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Research Article

Phenology, phyllochron and productivity of sorghum in response to varying growing environments and nitrogen levels in the semiarid irrigated condition

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Abstract
Climate change is likely to affect agricultural production in many parts of the world. Sorghum is the stable food crop in semiarid areas, and climate change has significant adverse effects on sorghum yields. The optimum time of sowing is one of the important technologies that allow the crop to better utilise natural resources by the crop to maximise productivity. For optimizing the sowing time, the field investigation was carried out in Tamil Nadu Agricultural University, Coimbatore, under summer irrigated conditions in 2022. The experiment was laid out in a split-plot design with three replications. The main plot consists of five dates of sowing and the subplot includes different nitrogen levels. The results revealed that advanced sowing (first fortnight of April) reduced the yield by 13.73% and delayed sowing (second fortnight of May) recorded the maximum yield (4230.3kg ha^{-1}) with higher phyllochron values. GDD manifested a significant negative relationship with a high correlation coefficient (r) value of -0.98** (p = 0.01) for days to anthesis, -0.98** (p = 0.01) for days to physiological maturity and -0.88* (p = 0.05) for phyllochron. Average temperature exhibited a significant negative correlation with days to anthesis (-0.75*), physiological maturity (-0.97**) and phyllochron (-0.89*). The best-fit regression model showed that a GDD-based model could better predict the phenology of sorghum compared to an average temperature-based model. The study indicated that understanding sorghum's phenological response and productivity level under varied dates of sowing and the nitrogen levels in semiarid environments can help determine the appropriate sowing time and optimum nitrogen level for achieving better yield in summer-irrigated sorghum.

Keywords: Growing degree days (GDD), Phenological response, Regression model, Sowing windows, Thermal indices

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is a C_4 crop, mostly cultivated in semiarid parts of India. Sorghum has a variety of uses like food, fodder, forage, and fuel and it plays a pivotal role in food security for many of the world's poor people, being considered the "King of Millets" (Khaton *et al.*, 2016). Nowadays sorghum is gaining much importance as a nutritious food source for the people and its potential for supplying additional fodder to India's expanding dairy industry. About 19.5 percent of the world's population and 27 percent of India's population take sorghum as their primary food (Hazarika *et al*., 2022). Globally, sorghum is cultivated on about 41 million hectares to produce 64.20 million tonnes, with a productivity level of 1.60 tonnes per hectare (Pagire *et al*., 2021). In India, Maharashtra secured the first position in sorghum production (1.76 million tonnes) followed by Karnataka (0.88 million tonnes), Rajasthan (0.59 million tonnes) and Tamil Nadu (0.45 million tonnes) (Praveenkumar *et al.,* 2023). Compared with the global average, sorghum productivity in India is rather low, mostly because the crop is cultivated under rainfed conditions and has undergone unfavourable climatic conditions during the growth stages (Rai *et al*., 2022).

Climate change is a serious concern today and an urgent evolving threat to global food security. Environmental factors such as temperature and precipitation highly affect sorghum growth, development, phenology and productivity. (El-Raouf *et al*., 2013). Right time of sowing is an important agronomic management strategy that alters the crop's vegetative, reproductive and physiological maturity and yield potential. The location-specific impact of the sowing date on sorghum production varied according to the environmental circumstances present during the crop's growing season (Bughdady, 2016). The length of the growth season is directly influenced by the planting date; this impacts varieties in various growth phases, phenology and yield. Plants need a specific growing degree day (GDD) based on daily temperature and sowing windows to reach the phenological stages (Bankole, 2022). Temperature plays a major role in determining the time of sorghum phenophasic stages, such as flower initiation and 50% flowering. Since the environment is changing daily, sowing windows has a profound influence on both the growth and yield of the crop. Understanding this, it is crucial to select the optimum time of sowing that provides ideal growing conditions to obtain the maximum sorghum yield.

Nitrogen is the most pivotal nutrient which limits the crop growth and yield. It is a vital element in chlorophyll and hence plays an important role in determining the plant's potential to form carbohydrates. It underpins the photosynthetic ability of the plants and helps in optimum photosynthates production. Nitrogen is a primary component of proteins and is indispensable for the vigorous growth of the crop and its physiological processes. Nitrogen is critical to perfectly manage because of its intricate reactivity and mobility in the soil environment. The rate and the time of nitrogen application have an impact on the sorghum growth, phenology and productivity (Ostmeyer *et al*., 2022). But, there is little or no information on sorghum phenology on variable dates of sowing and nitrogen levels. Considering the above fact, the study was conducted to obtain information on the influence of sowing windows and nitrogen levels on the response of sorghum variety K 12 under summer irrigated conditions in a semiarid environment.

MATERIALS AND METHODS

Study area

The study was conducted in the Department of Agronomy at Tamil Nadu Agricultural University (TNAU), Coimbatore, Tamil Nadu, India. The field is geographically located at latitude 11°N & longitude 77°E with an altitude of 426.7m above mean sea level. The study region is the western agro climate zone of Tamil Nadu, which comes under the semiarid region. The soil characteristics of the experimental plot are described in Table 1.

Experimental details

The field experiment was laid out in a split-plot design with three replications. The main plot was assigned to five dates of sowing, *viz*., D_1-first fortnight of April, D_2-second fortnight of April, D_3-first fortnight of May, D_4-second fortnight of May and D_5-first fortnight of June. The subplots comprised three levels of nitrogen: N_1-75% RDN (67.5 kg N ha^{-1}) (reduced level of nitrogen), N_2-100% RDN (90 kg N ha^{-1}) (recommended dose of nitrogen) and N_3-125% RDN (112.5 kg N ha^{-1}) (increased level of nitrogen).

Agronomic practices

The test crop is sorghum [*Sorghum bicolor* (L.) Moench] and the variety used for this experiment is K 12 (Kovilpatti 12), released by Tamil Nadu Agricultural University (TNAU), Coimbatore. The crop was raised under summer irrigated conditions in 2022. The spacing adopted for this experiment is 45×15 cm. The recommended dose of fertilizer for irrigated sorghum (90:45:45 kg NPK ha^{-1}) was applied in the form of urea, single super phosphate and muriate of potash. Fifty percent of the recommended dose of nitrogen (RDN), the entire dose of phosphorous and potash were applied basally at the time of sowing. The two-split application applied the remaining 50% of the nitrogen on 15^{th} day (25%) and 30^{th} day (25%) after the sowing of sorghum. Three levels of nitrogen were applied as per the subplot treatments schedule (N_1-75% RDN (67.5 kg N ha^{-1}); N_2-100% RDN (90 kg N ha^{-1}); N_3-125 % RDN (112.5 kg N ha^{-1}). As given in the TNAU crop production guide 2020, all the agronomic practices were followed to cultivate the crop successfully.

Data and methods

The crop phenological parameters were collected at the appropriate growth stages and the data were statistically analysed through Fisher's method as Gomez and

Gomez (1984) suggested. All the parameters were subjected to analysis of variance (ANOVA) and were analysed with AGRES statistical software.

The phenology of sorghum variety K12 was studied during the summer season of 2022 to understand the phenological response of sorghum to weather parameters. The phyllochron, also known as leaf appearance, is the interval between the successive emergence of leaves. To investigate the phyllochron, the appearance of each leaf in the plant was noticed in order to identify the leaf just after it became visible. The leaf appearance rate was calculated using the following formula (Williams *et al.*, 1999)

$$\text{Leaf appearance rate (Leaf/day)} = \frac{1}{\text{Phyllochron}} \qquad \text{Eq. 1}$$

Weather parameters and thermal indices

The daily weather data on maximum and minimum temperature, wind speed, rainfall, bright sunshine hours, and relative humidity during the crop season were obtained from the Agro Climatic Research Centre, TNAU, Coimbatore. The daily data were converted into standard meteorological data during the crop growth period. The weather prevailed during crop period at different sowing dates is presented in Fig 1. Thermal indices *viz.*, Growing Degree Days (GDD), and Heat Use Efficiency (HUE) were also computed for different dates of sowing to examine the response of summer irrigated sorghum in the western agroclimatic zone of Tamil Nadu. The base temperature of 10ºC is fixed for the above calculations for the different stages of sorghum growth: seedling, vegetative, reproductive, and maturity.

GDD is used to predict the growth and development of plants during the growing season. The fundamental idea is that development will only happen if the average daily temperature (Equation (2)) rises beyond a particular air temperature threshold, known as the base temperature (T_{base}). Depending on the crop and variety, T_{base} may change dramatically. The GDD value is zero, meaning that even though time has passed according to the calendar, plant growth has not advanced as expected (Equation (3)), if the daily mean average temperature (T_{ave}) is equal to or lower than T_{base}. Whenever T_{ave} exceeds T_{base}, the GDD is equal to the difference between T_{ave} and T_{base}.

$$T_{ave} = \frac{(T_{max} - T_{min})}{2} \qquad \text{Eq. 2}$$

$$\text{GDD} = \begin{cases} T_{\text{ave}} - T_{\text{base}} & \text{if } T_{\text{ave}} > T_{\text{base}} \\ 0 & \text{if } T_{\text{ave}} \leq T_{\text{base}} \end{cases} \qquad \text{Eq. 3}$$

Subsequently, the cumulative GDD (GDDs) over a target period were calculated according to Equation (4)

$$\text{GDD}s = \sum_{i=1}^{n} \text{GDD}i \qquad \text{Eq. 4}$$

(Iwata *et al.*, 1984)

Where, i is the date on the calendar. Growing Degree Days, despite their name, are actual cumulative shifts in temperature are expressed in temperature units.

$$\text{Heat Use Efficiency (HUE)} = \frac{\text{Yield}}{\text{GDD}} \qquad \text{Eq. 5}$$

(Haider *et al.*, 2003)

The Heat Use efficiency was also studied to examine the growth and yield of the sorghum variety K 12 based on Equation 5.

Statistical analysis of the influence of weather on sorghum

A correlation analysis was performed to assess the degree of relationship or closeness and the strength of the association between two variables. It is assumed that both X and Y variables are random variables and normally distributed. Correlation co-efficient r that describes the strength of relationship was calculated using Statistical Package for Social Sciences (SPSS) software. Statistical significance of correlation was seen at 1 (P=0.01) and 5(P=0.05) per cent significance levels.

RESULTS AND DISCUSSION

Phenology of sorghum

Phenology is the study of the timing of recurring biological events and the causes of their timing concerning biotic and abiotic forces. Crop phenology serves as an indicator for the growing conditions of the crop, correlated with the crop yield. It is determined by the complex interaction between genetic and environmental factors. The days regarding major phenological stages, such as days to flower initiation, days to 50% flowering and days to anthesis of sorghum were observed and presented in Table 2. The phenological stages of sorghum were highly responsive to different sowing windows and nitrogen levels. Among the sowing windows, delayed sowing of sorghum on the first fortnight of June (D_5) recorded significantly a greater number of days required to flower initiation (60 days), days to 50% flowering (63 days) and days to anthesis (67 days). This was on par with sowing on the second fortnight of May (D_4), which recorded 59 days for flower initiation, 62 days for 50 % flowering and 66 days for anthesis. Minimum number of days needed to flower initiation (55 days), 50 % flowering (58 days) and days to anthesis (63 days) in the sorghum sown early on the first fortnight of April (D_1). The higher temperature prevailed in early sowing, shortened the plant vegetative stage and quickened the plant physiology process that

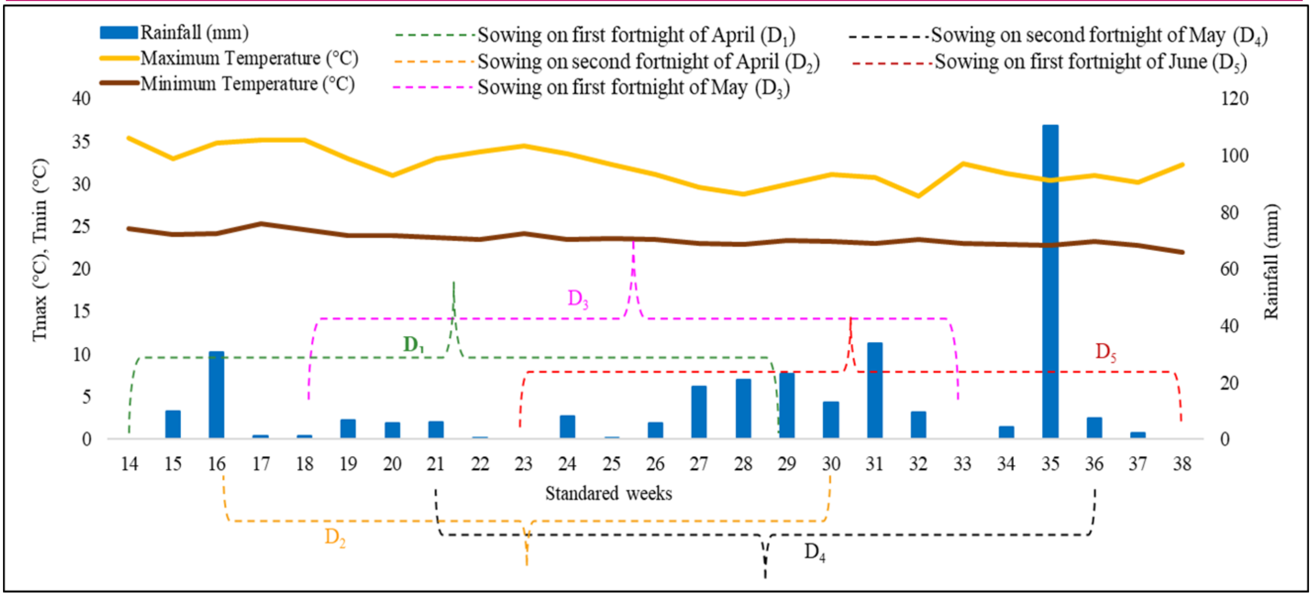

Fig. 1. *Weather variables recorded during the cropping period 2022 at TNAU, Coimbatore*

eventually resulted in early flowering (El Naim *et al.*, 2012).

Sowing dates primarily influenced the length of the vegetative period of sorghum. The delayed flowering observed in the delayed sowing of sorghum might have been due to increased or prolonged rainfall during the growth period (Fig. 1). Rainfall during the vegetative stage could extend the vegetative growth period and account for the increased plant height (Damilola *et al.,* 2022). Delayed sowing had less temperature than early

Table 1. Soil characteristics of the experimental plot

Parameters	Value	Methodology/ Reference
Texture	Sandy clay loam	Robinson's international pipette method (Piper,1966)
Organic carbon	Low (0.45%)	Chromic acid wet digestion method (Walkley and Black, 1934)
Soil pH	Neutral (7.43)	Potentiometry (Jackson, 1973)
EC (dS m^{-1})	0.42	Conductometry (Jackson, 1973)
Available N	Low (205 kg ha^{-1})	Alkaline Permanganate method (Subbiah and Asija, 1956)
Available P (Olsen)	High (29 kg ha^{-1})	Olsen method (Olsen et al., 1954)
Available K	High (420 kg ha^{-1})	Flame Photometry (Stanford and English, 1949)

Table 2. Sowing windows and nitrogen levels on the phenology of sorghum

Treatments	Days to flower initiation	Days to 50% flowering	Days to Anthesis
Sowing windows			
D_1 – First fortnight of April	55	58	63
D_2 – Second fortnight of April	56	59	64
D_3 – First fortnight of May	57	60	65
D_4 – Second fortnight of May	59	62	66
D5 – First fortnight of June	60	63	67
Sed	1.1	1.2	0.9
CD (P=0.05)	2.6	2.7	2.1
Nitrogen Levels			
N_1 – 75% RDN (67.5 kg N ha^{-1})	56	59	63
N_2 – 100% RDN (90 kg N ha^{-1})	57	60	65
N_3 – 125% RDN (112.5 kg N ha^{-1})	60	63	67
Sed	0.4	0.5	0.3
CD (P=0.05)	0.9	1.1	0.6
Interaction (D×N)			
Sed	1.4	1.5	1.0
CD (P=0.05)	NS	NS	NS

sowing, which slowed the growth of the crop (Fig. 1). This was due to the huge influence of temperature on vital cellular processes, including metabolism and photosynthetic activity (Rutayisire *et al*., 2020). The days the plants take to flower and reach physiological maturity are also controlled by the plant's genetic makeup and other environmental factors, especially temperature and photoperiod (Naoura *et al*., 2023).

The individual effect of nitrogen level revealed that application of an increased level of N (125% RDN) recorded a significantly higher number of days to attain flower initiation (60 days), 50% flowering (63 days) and anthesis (67 days) compared with other nitrogen levels. The minimum number of days required for flower initiation (56 days), 50% flowering (59 days) and anthesis (63 days) was observed in the reduced level of N (75% RDN) application. Delayed flower initiation and 50% flowering with a higher dose of nitrogen might be due to more vegetative growth, as reflected by increased plant height (Kaufman *et al*., 2013). The vegetative stage of delayed sown sorghum with a 125% RDN was lengthened by 4 days, and the crop might have used this extra time to extend the time for photosynthesis and the translocation of photosynthates from source to sink, which must have led to more seeds and test weight and increased production with proper translocation. Similar results were also reported by Andhale *et al*. (2017); in sorghum the grain and the straw yield were increased with increased nitrogen levels and Noori (2020) concluded that growth and the forage yield of sorghum enhanced with the application of increased nitrogen levels. The interaction effect was found to be non-significant in the phenology of sorghum for different dates of sowing and nitrogen levels.

Phyllochron and leaf appearance rate

The period between the visual appearance of successive leaf tips considered as phyllochron showed a significant difference between the date of sowing and the nitrogen levels (Table 3). Under the different sowing windows, the first fortnight of June sowing (D_5) took a significantly longer time interval of 3.93 days to produce one leaf and this was statistically on par with the second fortnight of May (D_4) (3.87 days) and the first fortnight of May (D_3) (3.77 days). A shorter interval of 3.44 days was required in the first fortnight of April sowing (D1) compared with the rest of the dates. At the same time, the leaf appearance rate was recorded at a minimum (0.26) when the phyllochron was higher (3.93) and a higher leaf appearance rate was noticed (0.29) when the phyllochron was lower (3.44). Phyllochron was higher in late-sowing crops compared with advanced-sowing sorghum. This might be attributed to the temperature differences between the different sowing times (Clerget *et al*., 2008). The leaf emergence rate was higher in the early sowing sorghum due to higher temperatures, which shortened the vegetative phase (Dos Santos *et al*., 2022).

It was also noticed that the nitrogen application rate impacts the sorghum phyllochron and leaf appearance rate. Application of an increased level of 125% RDN recorded a significantly higher phyllochron (3.85) with a lower leaf appearance rate (0.26). Meanwhile, the reduced rate of nitrogen (75% RDN application) registered a shorter phyllochron (3.57) in association with a higher leaf appearance rate (0.28). Excess application

Table 3. Sowing windows and nitrogen levels on phyllochron and leaf appearance rate of sorghum

Treatments	Phyllochron (Days)	Leaf Appearance Rate (Leaf/day)
Sowing windows		
D_1 – First fortnight of April	3.44	0.29
D_2 – Second fortnight of April	3.58	0.28
D_3 – First fortnight of May	3.77	0.27
D_4 – Second fortnight of May	3.87	0.26
D5 – Firt fortnight of June	3.93	0.26
Sed	0.104	0.007
CD (P=0.05)	0.240	0.015
Nitrogen Levels		
N_1 – 75% RDN (67.5 kg N ha^{-1})	3.57	0.28
N_2 – 100% RDN (90 kg N ha^{-1})	3.73	0.27
N_3 – 125% RDN (112.5 kg N ha^{-1})	3.85	0.26
Sed	0.072	0.005
CD (P=0.05)	0.151	0.011
Interaction (D×N)		
Sed	0.168	0.012
CD (P=0.05)	NS	NS

of 125% RDN delayed the emergence of leaves and the lowest phyllochron was observed with 75% RDN. Increasing the nitrogen levels will extend the vegetative growth phase of the crop, which requires a longer time to produce sequential leaves. Similar results were also observed by Hokmalipour (2011) in maize with increasing nitrogen rate, leaf appearance rate was increased and Phyllochron was decreased. Chakravarthy & Jagannathan (2013) observed that in maize, an increase in nitrogen levels had a significant and positive effect on leaf appearance rate while the phyllochron was negatively influenced.

Temperature and GDD influence on phenology and phyllochron

The accumulated Growing Degree Days at various growth stages of sorghum under varied sowing dates showed a highly significant negative relationship with a high r-value of -0.98**(p=0.01) for days to anthesis, -0.98** (p=0.01) for days to physiological maturity and a

a. GDD – Phenology and Phyllochron   b. Temperature - Phenology and Phyllochron

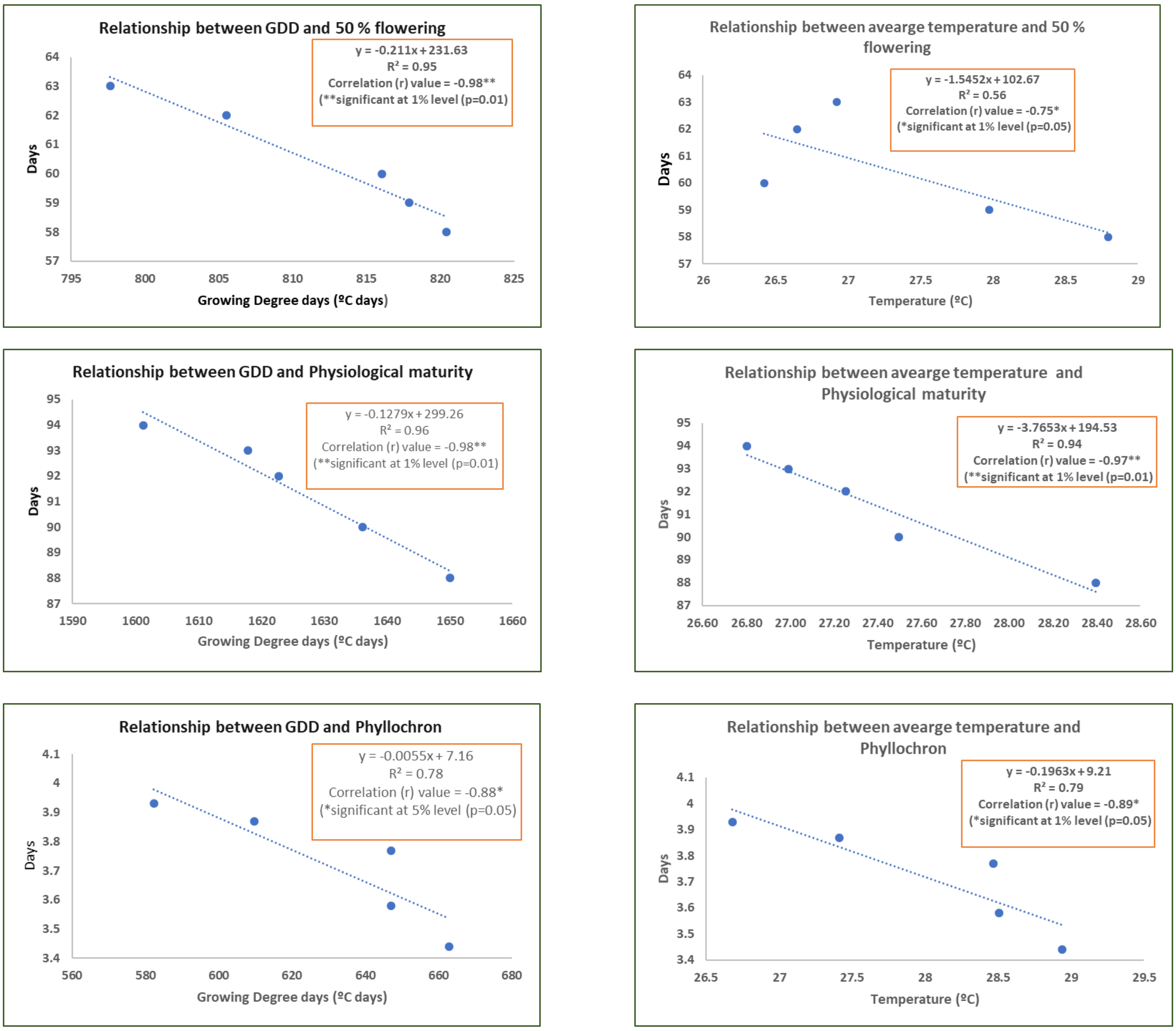

Fig. 2. *Sorghum phenology and phyllochron response to GDD and temperature*

Table 4. Regression model for predicting the phenology and phyllochron based on GDD and temperature

Crop variables	Growing Degree Day (GDD) (x value=GDD)	GDD – Goodness of fit - R^2	Temperature (x value=Temperature)	Temperature – Goodness of fit - R^2
Days to 50% flowering	y = -0.211x + 231.63	0.95	y = -1.5452x + 102.67	0.56
Days to maturity	y = -0.1279x + 299.26	0.96	y = -3.7653x + 194.53	0.94
Phyllochron	y = -0.0055x + 7.16	0.78	y = -0.1963x + 9.21	0.79

Fig. 3. *Yield and HUE of sorghum at the varied dates of sowing under irrigated condition during summer 2022*

significant negative correlation ((-0.88* (p=0.05)) between GDD and phyllochron (Fig. 2a). Average temperature showed a significant negative correlation with days to anthesis (-0.75*) and the negative relationship was highly significant with physiological maturity (-0.97**). Average temperature had a significant negative correlation (-0.89*) with phyllochron (Fig. 2b).

The regression best-fit model developed is presented in Table 4. The model's goodness of fit showed a high R2 value for GDD and Days to 50% flowering (0.95) and for GDD and Days to maturity (0.96), which are higher than between the temperature and both phenological stages. The R^2 value for average temperature and Days to 50% flowering was 0.56; for average temperature and Days to maturity, it was 0.94. For phyllochron prediction, the model's goodness of fit was found to be slightly higher between average temperature and phyllochron (0.78) than between the GDD and phyllochron (0.79). The regression model clearly indicated that GDD could predict the phenology of the sorghum crop, as the high goodness of fit of the model was observed between GDD and phenology compared to temperature and phenology. Regarding phyllochron prediction, both GDD (0.78) and average temperature (0.79) show almost similar goodness of fit to the model, which suggests that both GDD and temperature can predict the phyllochron.

A higher GDD was noticed when the sorghum was sown in advance. This might be because, during the summer, maximum and minimum temperatures were higher in the advanced sowing than in the late sowing of sorghum. The decreased GDD was registered in the delayed sowing of sorghum. Thus, the phenological phases became longer than the early sowing of sorghum. This might be attributed to the variation in temperature that prevailed under the different sowing dates (Sankar *et al*., 2023).

Temperature is a key factor controlling the flowering time and other physiological processes (Ruml and Vulic, 2005). Understanding the timing of phenological events and their variability can aid in enhanced and sustainable crop management by providing timely irrigation, fertilisation, and crop protection dates, resulting in more stable crop yields and quality. Additionally, crop phenology provides information that can be used to make decisions about the time and method of harvesting, processing, storing, transporting, and marketing agricultural commodities (Ji *et al*., 2021). Genotype, environment, and management interaction (G×E×M) have a significant role in the growth and development of the crop. Climate change variables affect the phenology of the crops and reduce their yield potential. The time of sowing and the cultivar selection are targeted so that flowering coincides with the period that will minimize abiotic stress (Smith *et al*., 2021). Forecasting phenology ahead of the actual occurring stage will be highly helpful in developing a suitable adaptation strategy for better crop management to avoid yield loss in the future on a larger scale.

Sorghum grain yield and Heat Use Efficiency

The sorghum grain yield varied significantly under different sowing windows (Fig. 3). Among the dates of sowing, sorghum sown on the second fortnight of May (D_4) recorded the highest grain yield (4230 kg ha^{-1}) with the highest HUE (2.33), which was followed by the first fortnight of May (D3) with a yield of 3978 kg ha^{-1}and 2.17 HUE. Lowest grain yield (3404 kg ha^{-1}) was obtained in delayed sowing of the first fortnight of June (D_5) with Heat Uses Efficiency of 1.91. The lowest HUE (1.85) was noticed in the first fortnight of April (D_1). Delayed sowing realised higher sorghum productivity compared with the rest of the sowing, and it was associated with a stronger source-sink relationship. This might be owing to ideal growth conditions such as temperature, light, and rainfall that prevailed during the cropping period, which helped fully exploit the crop's genetic potential (Mishra *et al.,* 2017). The crop sown on the first fortnight of June (D_5), exposed to sudden extreme rainfall of around 125 mm at the time of anthesis to the grain filling stage (Fig 1), led to poor pollination due to washout of the pollens from the panicle and ultimately affected the yield by poor grain filling and thereby resulted in reduced productivity and HUE. As sorghum is a short-day plant, advancing the sowing to the peak summer season will force the crop to enter the reproductive phase without attaining proper vegetative growth, which eventually affects the yield attributing character and yield (Ungata *et al.,* 2020). The ideal weather variables prevailing during the delayed sorghum sowing contributed to increasing sorghum productivity.

Conclusion

The days required to reach different phenological stages were increased with each subsequent sowing in summer irrigated sorghum. The findings revealed that weather variables prevailing during the summer season of the sorghum growth period have a significant impact on the phenology and productivity of sorghum in the western agroclimatic zone of Tamil Nadu. Higher temperatures and a higher GDD reduced the days to anthesis and physiological maturity, and finally, the total crop duration, as noticed in the early sorghum sowing dates in summer, compared to delayed sowing. The maximum sorghum grain yield with a longer crop duration was obtained under the delayed sowing dates. Optimum sowing dates can provide the ideal weather conditions for effective utilization of resources for better growth and productivity. Delayed sowing during the summer season could be practised to obtain the maximum yield potential of sorghum in a semiarid environment. It is evident from the results that GDD is able to predict the phenology of the sorghum crop well compared to considering the average temperature. Both GDD and average temperature showed a similar predictive capability of phyllochron in sorghum.

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Conflict of interest

The authors declare that they have no conflict of interest.

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