Influence of Diverse Growing Environments and Plant Densities on Phenological Development and Agrometeorological Indices of Groundnut (*Arachis hypogaea* L.) in the Hyper Arid Zone of Rajasthan, India

ABSTRACT

Groundnut (*Arachis hypogaea* L.) stands as a significant oilseed crop globally. The growth, development, and productivity of these plants are notably affected by the adverse impacts of global climate change. Therefore, the current study sought to examine how diverse growing environments and planting densities influence the phenological development of groundnut in the hyper-arid zone of Rajasthan, India. *A field experiment spanning the kharif seasons of 2017, 2018, and 2019 was conducted at Krishi Vigyan Kendra, Swami Keshwanand Rajasthan Agricultural University, Bikaner, India*. The experiment laid out in split-plot design with four replications. The treatments included three main plots for growing environments (sowing on May 15, May 30, and June 15) and three sub-plots for planting densities (1.67 lakh ha^{-1}, 2.50 lakh ha^{-1} and 3.33 lakh ha^{-1}).. The outcomes of the field experiment indicates that sowing groundnut on May 30 was statistically on par with sowing on June 15 and resulted in higher values of GDD, helio thermal units (HTU), PTI, heat use efficiency (HUE), photothermal use efficiency (PUE), and heliothermal use efficiency, as well as hygrothermal use efficiency (Hg TUE-I and II) at the initiation of flowers and peg formation stages. However, at later growth stages significantly higher values of GDD, HTU, HUE, PUE, HgTUE-I and II were observed with the May 15 sowing. These values gradually decreased with delayed sowing up to May 30 and June 15. Further, increasing the planting density from 1.67 lakh ha^{-1}, 2.50 lakh ha^{-1} and 3.33 lakh ha^{-1} significantly enhanced the HTU, HUE, PUE, HgTUE-I and II at various phenological stages of groundnut. Therefore, these findings underscore the significance of precise timing and density control in maximizing groundnut yields under challenging environmental circumstances.

lakhlakhlakh. By comprehending and adjusting these variables, farmers have the potential to alleviate the negative impacts of climate change and improve groundnut productivity, particularly in hyper-arid regions such as Rajasthan.

Keywords, Groundnut, Growing degree day, Heliothermal units, Heat use efficiency, Pheno-Thermal Index, Planting density, Time of sowing, Yield

1. INTRODUCTION

Groundnut (*Arachis hypogaea* L.) holds considerable importance as a legume crop worldwide scale [1, 2]. Groundnut, cultivated across tropical, subtropical, and temperate climates, plays a vital role as a versatile crop, serving as an essential oilseed, confectionery item, and feed for livestock [3, 4]. Annually, global groundnut production totals around 50.7 million tonnes, cultivated over 26.4 million hectares of land [5]. In India, groundnut occupies a pivotal role as an oilseed crop, leading in terms of cultivation area and ranking second in production, following soybean. China leads in groundnut production, yielding 17.57 million tonnes, followed by India with 6.73 million tonnes (FAO, 2021). Groundnut seeds are abundant in essential nutrients, comprising approximately 44–56% oil and 22–30% protein content [6, 7]. In addition, groundnut seeds serve as a valuable reservoir of essential minerals such as calcium, phosphorus, and iron, as well as vitamins [8]. Furthermore, groundnut serves as a substantial source of animal feed, available in the form of haulms and groundnut cake. Its suitability for crop rotation is noteworthy, owing to its capacity for atmospheric nitrogen fixation, which benefits subsequent crops [9]. The growth and development of groundnut are intricately shaped by numerous uncontrollable environmental factors [62]. It's documented that optimal diurnal air temperatures for groundnut's photosynthesis and vegetative growth typically range between 30 to 35°C [10, 11]. Conversely, the ideal diurnal temperature for reproductive growth and eventual yield tends to be somewhat cooler, typically ranging from 25 to 28°C, according to Ketring [12] and Prasad et al. [13]. Research has demonstrated that elevated daytime temperatures exceeding 35°C during the reproductive phases can lead to a reduction in dry matter production, hinder the formation of flowers into pegs, decrease pod count per plant, diminish individual seed size, lower harvest index, and ultimately reduce pod yield [10-12]. The duration of daylight plays a significant role in influencing growth dynamics. Longer days, exceeding 13 hours, tend to enhance vegetative growth and crop growth rate, while decreasing the allocation of photosynthate to pods. Conversely, shorter days, less than 12 hours, promote an increase in the number of flowers, pegs, and pods in groundnut, as highlighted by Bagnall and King [14, 15] and Nigam et al. [16]. In addition, the growth and development of groundnut are significantly influenced by incident solar radiation and the duration of sunshine [14-16].

The effective management of crops relies on several pivotal factors, namely cultivar selection, sowing time, and the duration of a cultivar's lifecycle, all of which exert significant influence on the growth, yield, and seed quality of groundnut. Among these factors, sowing time emerges as particularly crucial, as it can be strategically manipulated to alleviate the detrimental impact of environmental stress. Through the strategic adjustment of sowing dates, it becomes possible to safeguard plants from unfavorable environmental conditions during critical growth stages. Research on sowing date and planting density for groundnut has been conducted extensively in numerous groundnut-producing countries worldwide [4, 17-22]. The attainment of a substantial groundnut yield and the assurance of profitable economic outcomes are greatly dependent on achieving optimal plant density, which determines the spacing between individual plants. Numerous authors have emphasized the importance of higher plant densities in achieving the highest or most favorable groundnut yields [23-27]. In India, groundnut available year-round due to a two-crop cycle, with harvests in March and October. Groundnut are crucial protein crops in India, primarily cultivated under rain-fed conditions. Approximately 75% of the cultivated area for groundnut in India is located in regions with low to moderate rainfall, including parts of the peninsular, western, and central regions. As a leguminous crop, groundnut play a vital role in maintaining soil fertility by fixing atmospheric nitrogen (N_2), fulfilling their own nitrogen requirements, and benefiting subsequent crops. The potential productivity of groundnut hinges on the relationship between crop and weather conditions throughout the growing period, which is influenced by the growing environment. An optimal growing environment is determined for each crop to synchronize the duration of growth phases with favorable weather conditions. The length of each growth phase directives the accumulation and distribution of dry matter among various plant organs [28].

The growth and development of groundnut are significantly impacted by a myriad of uncontrollable environmental factors. The ideal diurnal air temperature range for photosynthesis and vegetative growth of groundnut is typically between 30 and 35^0C (Prasad et al., 2000; Craufurd et al., 2002) conversely, the optimal diurnal temperature for reproductive growth and eventual yield is somewhat cooler, ranging between 25 and 28^0C [11, 12]. Elevated daytime temperatures exceeding 35^0C during the reproductive stages lead to a decrease in dry matter production, the proportion of flowers forming pegs, the number of pods per plant, individual seed mass, harvest index, and pod yield. The groundnut crop's response to environmental factors also dictates its growth performance and yield. The initiation of flowering and the onset of pod development stages were identified as the most susceptible stages to temperature and photoperiod fluctuations, according to reports Bhatia *et* *al.,* [29]. The commencement and duration of different phenophases serve as crucial elements in crop coefficients and find widespread application in dynamic crop simulation models. Temperature and day length significantly impact the physiological and morphological growth of plants. The concept of heat units, derived from cumulative effective temperature and crop phenology, serves to elucidate crop-temperature relationships. Clearly, crop growth and developmental phases are dictated by heat units or growing degree days. The length of specific growth stages correlates directly with temperature, enabling the prediction of crop phenophases using growing degree days [30, 31]. Climate changes pose one of the most significant threats to future agriculture [32-34]. Anticipated shifts in climate patterns have the potential to profoundly impact crop production [35]. The estimates indicate that the global mean temperature is steadily increasing, potentially leading to a notable decline in crop yield [36]. The characterization of thermal response in various crops has relied on heat unit requirement or growing degree day (GDD). Additionally, heat use efficiency (HUE) serves as a valuable tool for evaluating the yield potential of a crop across diverse growing environments [37]. As temperatures are projected to rise in the future, field crops may face heightened GDD compressed into shorter periods. This could potentially impact their productivity and overall performance in agricultural fields.

GDD represent a temperature-driven developmental response that varies between day and night. Heat units play a crucial role in various physiological processes, with specific amounts required for each stage of a crop from germination to harvest [38]. Key processes influenced by heat units include growth and development, growth parameters, metabolism, biomass accumulation, physiological maturity, and ultimately, yield. GDD serve multiple purposes: they determine the growth stages of crops, help in assessing the optimal timing of agronomic practices, estimate heat stress accumulation on crops, and aid in predicting physiological maturity and harvest dates [39]. Different forms of temperature summations, often denoted as heat units and measured in GDD have been extensively employed in research to forecast phenological events in crops. Temperature-based indices such as GDD, Heliothermal Units (HTU), Pheno-Thermal Index (PTI), and Heat Use Efficiency (HUE) offer valuable insights into phenological behavior as well as other growth parameters such as biomass production and yield [40]. Utilizing agro-climatic indices offers a foundation for assessing the influence of temperature and photoperiod on the phenological behavior of crops. The physiological processes of crops are reliant on integrated atmospheric parameters [41], with temperature playing a pivotal role in affecting plant growth, development, and ultimately, yield. Therefore, the recognizing the potential significance of temperature on crop phenology, this investigation aimed to discern the effects of diverse growing environments and planting densities on the phenological development of groundnut. Hence, the findings of the study helps in emphasizing the importance of precise timing and density control in maximizing groundnut yields, especially under challenging environmental conditions. By understanding and adjusting these variables, farmers can mitigate the adverse effects of climate change and enhance groundnut productivity, particularly in hyper-arid regions like Rajasthan. Further research and on-farm validation are essential to refine these findings and develop tailored strategies for sustainable groundnut cultivation in similar agro-climatic zones

2. MATERIALS AND METHODS

2.1 Experimental Site

A three-year experimental trial was carried out during the *kharif* seasons of 2017, 2018, and 2019 at the instructional farm of Krishi Vigyan Kendra, Swami Keshwanand Rajasthan Agricultural University, Bikaner, India. The farm is located in a hyper-arid region, situated at approximately 28°01'N latitude and 73°22'E longitude, with an altitude of 234.70 meters above mean sea level (Arabian Sea). The experimental site's soil was identified as loamy sand, with nutrient levels measured at 258.67 kg/ha of nitrogen, 17.42 kg/ha of available phosphorus, and 223.4 kg/ha of potassium, along with an organic carbon content of 0.79%. Soil pH was recorded at 8.3 using a 1:2.5 soil-to-water ratio. Field capacity, permanent wilting point, and bulk density were measured at 8.3% (w/w), 1.83% (w/w), and 1.67 g/m^3, respectively, within the 0-30 cm soil depth.

2.2 Experimental Design

The experiment utilized a split-plot design with four replications, where nine treatments were assigned. These treatments comprised three main plot representing different growing environments: sowing on May 15th, sowing on May 30th, and sowing on June 15th. Additionally, three sub-plot treatments were applied, varying in planting density: 1.67 lakh ha^{-1}, 2.50 lakh ha^{-1} and 3.33 lakh ha^{-1}). Groundnut HNG-69 was sown according to the designated growing environment treatments and at varying planting densities. Specifically, seeding rates of 80, 120, and 160 kg per hectare were employed. The recommended doses of nitrogen (20 kg N) and phosphorus (40 kg P_2O_5) fertilizers were applied as basal, utilizing urea and single super phosphate as sources for supplying N and P_2O_5 nutrients, respectively. In addition to growing environment and planting density, the crop was managed according to the recommended package of practices. Daily meteorological data was collected from the Agriculture Research Station, Swami Keshwanand Rajasthan Agricultural University, Bikaner. Various agro-meteorological indices were calculated on a daily basis and accumulated during different phenological stages, viz., sowing to initiation of flowers, initiation of peg formation, 50% flowering, initiation of pod formation, and maturity of the crop, using the following formulas.

2.3 Data Collection and Analysis

Accumulated Growing Degree Days (GDD):

GDD at various phenological stages were computed by summing the daily mean temperatures above a base temperature (Tb=10°C) for the respective period from sowing, following the method recommended by Monteith (1984), and expressed in degrees Celsius (°C).

$\text{GDD} = \sum [(T_{Max} + T_{Min})/2 - \text{Base temperature}]$

Where,

T_{Max} = Daily maximum temperature

T_{Min} = Daily minimum temperature

Accumulated Photo thermal Unit (PTU):

PTU is determined by multiplying the GDD by the maximum possible sunshine hours (N).

PTU = GDD X Maximum possible sunshine hour

Accumulated Heliothermal Unit (HTU):

Helio thermal unit is calculated by multiplying GDD with actual sunshine hours (N).

HTU = GDD X Actual sunshine hours

Hygrothermal unit-I (HgTU- I):

HgTU – I = GDD X Relative humidity at morning (I)

Hygrothermal unit-II (HgTU- II):

HgTU – II = GDD X Relative humidity at afternoon (II)

Pheno thermal index (PTI):

PTI = Accumulated GDD/ Number of days between two phenological stages.

Heat use efficiency (HUE):

HUE (kg ha^{-1} ºC days) = above ground dry matter (kg ha^{-1})/Accumulated GDD

PTUE (kg ha^{-1} ºC days) = above ground dry matter (kg ha^{-1})/Accumulated PTU

HTUE (kg ha^{-1} ºC days) = above ground dry matter (kg ha^{-1})/Accumulated HTU

HgUE (kg ha^{-1} ºC days) = above ground dry matter (kg ha^{-1})/Accumulated HgTU

2.4 Statistical Data Analysis

All data collected from the groundnut trials conducted over three consecutive years, as well as the pooled data from these years, were subjected to statistical analysis using the F-test method [42]. Critical difference (CD) values at a significance level of P=0.05 were utilized to determine the significance of differences between the mean values of the treatments.

3. RESULTS AND DISCUSSION

3.1 The climatic conditions during crop period of 2017, 2018 and 2019

The meteorological parameters observed monthly during groundnut growth and development are presented in Table 1.

Table 1. The climatic conditions experienced during the crop periods of 2017, 2018, and 2019.

Months	Temperature (°C)						R.H. (%)						Total rainfall (mm)		
	Max.			Min.			RH1			RH2					
	201	201	201	201	201	201	201	201	201	201	201	201	2017	2018	2019

	7	8	9	7	8	9	7	8	9	7	8	9			
May	42.9	43.7	41.4	26.8	27.0	25.4	54.6	36.0	72.2	27.3	18.2	53.5	19.2	5.6	9.0
June	39.8	41.3	43.4	27.5	28.7	29.4	69.7	62.3	85.9	38.5	35.4	66.8	123.0	54.3	12.8
July	38.4	37.8	39.8	27.5	28.1	28.7	78.7	84.1	77.4	47.4	51.3	55.2	29.3	189.8	40.6
August	37.4	36.2	36.3	26.7	26.6	26.7	76.1	82.5	84.2	47.5	50.4	63.9	90.6	54.8	128.2
September	37.8	36.5	38.0	24.0	24.0	26.0	71.8	69.6	87.4	36.5	41.2	60.9	6.0	0.0	16.2
October	38.7	36.6	34.6	18.4	18.6	18.6	49.2	55.0	71.6	20.4	21.7	39.5	0.0	0.0	28.8
November	30.4	30.8	27.1	11.2	11.4	12.8	69.7	69.6	84.2	27.2	27.4	48.6	1.4	0.8	27.2

Source: Agricultural Research Station, Bikaner

In 2017, the monthly average maximum temperatures (T max) ranged between 42.9°C and 30.4°C, in 2018 they ranged from 43.7°C to 30.8°C, and in 2019 they varied from 43.4°C to 27.1°C. Minimum temperatures (T min) fluctuated from 11.2°C to 27.5°C in 2017, from 11.4°C to 28.7°C in 2018, and from 12.8°C to 29.4°C in 2019 (Figure 1).

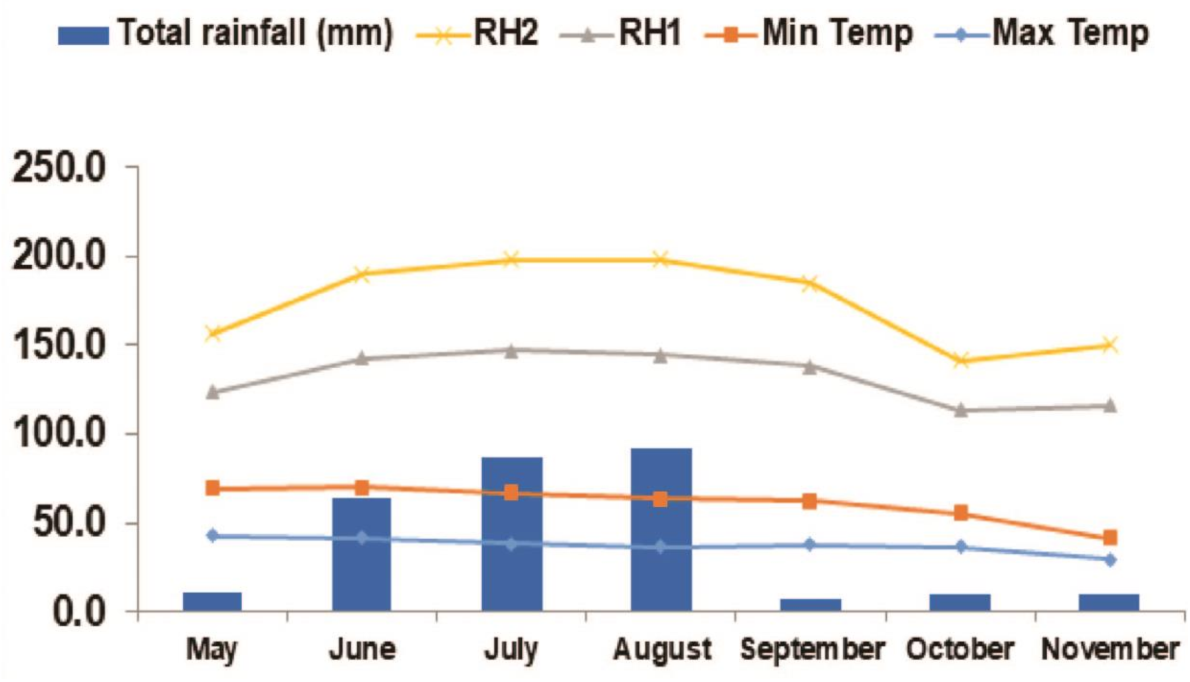

Figure 1. The climatic conditions during crop period (Combined data from 2017-2019).

The highest maximum temperature was registered in May, while the highest minimum temperature occurred in June. However, the lowest maximum and minimum temperatures were recorded during the month of November throughout the growing period. Morning relative humidity (RH-I) ranged from 49% to 78.7%, 36.0% to 84.1%, and 71.6% to 87.4% in 2017, 2018, and 2019, respectively. Afternoon relative humidity (RH-II) varied between 27.2% and 47.5%, 18.2% and 51.3%, and 39.5% and 66.8% during the growing periods of the years 2017, 2018, and 2019, respectively (Figure 1). The maximum rainfall occurred from June to August during the growing period.

3.2 Phenological development

The time taken to reach the initiation of flower, initiation of peg formation, and 50 percent flowering stages was shorter for the 15th May sowing (as shown in Table 2), progressively lengthening with delayed sowings up to 15th June.

Table 2. Effect of varied growing environments and planting densities on the phenological stages (DAS) and pheno-thermal index (PTI) across different stages of groundnut growth (aggregated data from 2017 to 2019).

Treatments	Phenological stages (DAS)					Pheno thermal index (PTI)				
	Initiation of flowers	50 % Flowering	Initiation of peg formation	Initiation of pod formation	Maturity	Initiation of flowers	50 % Flowering	Initiation of peg formation	Initiation of pod formation	Maturity
Growing environment										
Sowing at 15 May	25.06	48.42	34.39	85.28	144.86	25.83	25.05	25.59	24.07	22.87
Sowing at 30 May	28.61	44.11	37.94	81.61	135.19	25.17	24.91	24.99	23.57	22.37
Sowing at 15 June	29.81	38.64	39.81	75.72	127.50	24.00	23.64	23.63	22.73	21.64
SEm±	0.38	0.46	0.54	0.76	0.62	0.05	0.04	0.03	0.02	0.02
CD at 5%	1.13	1.38	1.61	2.26	1.85	0.14	0.11	0.09	0.05	0.07
Planting density										
1.67 lakh ha^{-1}	27.97	43.72	37.86	81.64	136.28	24.95	24.52	24.72	23.44	22.27
2.50 lakh ha^{-1}	27.72	43.53	37.61	80.39	135.94	24.99	24.57	24.75	23.47	22.29
3.33 lakh ha^{-1}	27.78	43.92	36.67	80.58	135.33	25.05	24.50	24.74	23.46	22.32
SEm±	0.27	0.43	0.36	0.54	0.46	0.05	0.03	0.02	0.01	0.02
CD at 5%	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

SEm is standard error of the mean; CD denotes the critical difference. NS represents non-significance.

Conversely, the initiation of pod formation and maturity stages took longer with the 15th May sowing and decreased gradually with sowings delayed up to 15th June. The crop planted on 15th May required the longest period for maturity (145 days), followed by the 30th May sowing (135 days), and the shortest period for maturity was observed with the 15th June sowing (128 days). Kumar et al. [43] similarly noted that lower temperatures during the early vegetative phase and higher temperatures during the reproductive phase of groundnut, resulting from late sowing, decreased the number of days needed to reach various phenological stages. The days required to attain different phenological developments in groundnut, including initiation of flowers, initiation of peg formation, 50 percent flowering, initiation of pod formation, and maturity stages, were found to be statistically non-significant due to planting density, as indicated in Table 2. This phenomenon may be attributed to the fact that groundnut sown early, such as on the 15th of May, has access to a greater number of degree days, which facilitates reaching maturity. Conversely, in late-sown crops, elevated temperatures during flowering hasten plant senescence, thereby shortening the maturity period. This observation aligns with the findings of Sidiqque et al. [44] and Towhida et al. [45].

3.3 Agrometeorological indices

3.3.1 Growing degree days

The data in Table 3 highlights the significant influence of different growing environments on GDD. Sowing groundnut on the 30th of May, which was statistically comparable to sowing on the 15th of June, required higher GDD for the initiation of flower and initiation of peg formation stages.

Table 3. The influence of diverse growing environments and planting densities on growing degree days (GDD) (ºC days) and heat use efficiency (HUE) (Kg/ha/ ºC days) across various phenological stages of groundnut cultivation (averaged data from 2017 to 2019).

Treatments	Growing degree days (GDD) (ºC days)					Heat use efficiency (HUE) (Kg/ha/ ºC days)				
	Initiation of flowers	**50 % Flowering**	**Initiation of peg formation**	**Initiation of pod formation**	**Maturity**	**Initiation of flowers**	**50 % Flowering**	**Initiation of peg formation**	**Initiation of pod formation**	**Maturity**
Growing environment										
Sowing at 15 May	647.04	1212.88	880.41	2052.97	3313.34	1.95	2.77	2.37	3.05	2.79
Sowing at 30 May	719.89	1098.82	948.10	1923.18	3024.55	1.76	3.10	2.23	3.33	3.14
Sowing at 15 June	715.91	913.78	940.15	1720.68	2757.89	1.75	3.65	2.21	3.60	3.30
SEm±	9.43	10.25	12.08	16.34	10.74	0.03	0.03	0.03	0.04	0.03
CD at 5%	28.02	30.44	35.89	48.56	31.90	0.08	0.08	0.09	0.11	0.08
Planting density										
1.67 lakh ha^{-1}	696.72	1074.40	934.22	1915.90	3038.67	1.78	3.05	2.17	3.09	2.86
2.50 lakh ha^{-1}	691.50	1072.33	928.89	1888.54	3033.33	1.85	3.23	2.29	3.42	3.17
3.33 lakh ha^{-1}	694.61	1078.75	905.56	1892.39	3023.77	1.84	3.25	2.35	3.46	3.21
SEm±	6.54	10.67	8.13	11.57	8.14	0.02	0.03	0.02	0.03	0.02
CD at 5%	NS	NS	NS	NS	NS	0.05	0.09	0.06	0.09	0.07

SEm is standard error of the mean; CD denotes the critical difference. NS represents non-significance.

However, for the stages of 50% flowering, initiation of pod formation, and maturity, GDD accumulation was notably higher with sowing on the 15th of May, gradually decreasing with delayed sowings up to the 30th of May and 15th of June. Groundnut sown on the 15th of May showed significantly higher GDD accumulation at 50% flowering (1212.88 °C days), initiation of pod formation (2052.97 °C days), and maturity (3313.34 °C days). This trend could be attributed to the longer duration of the growing period for crops sown on the 15th of May, while GDD accumulation was lowest in the 15th of June sowing due to forced maturity. The data depicted in Table 3 reveals that the GDD required to achieve various phenological developments in groundnut, including initiation of flowers, initiation of peg formation, 50 percent flowering, initiation of pod formation, and maturity stages, showed no statistically significant differences due to planting density. The observed decrease in GDD could be attributed to a reduction in the maturity period of the groundnut crop. This decline suggests the onset of thermal stress conditions during the latter part of the growth cycle, resulting in a shortened duration to reach specific phenophases. Flowering, a critical stage, is closely linked to mean air temperature and serves as a significant limiting factor in initiating flower development [46]. The GDD requirement for various phenophases varies based on the duration of each specific phase [47], a finding supported by Kingra and Kaur [37], Murty et al. [48], and Meena and Dahama [49].

3.3.2 Photo thermal unit

The Photothermal unit (PTU) at different phenological stages of groundnut was significantly influenced by various growing environments, as indicated in Table 4.

Table 4. Effect of various growing environments and planting densities on photothermal units (PTU) (Degree-days hour) and photothermal use efficiency (PTUE) (Kg/ha/ degree day hrs) across different phenological stages of groundnut cultivation (averaged data from 2017 to 2019).

Treatments	Photo thermal unit (PTU) (Degree-days hour)	Photothermal use efficiency (PTUE) (Kg/ha/ degree day hrs)

	Initiation of flowers	50 % Flowering	Initiation of peg formation	Initiation of pod formation	Maturity	Initiation of flowers	50 % Flowering	Initiation of peg formation	Initiation of pod formation	Maturity
Growing environment										
Sowing at 15 May	8717.56	16587.17	11974.87	28084.28	43921.24	0.145	0.202	0.176	0.222	0.210
Sowing at 30 May	9435.76	15142.78	13156.12	26275.83	39845.80	0.134	0.225	0.161	0.244	0.238
Sowing at 15 June	9663.77	12461.38	12960.60	23267.32	35845.75	0.130	0.267	0.160	0.265	0.254
SEm±	119.96	64.53	116.70	124.16	116.82	0.002	0.001	0.002	0.002	0.002
CD at 5%	356.42	191.74	346.73	368.90	347.10	0.006	0.004	0.005	0.007	0.006
Planting density										
1.67 lakh ha^{-1}	8892.19	14107.95	11431.60	24586.30	38589.01	0.139	0.232	0.178	0.241	0.226
2.50 lakh ha^{-1}	9233.96	14613.88	13112.23	26299.43	40331.74	0.138	0.237	0.162	0.246	0.238
3.33 lakh ha^{-1}	9690.95	15469.51	13547.77	26741.70	40692.04	0.132	0.226	0.157	0.244	0.239
SEm±	97.72	60.41	94.97	98.91	94.74	0.002	0.001	0.001	0.002	0.002
CD at 5%	277.07	171.29	269.28	280.43	268.63	0.004	0.003	0.004	0.005	0.005

SEm is standard error of the mean; CD denotes the critical difference. NS represents non-significance.

Sowing groundnut on the 15th of June, remaining statistically comparable to sowing on the 30th of May, showed significantly higher photothermal units at the initiation of flower and initiation of peg formation stages compared to sowing on the 15th of May. However, for the stages of 50 percent flowering, initiation of pod formation, and maturity, significantly higher PTU was recorded for the sowing date on the 15th of May, gradually decreasing with delayed sowings up to the 30th of May and 15th of June. Groundnut sown on the 15th of May recorded the significantly highest PTU values, with 16587.17 Degree-days hour at 50 percent flowering, 28084.28 Degree-days hour at initiation of pod formation, and 43921.24 Degree-days hour at maturity of groundnut. Furthermore, pooled data in Table 4 clearly indicate that increasing planting density from 1.67 lakh to 3.33 lakh ha-1 significantly enhanced the photothermal unit (PTU) across different phenological stages in groundnut, such as initiation of flowers, initiation of peg formation, 50 percent flowering, initiation of pod formation, and maturity. This enhancement is likely because the PTU is a product of growing degree days and day length, indicating that longer day lengths lead to more accumulated PTUs. Heat units are used to predict physiological maturity; as sowing is delayed, there is a decrease in thermal units required to attain physiological maturity, as reported by Chimmad and Kiran [50] and Rathod and Chimmad [51].

3.3.3 Heliothermal unit

The data in Table 5 indicate that the Helio Thermal Unit (HTU) at different phenological stages of groundnut was significantly influenced by the growing environment.

Table 5. The influence of varying growing environments and planting densities on heliothermal units (HTU) (Degree-days hour) and heliothermal use efficiency (HTUE) (Kg/ha/ degree day hrs)

throughout different phenological stages of groundnut cultivation (aggregated data from 2017 to 2019).

Treatments	Heliothermal units (HTU) (Degree-days hour)					Heliothermal use efficiency (HTUE) (Kg/ha/ degree day hrs)				
	Initiation of flowers	50 % Flowering	Initiation of peg formation	Initiation of pod formation	Maturity	Initiation of flowers	50 % Flowering	Initiation of peg formation	Initiation of pod formation	Maturity
Growing environment										
Sowing at 15 May	6271.43	10904.53	8084.11	17005.35	27241.60	0.202	0.313	0.263	0.370	0.341
Sowing at 30 May	5928.23	9285.71	8194.49	15019.98	24337.85	0.223	0.370	0.265	0.430	0.392
Sowing at 15 June	5779.58	6994.08	7283.25	13064.36	21948.17	0.218	0.480	0.288	0.476	0.417
SEm±	72.63	36.81	64.19	73.30	96.25	0.003	0.002	0.002	0.004	0.004
CD at 5%	215.78	109.38	190.73	217.79	285.98	0.008	0.007	0.007	0.012	0.011
Planting density										
1.67 lakh ha^{-1}	5756.50	8735.70	7110.71	14273.52	23484.78	0.219	0.385	0.290	0.421	0.373
2.50 lakh ha^{-1}	5978.55	8944.06	8090.85	15307.43	24878.02	0.216	0.399	0.267	0.429	0.389
3.33 lakh ha^{-1}	6244.18	9504.56	8360.27	15508.73	25164.82	0.209	0.379	0.259	0.426	0.388
SEm±	59.29	31.31	54.99	58.86	78.53	0.002	0.002	0.002	0.003	0.003
CD at 5%	168.11	88.77	155.91	166.88	222.67	0.007	0.005	0.006	0.009	0.009

SEm is standard error of the mean; CD denotes the critical difference. NS represents non-significance.

Groundnut sown on the 15th of May, which was statistically at par with sowing on the 30th of May for the initiation of peg formation, recorded significantly higher HTU at the stages of initiation of flowers, initiation of peg formation, 50 percent flowering, initiation of pod formation, and maturity. The HTU values gradually decreased with delayed sowing up to the 15th of June. Groundnut sown on the 15th of May accumulated the highest HTU values, with 6271.43 degree-days hour at the initiation of flowers, 8084.11 degree-days hour at the initiation of peg formation, 10904.53 degree-days hour at 50 percent flowering, 17005.35 degree-days hour at the initiation of pod formation, and 27241.60 degree-days hour at maturity. Additionally, pooled data in Table 5 explicitly show that increasing planting density from 1.67 lakh ha-1 to 3.33 lakh ha-1 significantly increased the HTU at various phenological stages, including initiation of flowers, initiation of peg formation, 50 percent flowering, initiation of pod formation, and maturity. This was due to the duration, temperature, and bright sunshine hours available during the period. HTU is the product of GDD and actual bright sunshine hours, resulting in higher accumulated HTU [52]. This may be attributed to cloudiness during the pod development stage of the later sown crop. However, it has been observed that reaching physiological maturity requires the highest HTU in an optimal growing environment, and these values decrease with delayed sowing. This is because thermal stress conditions develop in the later part of the crop growth cycle. The similar findings are reported by Nandini and Sridhara [53] and Kumar et al. [54].

3.3.4 Hygrothermal unit-I

The accumulated morning hygrothermal unit-I required by the crop for various phenophases was significantly influenced by different growing environments (Table 6).

Table 6. The effect of varied growing environments and planting densities on hygrothermal unit-I (HgTU-I) and hygrothermal use efficiency (HgTUE-I) ((kg/ ha degree day %)) across different phenological stages of groundnut cultivation (averaged data from 2017 to 2019).

Treatments	**Hygrothermal unit-I (HgTU- I)**					**Hygrothermal use efficiency (HgTUE-I) (kg/ ha degree day %)**				
	Initiation of flowers	**50 % Flowering**	**Initiation of peg formation**	**Initiation of pod formation**	**Maturity**	**Initiation of flowers**	**50 % Flowering**	**Initiation of peg formation**	**Initiation of pod formation**	**Maturity**
Growing environment										
Sowing at 15 May	37102.77	78583.19	53653.42	146659.67	242670.64	0.037	0.044	0.041	0.043	0.038
Sowing at 30 May	48200.94	81161.18	69784.24	148001.11	228957.98	0.027	0.043	0.031	0.043	0.042
Sowing at 15 June	53747.90	69706.16	72591.75	135676.60	209108.38	0.024	0.048	0.029	0.046	0.044
SEm±	691.23	366.82	675.40	775.16	591.18	0.0006	0.0003	0.0005	0.0004	0.0004
CD at 5%	2053.75	1089.87	2006.70	2303.13	1756.48	0.002	0.001	0.001	0.001	0.001
Planting density										
1.67 lakh ha^{-1}	44357.40	72946.27	58298.77	135479.57	220327.71	0.030	0.045	0.037	0.044	0.040
2.50 lakh ha^{-1}	46117.44	75809.03	67691.53	146022.82	229237.28	0.030	0.046	0.033	0.044	0.042
3.33 lakh ha^{-1}	48576.76	80695.23	70039.11	148834.99	231172.01	0.028	0.043	0.032	0.044	0.042
SEm±	530.23	325.52	532.37	621.08	474.63	0.0005	0.0002	0.0004	0.0004	0.0003
CD at 5%	1503.37	922.96	1509.43	1760.96	1345.74	0.001	0.001	0.001	NS	NS

SEm is standard error of the mean; CD denotes the critical difference. NS represents non-significance.

During the initial phenological stages, such as the initiation of flowers and peg formation, the highest hygrothermal unit-I was recorded for groundnut sown on June 15th, while the lowest was for groundnut sown on May 15th. For phenological stages such as 50% flowering and the initiation of pod formation, the highest hygrothermal unit-I was observed in the crop sown on May 30th. However, during the maturity stage, the maximum hygrothermal unit-I was recorded for groundnut sown on May 15th. Overall, the maturity stages showed significantly higher hygrothermal unit-I for groundnut sown on May 15th, with a gradual decrease as sowing was delayed until June 15th. Further, pooled data (Table 6) reveal that increasing planting density from 1.67 lakh ha^{-1} to 3.33 lakh ha^{-1} significantly enhanced hygrothermal unit-I during various phenological stages of groundnut, viz., the initiation of flowers, peg formation, 50% flowering, pod formation, and maturity stages. This enhancement is likely due to the duration, temperature, and morning relative humidity available during these periods. The similar findings are reported by Nandini and Sridhara [53] and Kumar et al. [54]

3.3.5 Hygrothermal unit-II

The accumulated afternoon hygrothermal unit-II required by the crop for various phenophases was significantly influenced by the growing environment (Table 7).

Table 7. The influence of diverse growing environments and planting densities on hygrothermal unit-II (HgTU-II) and hygrothermal use efficiency (HgTUE-II) (kg/ ha degree day %) across various phenological stages of groundnut cultivation (pooled 2017-2019).

Treatments	**Hygrothermal unit-II (HgTU- II)**					**Hygrothermal use efficiency (HgTUE-II) (kg/ ha degree day %)**				
	Initiation of flowers	**50 % Flowering**	**Initiation of peg formation**	**Initiation of pod formation**	**Maturity**	**Initiation of flowers**	**50 % Flowering**	**Initiation of peg formation**	**Initiation of pod formation**	**Maturity**
Growing environment										
Sowing at 15 May	21076.99	47877.18	30984.50	91235.83	151446.24	0.074	0.078	0.078	0.071	0.063
Sowing at 30 May	30297.88	52035.80	45288.48	95448.58	143448.48	0.048	0.071	0.052	0.069	0.069
Sowing at 15 June	35378.88	45557.96	47314.49	88668.21	130239.90	0.037	0.075	0.045	0.071	0.072
SEm±	436.60	237.47	421.21	526.55	294.81	0.001	0.000	0.001	0.001	0.001
CD at 5%	1297.21	705.55	1251.49	1564.46	875.92	0.003	0.001	0.003	0.002	0.002
Planting density										
1.67 lakh ha^{-1}	27544.83	46113.28	36728.75	86490.05	138729.70	0.055	0.076	0.064	0.070	0.065
2.50 lakh ha^{-1}	28778.74	48051.09	42700.31	93464.47	142768.89	0.054	0.077	0.057	0.071	0.069
3.33 lakh ha^{-1}	30430.19	51306.57	44158.41	95398.11	143636.03	0.050	0.072	0.055	0.070	0.070
SEm±	356.88	216.13	335.44	421.87	235.64	0.001	0.000	0.001	0.001	0.001
CD at 5%	1011.88	612.81	951.07	1196.14	668.13	0.003	0.001	0.002	NS	0.001

SEm is standard error of the mean; CD denotes the critical difference. NS represents non-significance.

During the initial phenological stages, such as the initiation of flowers and peg formation, the highest hygrothermal unit-II was recorded for groundnut sown on June 15th, followed by May 30th and May 15th. For the stages of 50% flowering and the initiation of pod formation, the highest hygrothermal unit-II was observed in the crop sown on May 30th. However, at the maturity stage, the highest hygrothermal unit-II was recorded for groundnut sown on May 15th, with a gradual decrease as sowing was delayed until June 15th. Furthermore, pooled data (Table 7) reveal that increasing planting density from 1.67 lakh ha^{-1} to 3.33 lakh ha^{-1} significantly enhanced hygrothermal unit-II during various phenological stages of groundnut, such as the initiation of flowers, peg formation, 50% flowering, pod formation, and maturity stages. This enhancement is likely due to the duration, temperature, and evening relative humidity available during these periods [54].

3.3.6 Phenothermal index

The pheno thermal index at different phenological stages of groundnut was significantly influenced by various growing environments (Table 2). Groundnut sown on May 15th recorded significantly higher pheno thermal indices at the initiation of flowers, peg formation, 50% flowering, pod formation, and maturity stages, with a gradual decrease as sowing was delayed until June 15th (Figure 2).

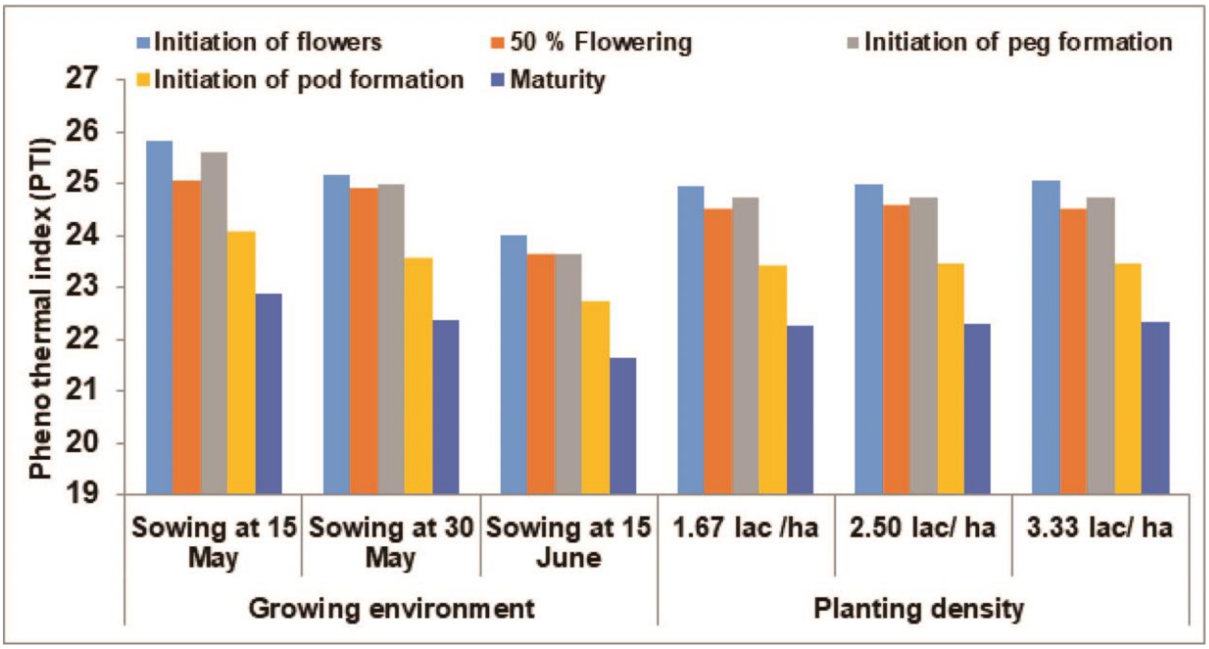

Figure 2. Effect of different growing environment and planting density on pheno thermal index (PTI) of different phonological stage of groundnut (pooled 2017-2019).

However, the pheno thermal index (PTI) for different phenological developments such as initiation of flowers, peg formation, 50% flowering, pod formation, and maturity stages was statistically similar across different planting densities (Table 2). The difference in phenothermal indices across various growth stages indicates that the accumulated temperature can be utilized to study biomass accumulation patterns at different phenological stages, ultimately influencing crop productivity. The phenothermal index is expressed as growing degree days per growth days. These findings are in accordance with those of Mahesh et al. [55].

3.4 Thermal and photothermal use efficiency

3.4.1 Heat use efficiency

Heat use efficiency (HUE) at different phenological stages of groundnut was significantly influenced by various growing environments (Table 3). In the early growth stages, such as the initiation of flowers and peg formation, significantly higher HUE was recorded for crops sown on May 15th compared to those sown on May 30th and June 15th (Figure 3).

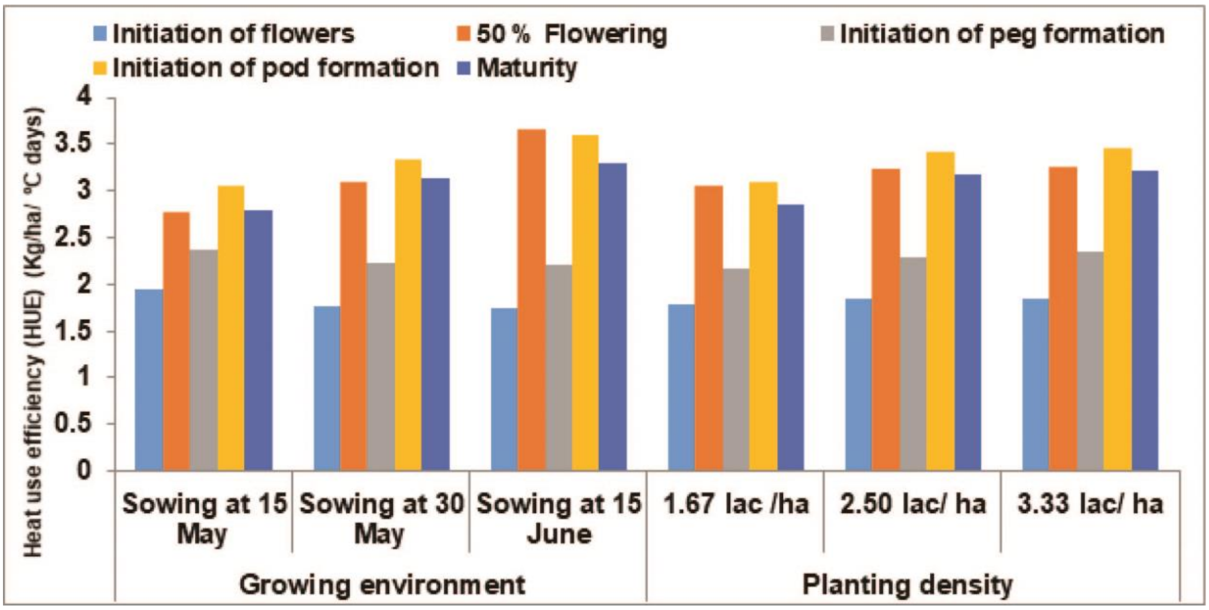

Figure 3. Effect of diverse growing environment and planting density on heat use efficiency (HUE) (Kg/ha/ ºC days) of different phenological stages of groundnut (pooled 2017-2019).

However, in the later stages, such as 50% flowering, initiation of pod formation, and maturity, the lowest HUE was recorded for crops sown on May 15th, with a gradual increase as sowing was delayed until June 15th. Furthermore, pooled data (Table 3) reveal that a planting density of 3.33 lakh ha^{-1}, which was statistically similar to 2.50 lakh ha^{-1}, recorded significantly higher HUE at the initiation of flowers, peg formation, 50% flowering, pod formation, and maturity stages compared to a planting density of 1.67 lakh ha^{-1}. Heat use efficiency involves converting heat energy into dry matter and is influenced by factors such as crop type, genetics, sowing time, and planting density. This efficiency may crops utilizing heat more effectively, leading to increased biological activity and ultimately higher yields. This improved efficiency indicates better allocation of dry matter to different plant parts. These findings align with studies conducted by Sulochana et al. [56] and Meena et al. [57].

3.4.2 Photothermal use efficiency

Photothermal use efficiency (PTUE) during different phenological stages of groundnut was significantly influenced by various growing environments, as shown in Table 4. During early growth stages, such as flower initiation and peg formation initiation, groundnut exhibits significantly higher PTUE when sown on May 15th, with a gradual decrease as sowing is delayed until June 15th (Figure 4).

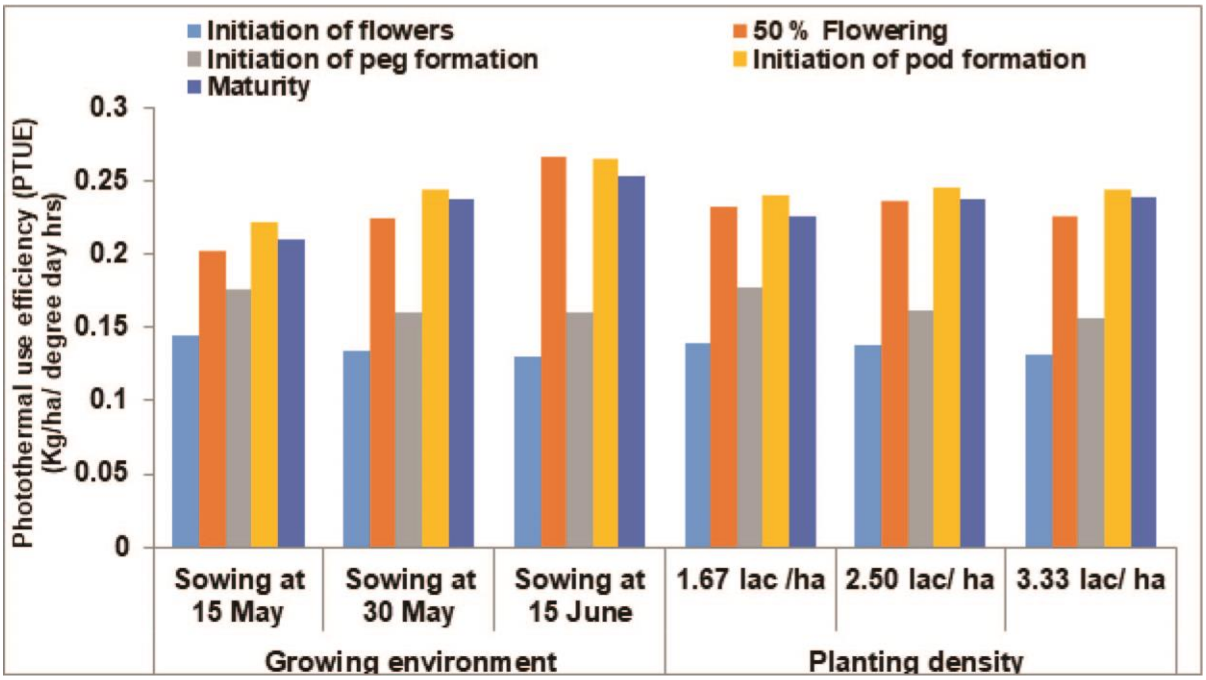

Figure 4. Influence of various growing environments and planting densities on photothermal use efficiency (PTUE) (kg/ha degree day hrs) across different phenological stages of groundnut (Combined data from 2017-2019).

However, at 50% flowering, pod formation initiation, and maturity stages, the crop sown on May 15th records the lowest PTUE, gradually increasing with delayed sowing up to June 15th. The highest PTUE (0.267 kg/ha/°C day) at 50% flowering, (0.265 kg/ha/°C day) at pod formation initiation, and (0.254 kg/ha/°C day) at maturity was observed when the crop is sown on June 15th. Additionally, pooled data (Table 4) indicates that flower initiation and peg formation initiation exhibit significantly higher PTUE at a planting density of 1.67 lakh ha^{-1}. However, at 50% flowering, pod formation initiation, and maturity stages, a planting density of 2.50 lakh ha^{-1} is statistically comparable to a density of 3.33 lakh ha^{-1}, both recording higher PTUE compared to a density of 1.67 lakh ha^{-1}. This enhanced use efficiency reflects better allocation of dry matter to various plant parts. These results are supported by the studies of Gouri et al. [58] and Bonelli et al. [59].

3.4.3 Heliothermal use efficiency

Heliothermal use efficiency (HTUE) during different phenological stages of groundnut was significantly influenced by the growing environment, as outlined in Table 5. Groundnut sown on May 30th exhibits similar HTUE to those sown on June 15th, accumulating significantly higher HTUE at the flower initiation stage compared to crops sown on May 15th (Figure 5).

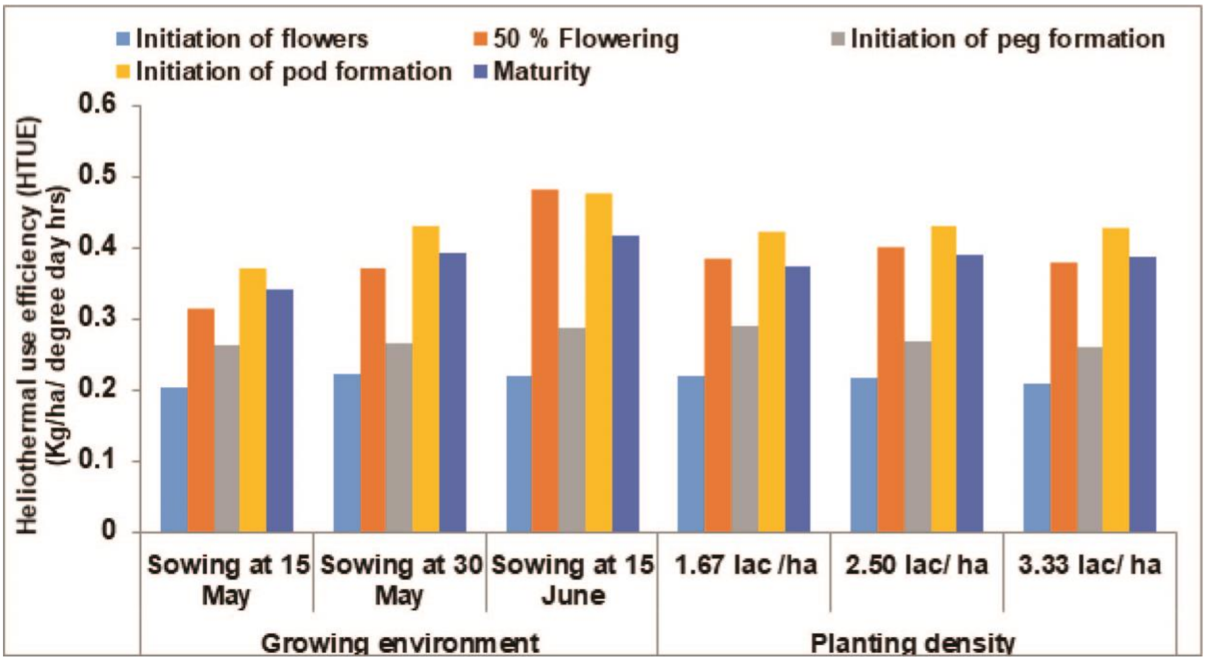

Figure 5. Effect of diverse growing environment and planting density on heliothermal use efficiency (HTUE) (Kg/ha/ degree day hrs) of different phenological stages of groundnut (pooled 2017-2019).

However, at 50% flowering, peg formation initiation, pod formation initiation, and maturity stages, crops sown on May 15th record the lowest HTUE, gradually increasing with delayed sowing up to June 15th. The highest HTUE (0.480 kg/ha/degree day hrs) at 50% flowering, (0.288 kg/ha/degree day hrs) at peg formation initiation, (0.476 kg/ha/degree day hrs) at pod formation initiation, and (0.417 kg/ha/degree day hrs) at maturity is observed when crops are sown on June 15th. Additionally, pooled data from Table 5 reveals that flower initiation and peg formation initiation recorded significantly higher photothermal use efficiency with a planting density of 1.67 lakh ha^{-1}. However, a planting density of 2.50 lakh ha^{-1} remained statistically comparable to 3.33 lakh ha^{-1}, showing higher heliothermal use efficiency at 50% flowering, pod formation initiation, and maturity compared to a density of 1.67 lakh ha^{-1}. Heliothermal use efficiency (HTUE) can be expressed in terms of dry matter accumulation or grain yield and is influenced by different weather conditions. The efficiency of heat utilization in terms of dry matter accumulation depends on genetic factors, sowing time, and planting density. Similar findings have also been reported by Rao et al. [60] and Nandini and Sridhara [53].

3.4.4 Hygrothermal use efficiency-I (HgTUE-I)

Hygrothermal use efficiency-I (HgTUE-I) during various phenological stages of groundnut was significantly influenced by the growing environment, as depicted in Table 6. Groundnut sown on May 15th accumulates significantly higher HgTUE-I at flower initiation and peg formation initiation stages compared to crops sown on May 30th and June 15th (Figure 6).

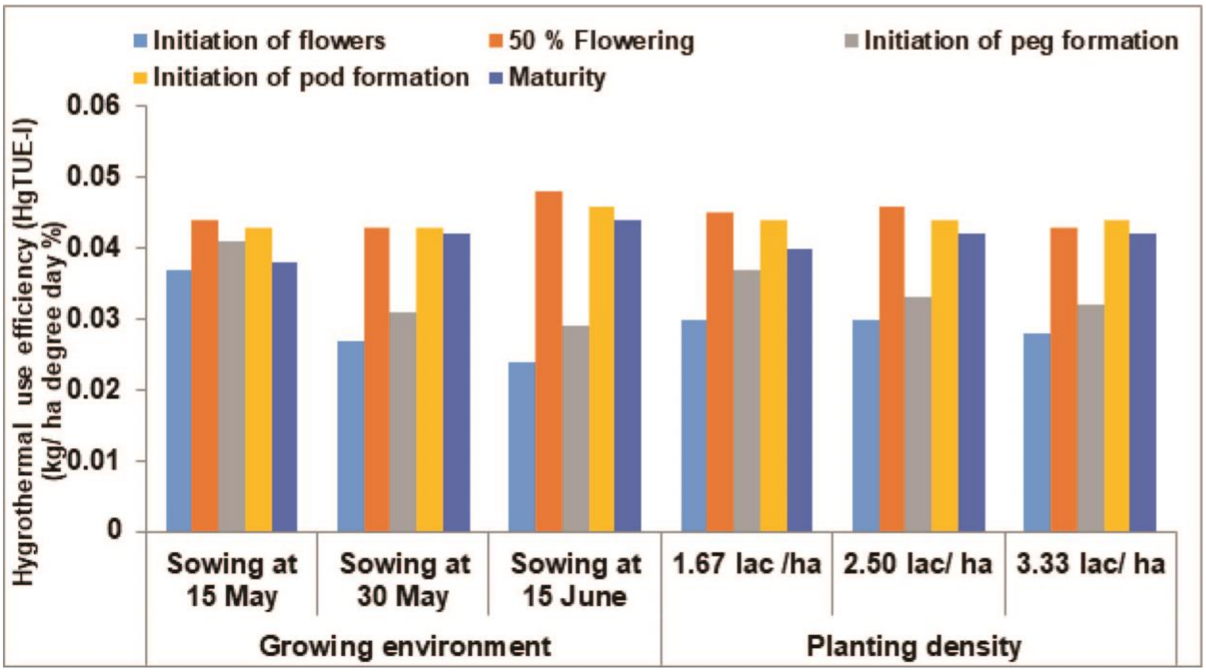

Figure 6. Influence of diverse growing environment and planting density on hygrothermal use efficiency (HgTUE-I) (kg/ ha degree day %) across different phenological stages of groundnut (Combined data from 2017-2019).

However, at 50% flowering, pod formation initiation, and maturity stages, crops sown on May 15th exhibit the lowest HgTUE-I, gradually increasing with delayed sowing up to June 15th. The highest HgTUE-I (0.048 kg/ha degree day %) at 50% flowering, (0.046 kg/ha degree day %) at pod formation initiation, and (0.044 kg/ha degree day %) at maturity is observed when crops are sown on June 15th. Additionally, pooled data from Table 6 reveals that flower initiation, 50% flowering, and peg formation initiation recorded significantly higher hygrothermal use efficiency-I with a planting density of 1.67 lakh ha^{-1}. However, at later stages of crop growth, such as initiation of pod formationand maturity, HgTUE-I remained statistically non-significant with planting density. This higher use efficiency indicates efficient allocation of dry matter to various plant parts. These results are supported by studies conducted by Praveen et al. [61] and Kumar et al. [43].

3.4.5 Hygrothermal use efficiency-II (HgTUE-II)

Hygrothermal use efficiency-II (HgTUE-II) during different phenological stages of groundnut was significantly influenced by the growing environment, as outlined in Table 7. Groundnut sown on May 15th accumulates significantly higher HgTUE-II at flower initiation, 50% flowering, and peg formation initiation compared to crops sown on May 30th and June 15th (Figure 7).

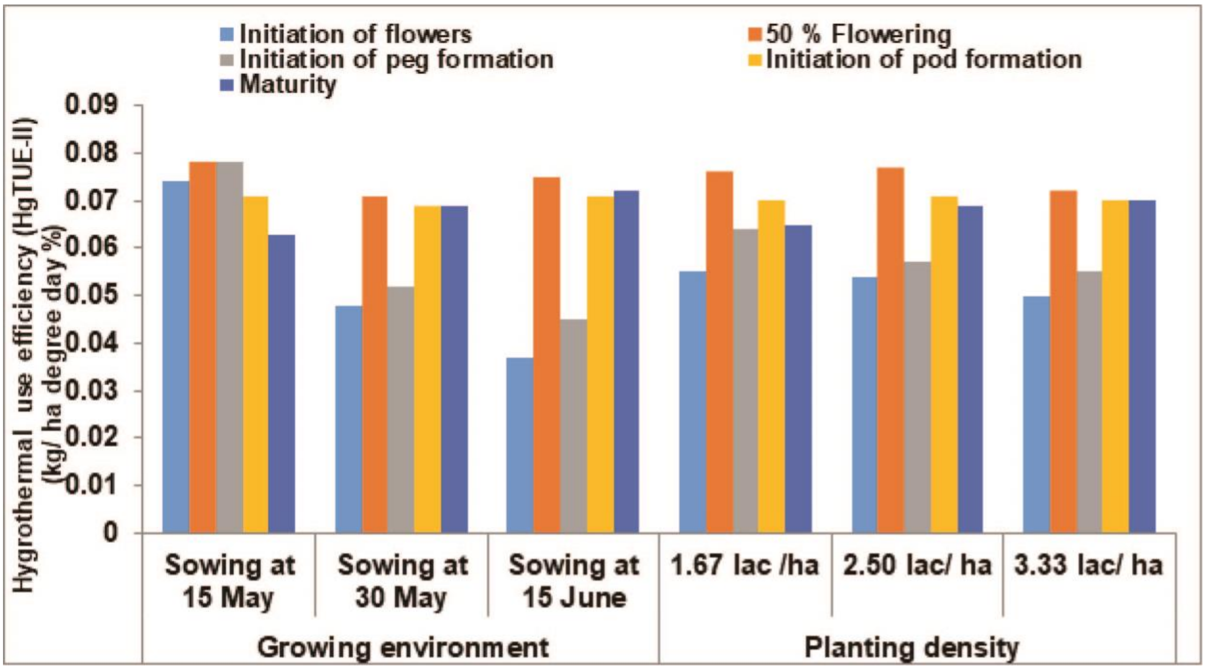

Figure 7. Effect of different growing environment and planting density on hygrothermal use efficiency (HgTUE-II) (kg/ ha degree day %) across different phenological stages of groundnut (pooled 2017-2019).

However, initiation of pod formation and maturity stages record significantly lower HgTUE-II in crops sown on May 15th, gradually increasing with delayed sowing up to June 15th. The highest HgTUE-II (0.071 kg/ha degree day %) at initiation of pod formation and (0.072 kg/ha degree day %) at maturity is observed when crops are sown on June 15th. Furthermore, pooled data from Table 7 reveals that flower initiation, 50% flowering, and peg formation initiation recorded significantly higher hygrothermal use efficiency-II with a planting density of 1.67 lakh ha^{-1}. However, a planting density of 3.33 lakh ha^{-1} remained statistically comparable to 2.50 lakh ha-1, showing higher heliothermal use efficiency at maturity compared to a density of 1.67 lakh ha^{-1}. Initiation of pod formation stage remained statistically non-significant with planting density. This enhanced use efficiency indicates efficient allocation of dry matter to various plant parts. These findings are consistent with the studies conducted by Praveen et al. [61] and Kumar et al. [54].

3.5 Yield

Pooled data from Table 8 demonstrates that groundnut sown on May 30th yielded significantly higher pod, kernel, and biological yields compared to crops sown on May 15th. Nevertheless, it was on par with the yields obtained from sowing on June 15.

Table 8. The impact of various growing environments and planting densities on the yield of groundnut, based on pooled data from 2017 to 2019.

Treatments	Yield of groundnut			
	Pod yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	Kernel Yield (kg ha^{-1})	Biological yield (kg ha^{-1})
Growing environment				
Sowing at 15 May	3353.94	5474.94	2273.55	8828.88
Sowing at 30 May	3831.56	5410.33	2735.62	9241.89
Sowing at 15 June	3878.42	5144.32	2784.23	9022.74
SEm±	53.69	28.96	40.90	80.43
CD at 5%	159.52	86.05	121.51	238.96
Planting density				
1.67 lakh ha^{-1}	3753.31	5205.25	2660.17	8958.56
2.50 lakh ha^{-1}	3871.10	5421.44	2768.98	9292.54
3.33 lakh ha^{-1}	3439.52	5402.90	2364.26	8842.41

SEm±	46.79	24.58	34.97	68.21
CD at 5%	132.65	69.70	99.14	193.39

However, groundnut sown on May 15th yielded higher haulm. This can be attributed to the short-duration variety's determinate growth habit, which resulted in the highest yields when sown on May 30th, providing the optimal maturity period required for this variety. Conversely, earlier sowing dates provided excessively long periods and harsh environments for this determinate variety, resulting in significantly lower yields (Figure 8).

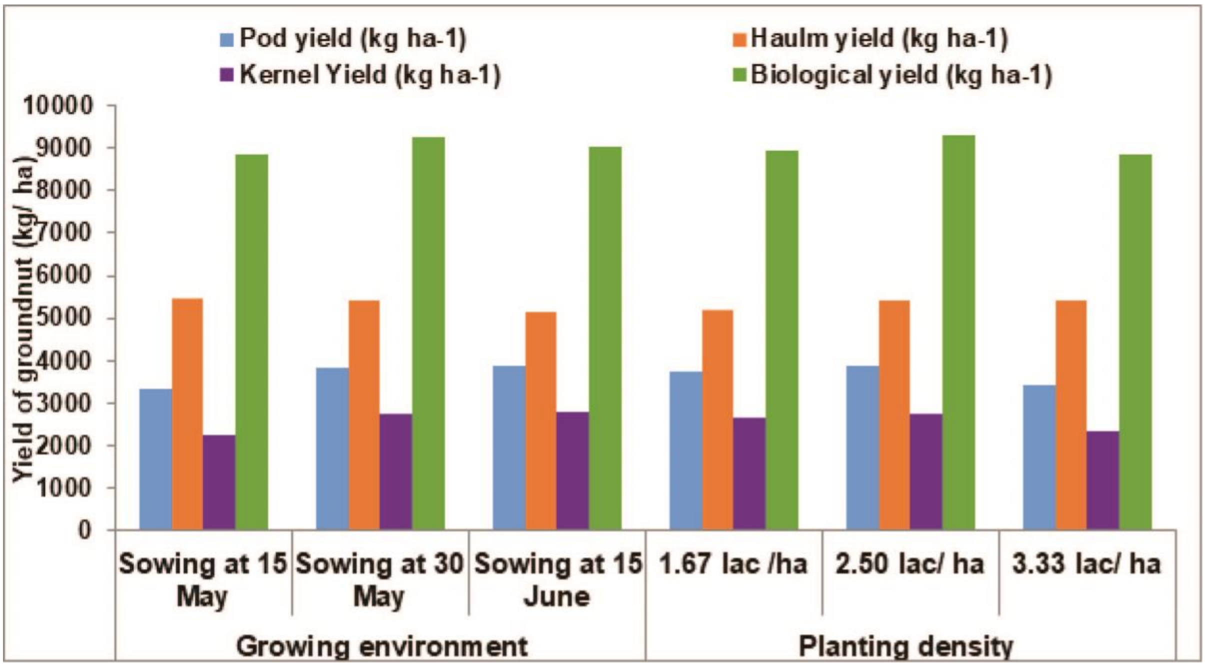

Figure 8. Effect of different growing environment and planting density on groundnut yield (Combined data from 2017-2019).

Since pod and kernel yields are cumulative functions of various yield attributes, variations in pod and kernel yields are influenced by sowing dates. Furthermore, pooled data from Table 8 reveals that pod, haulm, kernel, and biological yields were significantly higher with a planting density of 2.50 lakh ha^{-1}. However, a planting density of 3.33 lakh ha^{-1} remained statistically comparable to 2.50 lakh ha^{-1}, yielding higher haulm compared to planting density of 1.67 lakh ha^{-1}.

4. CONCLUSION

Groundnut is immensely significant as an oilseed crop globally. The growth and development of plants, as well as crop productivity, are significantly affected by the adverse impacts of global climate change. In this study, we investigated the effects of the different growing environment and planting density on the phenological development of groundnut. Remarkably, the findings of this study highlight the complex relationship between growing environments, planting densities, and the phenological development of groundnut in the hyper-arid zone of Rajasthan, India. Sowing groundnut on May 30 yielded similar results to sowing on June 15 regarding several growth parameters. However, sowing on May 15 consistently led to superior values of various developmental indicators during later growth stages. Furthermore, elevating the planting density from 1.67 lakh ha^{-1} to 3.33 lakh ha^{-1} notably improved several crucial metrics across groundnut phenological stages. These results emphasize the importance of careful timing and density management in optimizing groundnut production in challenging environmental conditions. By understanding and manipulating these factors, farmers can potentially mitigate the adverse effects of climate change and enhance groundnut productivity in hyper-arid regions like Rajasthan. Additional research and on-farm validation are essential to refine these findings and develop tailored strategies for sustainable groundnut cultivation in similar agro-climatic zones.

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AUTHOR CONTRIBUTIONS

The manuscript was conceptualized, designed and written by M.L.R., B.S.K., and M.S.K. The valuable feedback provided by S.C., S.P.S., R.C.B., N.K., R.P., C.K.D., S.-M.C., A.S., C.M., S.P., M.B., A.M. and M.K. All authors have read and consented to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

Data is available in the manuscript.

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