenced phenology, growth and yield of rainfed pearl millet under the semi-arid conditions of Hisar. The variability was mainly associated with the thermal and radiation conditions experienced by the crop during its growth period. The 24th June sown crop resulted in a longer crop duration and more favourable growing conditions, resulting in higher accumulation of GDD, HTU and PTU, better heat use efficiency and higher grain, stover and biological yields than the 18th July sown crop. In contrast, the 10th August sown crop encountered heavy monsoon rainfall and waterlogging, leading to severe crop damage and failure to reach physiological maturity. This indicated the production risk associated with very late sowing under the variable monsoon conditions of the region. Among the varieties, GHB 558 performed better than HHB 197 and HHB 67 Improved, recording higher thermal-unit accumulation, heat use efficiency, grain yield, biological yield, test weight and harvest index. The longer duration of this variety allowed greater accumulation and utilisation of thermal resources during crop growth. The weather–growth relationships showed that bright sunshine hours and evening relative humidity were important factors associated with yield formation. Adequate temperature and moisture during the vegetative period enhanced tillering, leaf development and dry matter accumulation, whereas better sunshine availability during the later stages contributed to crop growth and yield formation. The accumulated GDD, HTU and PTU showed very close relationships with phenological development (**$R^2 > 0.97$**), confirming their usefulness in explaining crop progression. Their relationship with grain yield was moderate (**$R^2 = 0.50–0.53$**), indicating that yield was influenced by several environmental factors in addition to thermal conditions. Combining the three indices in a multiple regression model slightly improved grain-yield prediction (**$R^2 = 0.54$**). Under the agro-meteorological conditions prevailing at the experimental location during the study season, the results indicated that timely sowing around the latter part of June, particularly with GHB 558, is suitable for improving rainfed pearl millet productivity under the semi-arid conditions of Hisar. Sowing beyond mid-July, particularly during August, may expose the crop to greater weather-related risks and should therefore be avoided. The thermal indices computed from daily weather observations can also be used for predicting phenological stages, planning crop operations and developing simple weather-based yield forecasting approaches for pearl millet in the region.

5. Limitations

The investigation was conducted at a single location during one kharif season, limiting the extent to which the observed sowing-date and varietal responses can be generalised across years or agroclimatic conditions. Severe waterlogging damaged the August-sown crop before physiological maturity, preventing a comparable yield assessment for that sowing date. The reported correlations describe associations and do not establish causal effects of individual weather variables. Although thermal indices were strongly related to phenological development, the combined regression explained only part of the observed variation in grain yield.

Acknowledgements

We are grateful to all faculty members of the agricultural meteorology department, CCS HAU, Hisar for their kind support, knowledge and direction related to the research problem. I sincerely thank the ICAR-CRIDA for providing me the facility to conduct my research under the project AICRP-Agrometeorology.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Alsaber, A., Setiya, P., Satpathi, A., Aljamaan, A., & Pan, J. (2025). Advancing pearl millet yield forecasting: Comparative analysis of individual and ensemble machine learning approaches over Rajasthan, India. *PLOS ONE*, *20*(3), e0317602. https://doi.org/10.1371/journal.pone.0317602

Amanullah, Khalid, S., Khalil, F., Elshikh, M. S., Alwahibi, M. S., Alkahtani, J., Imranuddin, & Imran. (2021). Growth and dry matter partitioning response in cereal-legume intercropping under full and limited irrigation regimes. *Scientific Reports*, *11*(1), 12585. https://doi.org/10.1038/s41598-021-92022-4

Andrade, J. A., & Abreu, F. G. (2007). Influência da temperatura e do teor de humidade do solo na área foliar e acumulação de matéria seca durante o estabelecimento da ervilha, do milho e do girassol [Influence of temperature and soil moisture on leaf area and dry matter accumulation during establishment of pea, maize and sunflower]. *Revista de Ciências Agrárias*, *30*(2), 27–37. https://doi.org/10.19084/rca.15461

Ashraf, M., & Hafeez, M. (2004). Thermotolerance of pearl millet and maize at early growth stages: growth and nutrient relations. *Biologia* P*lantarum*, *48*(1), 81-86. https://doi.org/10.1023/B:BIOP.0000024279.44013.61

Balagond, S., Jadhav, J. D., Wale, V. D., Shaikh, A. A., Sthool, V. A., & Akashe, V. B. (2020). Effect of weather parameters on growth and yield of pearl millet. *Journal of Pharmacognosy and Phytochemistry*, *9*(6), 2053-2056. https://www.phytojournal.com/archives/2020.v9.i6.13264/effect-of-weather-parameters-on-growth-and-yield-of-pearl-millet

Banerjee, P., Mukherjee, B., Venugopalan, V. K., Nath, R., Chandran, M. A. S., Dessoky, E. S., Ismail, I. A., El-Hallous, E. I., & Hossain, A. (2021). Thermal response of spring–summer-grown black gram (*Vigna mungo* L. Hepper) in Indian subtropics. *Atmosphere*, *12*(11), 1489. https://doi.org/10.3390/atmos12111489

Bhagat, M. A., Kaur, N., & Kaur, S. (2023). Effect of sowing dates on the phenology, grain yield and stress tolerance indices of barley (Hordeum vulgare L.) genotypes under subtropical conditions of Punjab. *Journal of Agrometeorology*, *25*(1), 113-119. https://doi.org/10.54386/jam.v25i1.1841

Bisht, H., Singh, D. K., Mishra, A. K., Sarangi, A., Prajapati, V. K., Singh, M., & Krishnan, P. (2019). Heat unit requirement of wheat (Triticum aestivum L.) under different thermal and moisture regimes. *Journal of Agrometeorology*, *21*(1), 36-41. https://doi.org/10.54386/jam.v21i1.201

Bonelli, L. E., Monzon, J. P., Cerrudo, A., Rizzalli, R. H., & Andrade, F. H. (2016). Maize grain yield components and source-sink relationship as affected by the delay in sowing date. *Field Crops Research*, *198*, 215-225. https://doi.org/10.1016/j.fcr.2016.09.003

Cao, Z. Y., Chen, Z. H., Tang, B., Zeng, Q., Guo, H. L., Huang, W. H., Luo, Y., Shen, S., & Zhou, S. L. (2024). The effects of sowing date on maize: Phenology, morphology, and yield formation in a hot subtropical monsoon region. *Field Crops Research*, *309*, 109309. https://doi.org/10.1016/j.fcr.2024.109309

Capo, L., Sopegno, A., Reyneri, A., Ujvari, G., Agnolucci, M., & Blandino, M. (2023). Agronomic strategies to enhance the early vigor and yield of maize part II: the role of seed applied biostimulant, hybrid, and starter fertilization on crop performance. *Frontiers in* P*lant* S*cience*, *14*, 1240313. https://doi.org/10.3389/fpls.2023.1240313

Carcedo, A., Maddonni, G., Ramalingam, A. P., Parray, S. A., Tugoo, M. Z., Pereira, T. A., Perumal, R., Prasad, P. V. V., & Ciampitti, I. (2024). Pearl millet phenology assessment: An integration of field, a review, and in silico approach. *Crop Science, 64*(6), 3028–3042. https://doi.org/10.1002/csc2.21352

Cheng, C., Yan, J., Lyu, Y., Tang, S., Chen, S., Chen, X., Wu, L., & Gong, Z. (2026). Simulation study on the yield reduction risk of late sowing winter wheat and the compensation effect of soil moisture in the North China Plain. *Agriculture*, *16*(2), 183. https://doi.org/10.3390/agriculture16020183

Department of Agriculture & Farmers Welfare. (2024). *Agricultural statistics at a glance 2024*. Government of India. https://desagri.gov.in/document-report-category/agriculture-statistics-at-a-glance/

Detroja, A. C., Bhuva, H. M., Chaudhari, N. N., Patel, P. R., & Kikani, V. L. (2018). Production potential of improved pearlmillet (Pennisetum glaucum L.) cultivars under staggered sowing in raifed areas of western India. *International Journal of Environmental Sciences & Natural Resources*, *12*(4), 119-122. https://doi.org/10.19080/IJESNR.2018.12.555845

Divya, G., Vani, K. P., Babu, P. S., & Devi, K. B. S. (2017). Yield attributes and yield of summer pearl millet as influenced by cultivars and integrated nutrient management. *International Journal of Current Microbiology and Applied Sciences*, *6*(10), 1491-1495. https://doi.org/10.20546/ijcmas.2017.610.177

El-Ashmouny, A. A., Hegab, A. S., Ali, B. A., & Saudy, H. S. (2026). Response of phenological and agronomical attributes and thermal utilization efficiency of cotton cultivars to cumulative heat units under different sowing dates. *BMC Plant Biology*, *26*(1), 162. https://doi.org/10.1186/s12870-025-08076-3

Fisher, R. A. (1950). *Contributions to mathematical statistics*. Wiley. https://books.google.com/books/about/Contributions_to_Mathematical_Statistics.html?id=zBnvAAAAMAAJ

Gao, X., Yan, Z., Cheng, B., Yang, X., Jia, Y., & Cao, Y. (2026). Responses of millet growth and physiological traits to combined supplementary irrigation and foliar selenium applications. *Agriculture*, *16*(15), 1627. https://doi.org/10.3390/agriculture16151627

Halder, T., Biswas, A., Barman, H. N., Akter, S., Shupta, S. A., & Pervin, M. S. (2023). Thermal requirement for the phenological development and yield of rice as influenced by seeding date. *Bangladesh Rice Journal*, *27*(2), 39-50. https://doi.org/10.3329/brj.v27i2.77303

Jat, G. P., Dhayal, L. S., Shekhawat, A. S., Sain, R. S., Yadav, I. R., & Jat, M. K. (2025). Assessment of genotype-environment interactions for identification of stable and high-performing pearl millet [Pennisetum glaucum (L.) R. Br.] hybrids. *Plant Cell Biotechnology and Molecular Biology, 26*(11–12), 10–19. https://doi.org/10.56557/pcbmb/2025/v26i11-129929

Joshi, A. K., Pandya, J. N., Buhecha, K. V., Dave, H. R., Pethani, K. V., & Dangaria, C. J. (2003). Grain yield in pearl millet in relation to source size and proximity to sink. *Photosynthetica*, *41*(1), 157-159. https://doi.org/10.1023/A:1025841320024

Joshi, M. A., Faridullah, S., & Kumar, A. (2016). Effect of heat stress on crop phenology, yield and seed quality attributes of wheat (*Triticum aestivum* L.). *Journal of Agrometeorology*, *18*(2), 206-215. https://doi.org/10.54386/jam.v18i2.937

Khajuria, S., Rai, A. K., Khadda, B. S., Kumar, R., & Jadav, J. K. (2018). Pearl millet (bajra). In M. Hedayetullah & P. Zaman (Eds.), *Forage crops of the world: Vol. I. Major forage crops* (pp. 57–86). Apple Academic Press. https://appleacademicpress.com/forage-crops-of-the-world-volume-i-major-forage-crops/9781771886840

Kumar, A., Dagar, C. S., Ambika, & Khichar, M. L. (2024). Study impact of weather entities on pearl millet growth under semi-arid condition. *Forage Research*, *50*(2), 183–188. https://forageresearch.in/study-impact-of-weather-entities-on-pearl-millet-growth-under-semi-arid-condition/

Liu, W., Hou, P., Liu, G., Yang, Y., Guo, X., Ming, B., Xie, R., Wang, K., Liu, Y., & Li, S. (2020). Contribution of total dry matter and harvest index to maize grain yield—A multisource data analysis. *Food and Energy Security*, *9*(4), e256. https://doi.org/10.1002/fes3.256

Liu, Z., Gao, J., Zhao, S., Sha, Y., Huang, Y., Hao, Z., & Mi, G. (2023). Nitrogen responsiveness of leaf growth, radiation use efficiency and grain yield of maize (*Zea mays* L.) in Northeast China. *Field Crops Research*, *291*, 108806. https://doi.org/10.1016/j.fcr.2022.108806

Liu, Z., Tao, L., Liu, T., Zhang, X., Wang, W., Song, J., Yu, C., & Peng, X. (2019). Nitrogen application after low-temperature exposure alleviates tiller decrease in rice. *Environmental and Experimental Botany*, *158*, 205-214. https://doi.org/10.1016/j.envexpbot.2018.11.001

Lizaso, J. I., Ruiz-Ramos, M., Rodríguez, L., Gabaldon-Leal, C., Oliveira, J. A., Lorite, I. J., Sánchez, D., García, E., & Rodríguez, A. (2018). Impact of high temperatures in maize: Phenology and yield components. *Field Crops Research*, *216*, 129-140. https://doi.org/10.1016/j.fcr.2017.11.013

Londhe, V. M., Birajdar, S. G., Jadhav, V. T., Jadhav, J. D., & Amrutsagar, V. M. (2020). Effect of weather parameters on pearl millet (Pennisetum glaucum L.) cultivars under different sowing windows. *International Journal of Current Microbiology and Applied Sciences*, *9*(9), 1190-1202. https://doi.org/10.20546/ijcmas.2020.909.147

Maurya, S. K., Nath, S., Patra, S. S., & Rout, S. (2016). Effect of different sowing dates on growth and yield of pearl millet (*Pennisetum glaucum* L.) varieties under Allahabad condition. *International Journal of Science and Nature*, *7*(1), 62–69. https://www.scienceandnature.org/IJSN/IJSN_Vol7%281%29J2016/IJSN-VOL7%281%2916-11.pdf

Maya, Mishra, S. R., Singh, A. K., Kumar, K., Pandey, A., Mishra, A. N., Yadav, L. P., & Jinger, D. (2026). Optimising growing environment and cultivar in rainfed pearl millet (Pennisetum glaucum) cultivation for higher growth and productivity. *The Indian Journal of Agricultural Sciences, 96*(6), 824–827. https://doi.org/10.56093/ijas.v96i6.163266

McIntyre, B. D., Flower, D. J., & Riha, S. J. (1993). Temperature and soil water status effects on radiation use and growth of pearl millet in a semi-arid environment. *Agricultural and Forest Meteorology*, *66*(3-4), 211-227. https://doi.org/10.1016/0168-1923(93)90072-P

Moseki, O., Kangueehi, G., Chiteculo, V., Zink, M., & Wanga, M. A. (2025). Agro-physiological and morphological responses of pearl millet to varying water regimes in semi-arid conditions of Namibia. *Agronomy*, *15*(2), 381. https://doi.org/10.3390/agronomy15020381

Mudassir, M. A., Rasul, F., Khaliq, T., & Yaseen, M. (2022). Conformance of sowing dates for maximizing heat use efficiency and seed cotton yield in arid to semi-arid cotton zone of Pakistan. *Environmental Science and Pollution Research*, *29*(8), 11359-11373. https://doi.org/10.1007/s11356-021-16067-8

Murria, S., Gupta, N., Kingra, P. K., Sharma, A. B., Bhardwaj, R., & Kaur, N. (2022). Influence of agro-meteorological variables on downy mildew development in pearl millet (*Pennisetum glaucum* (L.) R. Br.). *Journal of Agrometeorology*, *24*(1), 113-116. https://doi.org/10.54386/jam.v24i1.790

Ort, N. W., Morrison, M. J., Cober, E. R., Samanfar, B., & Lawley, Y. E. (2022). Photoperiod affects node appearance rate and flowering in early maturing soybean. *Plants*, *11*(7), 871. https://doi.org/10.3390/plants11070871

Patel, P. R., Parmar, G. M., Chaudhari, N. N., Mungra, K. D., & Kandoriya, D. V. (2025). Studies on effect of photosynthate partitioning and remobilization on growth and yield of pearl millet [*Pennisetum glaucum* (L.)] under rainfed condition. *International Journal of Plant & Soil Science*, *37*(12), 47-52. https://doi.org/10.9734/ijpss/2025/v37i125871

Pathania, R., Prasad, R., Rana, R. S., & Mishra, S. K. (2019). Heat unit requirement and yield of wheat (*Triticum aestivum* L.) varieties under different growing environment in mid hill conditions of Himachal Pradesh. *Journal of Agrometeorology*, *21*(3), 282-287. https://doi.org/10.54386/jam.v21i3.250

Ramanjineyulu, M., Paul Pandi, V. K., Geethalakshmi, V., Vannirajan, C., Venkataraman, N. S., & Prabharan, J. (2024). Evaluation on adaptation strategies for enhancing pearl millet productivity under changing climate using DSSAT-CROPGRO model over semi-arid tracts of Tamil Nadu. *International Journal of Environment and Climate Change, 14*(12), 663–674. https://doi.org/10.9734/ijecc/2024/v14i124652

Reager, M. L., Chandra, S., Kishor, N., Kherawat, B. S., & Pant, R. (2023). Effect of different dates of sowing on pearl millet (Pannisetum glaucum L.) hybrids under semi-arid region of Rajasthan: Effect of sowing date on pearl millet yield. *Annals of Arid Zone, 62*(2), 109–115. https://doi.org/10.59512/aaz.2023.62.2.2

Reddy, B. S., Reddy, B. R., Kumari, C. R., Sankar, G. M., Reddy, Y. A., & Reddy, A. M. (2019). Effect of date of sowing and rainfall on sustainability of yield and rainwater use efficiency in cereal crops under arid alfisols. *Journal of Agrometeorology*, *21*(2), 203-209. https://doi.org/10.54386/jam.v21i2.234

Salack, S., Sarr, B., Sangare, S. K., Ly, M., Sanda, I. S., & Kunstmann, H. (2015). Crop-climate ensemble scenarios to improve risk assessment and resilience in the semi-arid regions of West Africa. *Climate Research*, *65*, 107-121. https://doi.org/10.3354/cr01282

Sattar, A., Nanda, G., Singh, G., Jha, R. K., & Bal, S. K. (2023). Responses of phenology, yield attributes, and yield of wheat varieties under different sowing times in Indo-Gangetic Plains. *Frontiers in Plant Science*, *14*, 1224334. https://doi.org/10.3389/fpls.2023.1224334

Shao, J., Wang, Q., Liu, P., Zhao, B., Han, W., Zhang, J., & Ren, B. (2024). The complex stress of waterlogging and high temperature accelerated maize leaf senescence and decreased photosynthetic performance at different growth stages. *Journal of Agronomy and Crop Science*, *210*(2), e12689. https://doi.org/10.1111/jac.12689

Singh, G., Singh, A., Bindra, A. D., Saini, A., Manuja, S., & Fayezizadeh, M. R. (2024). Assessment of sowing environment for wheat cultivars and evaluation of growing degree days for phenological stages in the Northwest Himalayan region of Himachal Pradesh. *Discover Applied Sciences*, *6*(11), 571. https://doi.org/10.1007/s42452-024-06290-6

Singh, P. N., Srivastava, P. K., Sharma, B., & Mall, R. K. (2025). Assessing climate-driven phenological responses of tomato crops under future climate change trajectories: A Central India perspective. *Smart Agricultural Technology*, 12, 10*12*56. https://doi.org/10.1016/j.atech.2025.101256

Singh, R. S., Joshi, N. L., & Singh, H. P. (1998). Pearl millet phenology and growth in relation to thermal time under arid environment. *Journal of Agronomy and Crop Science*, *180*(2), 83-91. https://doi.org/10.1111/j.1439-037X.1998.tb00375.x

Singh, R. S., Khichar, M. L., & Niwas, R. (2017). Photosynthesis in relation to light interception under different fertility level in pearl millet under rainfed environment. *Environment and Ecology*, *35*(2C), 1213-1217. https://environmentandecology.com/35-2c-2017/

Snedecor, G. W., & Cochran, W. G. (1968). *Statistical methods* (6th ed.). Oxford & IBH Publishing Company. https://igmlnet.uohyd.ac.in/chamo/lib/item?id=chamo%3A60099&theme=hcu

Subbulakshmi, S. (2022). Effect of early sowing on growth and yield of blackgram varieties under rainfed condition. *International Journal of Agricultural Sciences*, *18*(1), 489–495. https://doi.org/10.15740/HAS/IJAS/18.1/489-495

Susmita, P., Basudev, B., Bijay, K. M., Anupama, B., Rabindra, K. N., Rajkumari, B., & Monika, R. (2025). Sowing dates and establishment methods determine weed dynamics, yield and economics of rainfed lowland rice. *Plant Science Today*, *12*, 11428. https://horizonepublishing.com/journals/index.php/PST/article/view/11428

Toyota, M., & Morokuma, M. (2021). Morphological and phenological adaptation for convergent development of tillers in widely spaced wheat sown on different dates. *Plant Production Science*, *24*(1), 52-64. https://doi.org/10.1080/1343943X.2020.1808485

White, J. W., & Reynolds, M. P. (2003). A physiological perspective on modeling temperature response in wheat and maize crops. In J. W. White (Ed.), *Modeling temperature response in wheat and maize: Proceedings of a workshop, CIMMYT, El Batán, Mexico, 23–25 April 2001* (NRG-GIS Series 03-01). CIMMYT. https://repository.cimmyt.org/server/api/core/bitstreams/d4c07b4c-0664-4529-9f03-b9ec4c09d9b0/content

Wu, W., Yue, W., Bi, J., Zhang, L., Xu, D., Peng, C., Chen, X., & Wang, S. (2024). Influence of climatic variables on maize grain yield and its components by adjusting the sowing date. *Frontiers in Plant Science*, *15*, 1411009. https://doi.org/10.3389/fpls.2024.1411009

Yang, Y., Liu, G., Guo, X., Liu, W., Xue, J., Ming, B., Xie, R., Wang, K., Hou, P., & Li, S. (2022). Quantitative relationship between solar radiation and grain filling parameters of maize. *Frontiers in Plant Science*, *13*, 906060. https://doi.org/10.3389/fpls.2022.906060

Zhiipao, R. R., Pooniya, V., Biswakarma, N., Kumar, D., Shivay, Y. S., Dass, A., Mukri, G., Lakhena, K. K., Pandey, R. K., Bhatia, A., Govindasamy, P., Burman, A., Babu, S., Jat, R. D., Dhaka, A. K., & Swarnalakshmi, K. (2023). Timely sown maize hybrids improve the post-anthesis dry matter accumulation, nutrient acquisition and crop productivity. *Scientific Reports, 13*, 1688. https://doi.org/10.1038/s41598-023-28224-9

Annexure

Annexure 1. Weekly meteorological data at during *Kharif* 2022 at Agromet Observatory, CCSHAU Hisar

SMW	Temperature (°C)		Relative Humidity(%)		Bright Sun Shine (Hours/day)	Rainfall (mm)
	MAX	MIN	M	E		
25	33.1	22.9	84.3	49.5	4.6	10.9
26	39.8	28.6	68.0	43.2	5.0	0.0
27	36.5	28.5	82.3	55.8	6.3	2.4
28	35.6	27.0	84.4	66.1	7.4	45.6
29	35.2	26.6	89.5	73.1	7.9	101.0
30	33.0	27.0	90.0	77.0	8.7	17.6
31	32.3	26.4	95.0	83.0	8.9	132.1
32	33.7	27.6	85.7	65.1	8.4	2.4
33	33.5	26.1	88.0	63.6	7.7	55.0
34	34.3	26.1	89.9	64.1	6.6	0.0
35	35.5	25.6	85.9	53.0	6.1	0.0
36	36.7	25.3	84.4	48.4	5.7	0.0
37	35.3	26.5	85.4	58.5	5.3	1.2
38	34.6	24.7	88.8	65.2	5.3	44.3
39	30.3	24.0	92.9	69.1	6.5	146.5
40	33.5	23.4	84.3	51.6	7.2	0.0
41	27.0	20.5	93.8	72.1	7.8	1.3
42	32.9	18.2	83.9	40.5	7.3	0.0

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2026): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here: https://pr.sdiarticle5.com/review-history/169112