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**Usha N**
Department of Agronomy, College of Agriculture, Vijayapura, Karnataka, India

**Patil SB**
University of Agricultural Sciences, Dharwad, Karnataka, India

**Corresponding Author:**
**Usha N**
Department of Agronomy, College of Agriculture, Vijayapura, Karnataka, India

# Thermal variations in pigeonpea genotypes with change of growing environment in semi-arid regions of India

**Usha N and Patil SB**

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**Abstract**
Time of sowing is one of the most important agronomic factors for realizing the potential yield of the crop. The field experiment was conducted at RARS, Vijayapura, during *Kharif* 2021. The experiment was laid out in a split-plot design assigning four sowing windows to main plots *viz*., first fortnight of June (23-24$^{th}$ Standard Meteorological Week), second fortnight of June (25-26$^{th}$ SMW), first fortnight of July (27-28$^{th}$ SMW) and second fortnight of July (29-30$^{th}$ SMW), whereas genotypes to subplot *viz*.,TS-3R, GRG-152 and GRG-811 and replicated thrice. The early sown pigeonpea accumulated higher GDD, PTU, HTU, PTI, HUE, PTUE and HTUE at different phenophases. However, accumulated heat units and thermal efficiencies decrease with delay in sowing. The results revealed that the phenophase 50% podding to physiological maturity recorded higher heat unit and thermal efficiencies among all the phenophase. The total GDD required for crop growth was higher in first fortnight of June sowing (3209.2 $^0$C days). Genotype differed significantly for GDD accumulation where, GRG-811 accumulated more GDD (3114.4 $^0$C days) compared to other two genotypes GRG-152 (3096.0 $^0$C days) and TS-3R (2867.8 $^0$C days). Similarly, early sown pigeonpea recorded more PTU (38430 $^0$C day hrs), PTI (120.47 $^0$C days day$^{-1}$) and HTU (16540 $^0$C day hrs). Among the genotype GRG-811 recorded higher PTU (37308 $^0$C day hrs) and HTU (16095 $^0$C day hrs). However, TS-3R recorded higher PTI (119.77 $^0$C days day$^{-1}$). The correlation studies revealed that heat units showed non-significant and positive correlation with seed yield wherein, it showed highly significant ($p \leq 0.01$) and positive correlation with biological yield except PTI which showed non-significant correlation with biological yield. Likewise, thermal efficiencies showed highly significant ($p \leq 0.01$) and positive correlation with seed yield and significant ($p \leq 0.05$) and positive correlation with biological yield. Which means the temperature and sunshine hours significantly influenced the seed yield and biological yield.

**Keywords:** Standard meteorological week, growing degree days, agrometeorological use efficiencies, principal component analysis, correlation

## Introduction
Pigeonpea (*Cajanus cajan* L.) is commonly known as red gram / arhar / tur, and its origin is in South Africa. It is an important grain legume that belongs to the fabaceae (leguminaceae) family and widely cultivated pulse crop in India. It is a drought tolerant, deep-rooted, often cross-pollinated, $C_3$, short-day plant and hypogeal germination in nature. It is a common food grain crop and offers nutritional security due to its richness in protein (21%) with essential amino acids such as methionine, lysine and tryptophan along with mineral supplementation *viz*., iron and iodine. In addition to its nutritional value, it also has a unique property of maintaining and restoring soil fertility through biological nitrogen fixation and improvement of physical properties of the soil by virtue of its deep root system. Pigeonpea is one of the major pulse crops which attract farmers with its significant yields despite its demand in the market. The growth and development of pigeonpea vary from location to location due to variability in agro-climatic and soil-water related parameters. Even in the same location, variability in growth takes place due to different growing environments created by sowing dates, cultivars and other cultural and management practices (Ahlawat and Rana, 2005) [1].

Pigeonpea is grown throughout the tropical and sub-tropical regions of the world and warmer temperature regions between 30$^0$ N and 35$^0$ S latitudes. However, a major area under pigeonpea in India is lying between 14$^0$ and 28$^0$ N latitudes. India has the distinction of being the world's largest producer and consumer of pulses, including pigeonpea. The area under pigeonpea cultivation in India is 4.90 m ha and production of 4.22 m tonnes with a productivity of 861 kg ha$^{-1}$ (Anonymous, 2022) [2]. Karnataka ranks first in terms of area (35.08%), followed by Maharashtra (27.24%). Karnataka is one of the pigeonpea growing state having an area of 1.72 m ha with a production of 1.14 m tonnes and productivity of 666 kg ha$^{-1}$ (Anonymous, 2022) [2].

The rate of growth and development of crop depends on the temperature surrounding the plant, and each species has a minimum, maximum, and optimum specific temperature range for better growth and development (Hatfield *et al*., 2015) [4] and Praveenkumar *et al*., 2020 [17]. The vegetative phase of development normally coincides with relatively long days and warm temperatures (Reddy and Virmani, 1981) [21]. Reproductive phase of development coincides with the period when temperatures are cool and day-length is short and as a result, flowering is triggered only by short days. Richards (1989) [23] reported that the first step towards maximising yield is to ensure that the phenology of the crop matches the resources of the production environment. The pigeonpea phenological events/stages identified by Nihalani (1989) [13] was adopted for the present study are: $P_1$: Emergence to initiation of primary branches, $P_2$: Initiation of primary branches to initiation of secondary branches, $P_3$: Initiation of secondary branches to flower bud initiation, $P_4$: Flower bud initiation to 50% flowering, $P_5$: 50% flowering to 50% podding and $P_6$: 50% podding to physiological maturity. These are useful in selecting prospective genotypes for production in different growing environments that have optimum production conditions. The temperature range in which plant growth and development occurs is characterized by base temperature ($T_b$) below which the rate of development is zero, an optimum temperature ($T_o$) at which the rate of development is most rapid, and a warmer ceiling limit ($T_{ce}$) beyond which development ceases (Summerfield *et al*., 1991) [29]. The duration of a particular growth stage is directly related to temperature, and this duration for particular species could be predicted using the mean sum of daily air temperatures (Tewari and Singh, 1993) [31]. The environmental interaction plays a very important role in desired grain production. Presently, the knowledge regarding the effect of environmental factors on crop production is meager, especially in pigeonpea and other pulses in dry areas. Pigeonpea is also known to be sensitive to photoperiod and temperature, and the plant morphology changes with the environment, particularly the temperature. A study on phenological changes under varying weather scenarios is required to determine optimum sowing windows and suitable genotypes under different weather scenarios and evaluate their subsequent effect on pigeonpea productivity. It is, therefore, important to study how pigeonpea genotypes perform in changing weather scenarios through sowing windows, especially in the Northern Dry Zone of Karnataka.

## Materials and Methods

The experiment was conducted at the Regional Agricultural Research Station (RARS), Vijayapura and it is located at latitude of 16$^0$46' 15.16" North, the longitude of 75$^0$44' 53.78' 'East and an altitude of 593.8 meters above the mean sea level. The experimental site is in the jurisdiction of the Northern Dry Zone of Karnataka (Zone 3).The soil of the experimental site is medium deep black and the texture of the soil is a clayey loam belonging to the order *Vertisols*. The experiment was laid out in a split-plot design with three replications consisted of 12 treatment combinations. Treatments included four main plots with sowing windows (D) *viz*., $D_1$: first fortnight of June (23-24$^{th}$ SMW), $D_2$: second fortnight of June (25-26$^{th}$ SMW), $D_3$: first fortnight of July (27-28$^{th}$ SMW), $D_4$: second fortnight of July (29-30$^{th}$ SMW) and three subplots with three genotypes (G) *viz*., $G_1$: TS-3R, $G_2$: GRG-152 and $G_3$: GRG-811. The field was ploughed once after the harvest of the previous crop and harrowed to obtain fine seedbed. During sowing, the land was prepared to a fine seedbed and the plots were laid out as per the experiment's layout and staggered sowing was done as per the treatments at different sowing windows by hand dibbling with 1-2 seeds per hill. The crop was sown by providing recommended spacing of 120 cm inter-row and 20 cm intra-row as per the treatments. The gap filling and thinning were carried out 10 and 20 days after sowing, respectively, by keeping only one healthy seedling per hill. Hand weeding was done at 25 days after sowing (DAS) to avoid crop weed competition. One intercultural operation was carried out at 45 DAS to hold the soil moisture and provide opportunate conditions for plant growth. Due to the incidence of pod borer (*Helicoverpa armigera*) the spray of emamectin benzoate 5% SG @ 0.5 g per liter of water was taken up to control the pest. The crop was considered to mature when 95% of pods have obtained their mature colour after that harvesting was done.

The data collected from the experiment at different phenological stages were subjected to statistical analysis as per split-plot design described by Gomez and Gomez (1984) [3]. The influence of four sowing windows as main plot and three genotypes as subplot in the split plot design which was replicated thrice which is subjected for test of two way ANOVA. The means of treatment combination were compared by the LSD (Least significant difference) test upon significant results of F test at $p<0.05$. Summary tables for treatment effect have been prepared and furnished with standard error of means (S.Em±) and critical difference (C.D.) at 5% level of probability (p=0.05) has also been given where the treatment differences were significant.

### Agrometeorological indices

Several agrometeorological indices developed by utilizing various meteorological elements are found in the literature to study crop-weather relationships. The indices such as (i) Growing degree days (GDD), (ii) Photo-thermal units (PTU), (iii) Photo-thermal index (PTI), (iv) Helio-thermal units and Heat use efficiency (HUE) were employed in the present study. By using the 10 °C base temperature (Nihalani, 1989) [13], thermal and photo-thermal indices were computed for each stage using appropriate formula suggested by different research workers. The methods of computation of the indices are presented here under.

### Growing Degree Days (GDD)

Growing degree days (GDD) at different phenological stages were calculated by summation of daily mean temperature above base ($T_b$ = 10 $^0$C) temperature for a corresponding period from sowing to physiological maturity, as suggested by Monteith (1977) [10] and expressed in $^0$C days.

$$\text{GDD (°C days)} = \sum \frac{(T_{max} + T_{min})}{2} - T_b$$

Where, $T_{max}$ = maximum temperature, $T_{min}$ = minimum temperature, $T_b$ = base temperature (Nihalani, 1989) [13].

**Photo-thermal units (PTU)**

The photo-thermal units (PTU) which takes into account the maximum possible duration of day light (Day length factor or maximum possible sunshine hours) were also worked out for each day by multiplying the adjusted values of growing degree days for a day with the corresponding day length factor (Rajput, 1980) [19].

$$\text{PTU } (^\circ\text{C day hrs}) = \sum(\text{GDD} \times \text{length of day})$$

Where, GDD = Growing degree days ($^0$C days)

**Photo-thermal index (PTI)**

Photo-thermalindex (PTI) expressed as degree days per growth days for different phenophases of the crop *i.e.*, $P_1$ to $P_6$. It can be obtained by using the following formula suggested by Neog and Chakravarty (2005) [12].

$$\text{PTI } (^\circ\text{C days day}^{-1}) = \frac{\text{GDD between two phenological stages}}{\text{No. of days taken between two phenological stages}}$$

Where, GDD = Growing degree days ($^0$C days)

**Helio-thermal unit (HTU)**

The helio-thermal unit (HTU) for a day represents the product of GDD and bright sunshine hours for a particular day as recorded by the sunshine recorder and are expressed in $^0$C day hours. The sums of HTU for particular phenophases of interest were determined according to the equation

$$\text{HTU } (^\circ\text{C day hrs}) = \sum(\text{GDD} \times \text{BSS})$$

Where,
GDD = Growing degree days ($^0$C days), BSS = Bright sunshine hours.

**Agrometeorological efficiency**

**Heat use efficiency (HUE)**

Heat use efficiency (HUE) is defined as the biomass accumulated during the given period per degree-day and was also computed to compare the relative performance of pigeonpea genotypes under various treatments using the following formula (Sastry *et al*., 1985; Saha and Ghosh 2012) [25, 24].

$$\text{HUE } (\text{kg ha}^{-1}\ ^\circ\text{C day}) = \frac{\text{Seed yield (Kg ha}^{-1})}{\text{Accumulated growing degree day } (^\circ\text{C day})}$$

**Helio-thermal use efficiency (HTUE)**

Helio-thermal use efficiency (HTUE) indicates the efficiency of crop to utilize the available actual bright sunshine hours. It is defined as yield per degree day hrs and calculated using formula reported by Lavand (2012) [9].

$$\text{HTUE } (\text{kg ha}^{-1}\ ^\circ\text{C days}^{-1}\text{ hrs}^{-1}) = \frac{\text{Seed yield (kg ha}^{-1})}{\text{Accumulated HTU } (^\circ\text{C day hrs})}$$

**Photo-thermal use efficiency (PTUE)**

The photo-thermal use efficiency (PTUE) indicates the efficiency of crop to utilize the available maximum possible bright sunshine hours, It is expressed as yield per degree day hrs and calculated by the formula given by Lavand (2012) [9].

$$\text{PTUE } (\text{kg ha}^{-1}\ ^\circ\text{C days}^{-1}\text{ hrs}^{-1}) = \frac{\text{Total seed yield (kg ha}^{-1})}{\text{Accumulated PTU } (^\circ\text{C day hrs})}$$

**Correlation studies**

Correlation studies of agrometeorological indices and efficiencies with seed yield and biological yield was carried out in OPSTAT with the help of methodology described by the Sheoran (1998) [26]. The level of significance used for 'F' tests was p=0.05 and p=0.01. Critical Difference (CD) values were calculated at 5% probability level and 1% if the F test will found to be significant.

**Result**

**Weather variable**

Crop growth is mainly dependent on environmental factors. The fluctuations in weather variables greatly influence crop growth, development and yielding potential. The adequate availability of soil moisture over the growing period of a crop is essential for fortunate crop production in rainfed areas. The total annual rainfall during cropping period was 521 mm, with 40 rainy days. The higher maximum air temperature was recorded in the month of June (32.3 $^0$C), and the lower maximum air temperature was recorded in the month of December (28.8 $^0$C). Similarly, the lower minimum temperature was recorded in the month of December (15.0 $^0$C) and the higher in June (22.0 $^0$C). Mean monthly maximum relative humidity in the morning (RH- I) was recorded in the month of September (91%) and the lower in the month of October (85%). Similarly, the higher relative humidity in the afternoon (RH- II) was recorded in the month of July (68%) and the lower in the month of October (47%). Likewise, sunshine duration was higher in the month of October (8.1 h) and lower sunshine duration in the month of July (3.3 h). Lower wind velocity helps in decreasing evapotranspiration, however higher wind speed was recorded in the month of June (13.5 km hr$^{-1}$) and lower wind speed recorded in the month of July (3.0 km hr$^{-1}$). The ambient weather parameters like maximum and minimum temperature, relative humidity and wind speed were higher in the morning hours (07:00 h) than in the afternoon (14:00 h). By and large, the weather conditions are in the optimum range for normal growth and yield of pigeonpea.

**Analysis of variance**

Agrometeorological indices and efficiencies during different phenophases were significantly influenced by sowing windows, genotypes and their interaction (Table 1 and 2). Analysis of variance showed significant and positive effects of sowing windows, genotype performance and their interaction on GDD, PTU, HTU, PTI, HUE and PTUE except at emergence to primary branch initiation stage ($P_1$) for GDD and PTI which showed non-significant relationship. However, sowing window showed strong correlation with GDD and PTU at emergence to initiation of primary branch with F value 20.25 and 16.92, respectively. Whereas, HTU showed significantly higher correlation at 50 per cent podding to physiological maturity stage. However, PTI showed highest correlation at 50 per cent flowering to 50 per cent podding.

**Growing degree days**

Data pertaining to growing degree days during different phenological phases of pigeonpea is presented in Table 3. The attainment and duration of different phenophases is determined by requirement of GDD. The requirement of heat units is different at different phenophases of pigeonpea. The higher GDD accumulated at physiological maturity stage under early sowing (753.9 $^0$C days). The requirement of heat units decreased gradually with delayed sowing. The maximum total accumulated GDD required for the completion of the crop growth period of pigeonpea from emergence to physiological maturity stage was observed in the first and second fortnight of June sowing (3209.2 and 3074.6 $^{0}$C days, respectively). They were statistically on par with each other. However, the reduction in $^{0}$C days by 10.3% when sown in second fortnight of July (2877.2 $^{0}$C days) compared to first fortnight of June sowing. Among the genotypes, TS-3R indeed took fewer days and less GDD to attain all phenological stages. The mean total heat unit requirement up to maturity of TS-3R is lower, followed by GRG-152 and GRG-811 were 2867.8, 3096.0 and 3114.4 $^{0}$C days, respectively.

**Photo-thermal unit**

The maximum accumulated photo-thermal unit (PTU) was determined for various phenophases under different sowing windows. The result revealed that on an average, pigeonpea utilized 38430 $^{0}$C day hrs upto physiological maturity was observed in the first fortnight of June sowing, while the minimum accumulated PTU (34526 $^{0}$C day hrs) was observed in second fortnight of July sowing. There was a reduction in PTU accumulation by 10.1% in delayed sowing on second fortnight of July over first fortnight of June sowing due to the higher maximum temperature and sunshine hours in most of the stages of plant growth (Table 4). Among the genotype GRG-811 recorded higher PTU (37308 $^{0}$C day hrs) followed by other two genotypes.

**Photo-thermal index**

The PTI indicated the rate of development of different phenophases by using the GDD. A significantly higher accumulation of photo-thermal index (PTI) was noticed in first fortnight of June sowing (120.47 $^{0}$C days day$^{-1}$) from emergence to physiological maturity ($P_1$ to $P_6$). The values decreased with the delay in the sowing from second fortnight of June to second fortnight of July. PTI was higher in TS-3R (119.77 $^{0}$C days day$^{-1}$) than the other two genotypes GRG-152 (119.22 $^{0}$C days day$^{-1}$) and GRG-811 (117.78 $^{0}$C days day$^{-1}$) (Table 5).

**Helio-thermal unit**

Helio-thermal unit (HTU) was noticed higher in first fortnight of June sowing (16540 $^{0}$C day hrs) from emergence to physiological maturity ($P_1$ to $P_6$). However, HTU observed at different phenophases from sowing to maturity were comparatively higher in genotype GRG-811 (16095 $^{0}$C day hrs), followed by GRG-152 (15900 $^{0}$C day hrs) and lower in TS-3R (14817 $^{0}$C day hrs) (Table 6).

**Agrometeorological efficiencies**

The heat use efficiency (HUE) in terms of economic yield, helio-thermal use efficiency (HTUE) and photo-thermal use efficiency (PTUE) was higher in second fortnight of June sowing (0.500 kg ha$^{-1}$ $^{0}$C day, 0.097 kg ha$^{-1}$ $^{0}$C day$^{-1}$ hrs$^{-1}$ and 0.042 kg ha$^{-1}$ $^{0}$C day$^{-1}$ hrs$^{-1}$, respectively). However, lower HUE, HTUE and PTUE were observed in second fortnight of July (0.416 kg ha$^{-1}$ $^{0}$C day, 0.080 kg ha$^{-1}$ $^{0}$C day$^{-1}$ hrs$^{-1}$ and 0.035 kg ha$^{-1}$ $^{0}$C day$^{-1}$ hrs$^{-1}$, respectively). Among the genotypes TS-3R recorded higher HUE, HTUE and PTUE (0.507 kg ha$^{-1}$ $^{0}$C day, 0.098 and 0.042 kg ha$^{-1}$ $^{0}$C day$^{-1}$ hrs$^{-1}$, respectively) (Table 7).

**Yield**

The higher seed yield per hectare was also attributed directly by yield plant$^{-1}$. The pigeonpea sown in first and second fortnight of June produced significantly higher seed yield (1539 and 1535 kg ha$^{-1}$, respectively) and were on par with each other. And we observed that each consecutive 15 days delay in the sowing from first fortnight of June sowing caused a reduction in seed yield by 10.01% under first fortnight of July (1385 kg ha$^{-1}$) and 23.61% under second fortnight of July sowing (1191 kg ha$^{-1}$) (Fig. 2). The significantly higher biological yield was observed in first and second fortnight of June sowing (5865 and 5464 kg ha$^{-1}$, respectively) compared to other sowing windows and which were on par with each other. The improvement of biological yield in first fortnight of June to the tune of 26.93% and 57.74% over first and second fortnight of July sowing. However, a significantly lower biological yield was registered in second fortnight of July sowing (3718 kg ha$^{-1}$).

**Correlation studies**

The correlation coefficients of agrometeorological indices and efficiencies with seed yield and biological yield is presented in Table 8. Agrometeorological indices *viz*., GDD, PTU, PTI and HTU showed non-significant and positive correlation with seed yield. However, it ranged from 0.168 to 0.487. Whereas, agrometeorological efficiencies showed highly significant ($p \leq 0.01$) and positive correlation with seed yield and it ranged from 0.844 to 0.846 (Table 8 and Fig. 3). Similarly, GDD, PTU and HTU showed highly significant ($p \leq 0.01$) and positive correlation with biological yield except for PTI which showed non-significant correlation. However, HUE, HTUE and PTUE showed significant and positive correlation with biological yield (Fig. 4).

**Discussion**

All biological processes of crops respond to temperature and all responses can be summarized in terms of cardinal temperature: a base or minimum, an optimum and a maximum temperature, sunshine hours, rainfall and available moisture content of the soil. Heat energy is required for physiological growth and various physicochemical processes take place in the plant. These processes are affected when temperature fluctuations are greater. The nature of the response to temperature is important for calculating the phenology, adaptation and yield of a crop (Singh and Singh, 1983) [28]. Air temperature based meteorological indices *viz.*, growing degree day (GDD) and helio-thermal units (HTU) are used to describe changes in phenology and growth parameters (Prakash *et al*., 2015) [16].

The higher GDD with early sown crop may be due to longer crop duration, crop sown on early dates accumulated higher GDD quicker in a shorter time due to relatively higher ambient temperatures coupled with longer sunshine hours. Ram *et al*. (2011) [20] and Rajbongshi *et al*. (2016) [18] revealed that a decreasing trend in accumulated GDD for attaining any phenological event was observed with successive delays in sowings in pigeonpea. The progress in terms of growth is estimated by integrating a developmental rate, which is usually a function of temperature and photoperiod. The efficiency of heat energy conversion for dry matter production depends on genetic factors, crops and the growing environment. Plants have a definite temperature requirement before they attain certain phenological stages. The heat unit system was adopted for determining the maturity dates of different crops from which accurate yield and maturity prediction could be assessed. The result revealed that on an average, pigeonpea utilized 38430 $^{0}$C day hrs upto physiological maturity was observed in the first fortnight of June sowing. These results obtained in the present study are in accordance with the findings of Patel *et al*. (2000) [15], Nagamani *et al*. (2015) [11] and Nikam (2016) [14]. The increase in PTI in early sowings (Table 5) might be due to thermal stress conditions developing in the later part of the growth cycle of pigeonpea (Kumar *et al*., 2019) [7]. The mean of total heat units requirement up to maturity of low yielding genotypes was relatively lower, followed by medium and high yielding cultivars (Kiran and Chimmad, 2015) [6]. The variation in HTU amongst sowing windows was because of a reduction in the growing period, an increase in the length of bright sunshine hours, as well as less GDD accumulated in delayed sowings. However, in general, a decreasing trend in total accumulated HTU with delayed sowing date was observed. These results are in conformity with Patel *et al*. (2000) [15]. This higher use efficiency shows the higher yield production, this heat use efficiency is a conversion of heat energy into seed yield and depends on crop type and genetic factors. The results also are evidenced in the studies of Revathi and Rekha (2017) [22] in finger millet. Lower yields under late-sown crops were reason for less HUE in late-sown conditions (Kumar *et al*., 2008) [8] in pigeonpea. The increased seed yield due to early sowings is ascribed to the high LAI and its persistence, branches, PAR interception and absorption, leading to higher dry matter accumulation before the crop reaches the reproductive stage (Patel *et al*., 2000) [15]. Under late sown, the plant could not accumulate sufficient photosynthates due to the short vegetative growth period (Singh *et al*., 2012) [27]. This improvement in biological yield might be due to higher seed and straw yield produced in first and second fortnight of June sowing with better performance of growth parameters *viz*., plant height, number of branches, number of pods, leaf area and total dry matter production and its distribution in different plant parts compared to other sowing windows.

Jan *et al*., 2022 [5] revealed both green cob and biological yield of sweet corn was positively corelated with various agrometeorological indices and thermal use efficiencies *viz*. heat use efficiency, heliothermal efficiency, photothermal use efficiency and hydrothermal use efficiency showed strong correlation. Tauseef *et al*., 2015 [30] also obtained the correlation analysis between agrometeorological indices and grain yield and biological yield and results were significant.

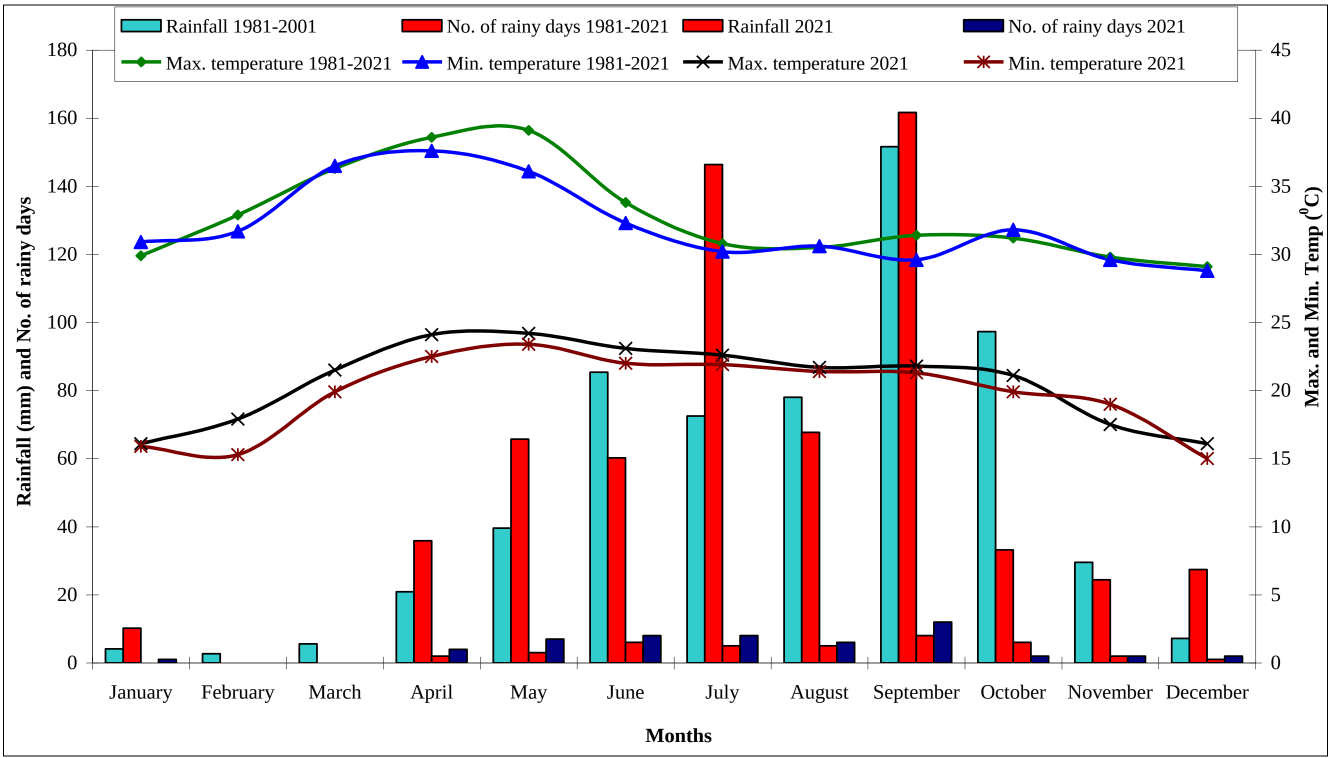


Fig 1: Monthly meteorological data for experimental Year Against normal for 40 year (1981-2020) at RARS, Vijayapur (Karnataka)

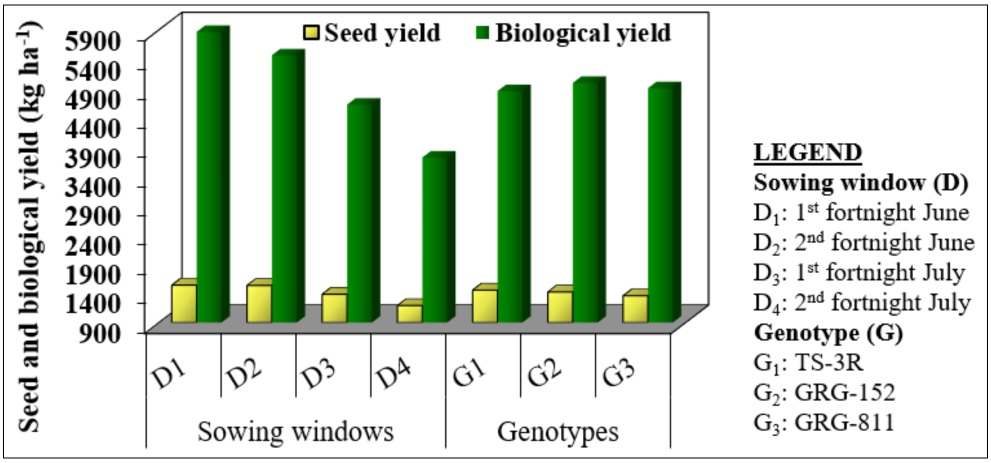


**Fig 2:** Seed and Biological yield pigeonpea genotypes influenced by the growing environments

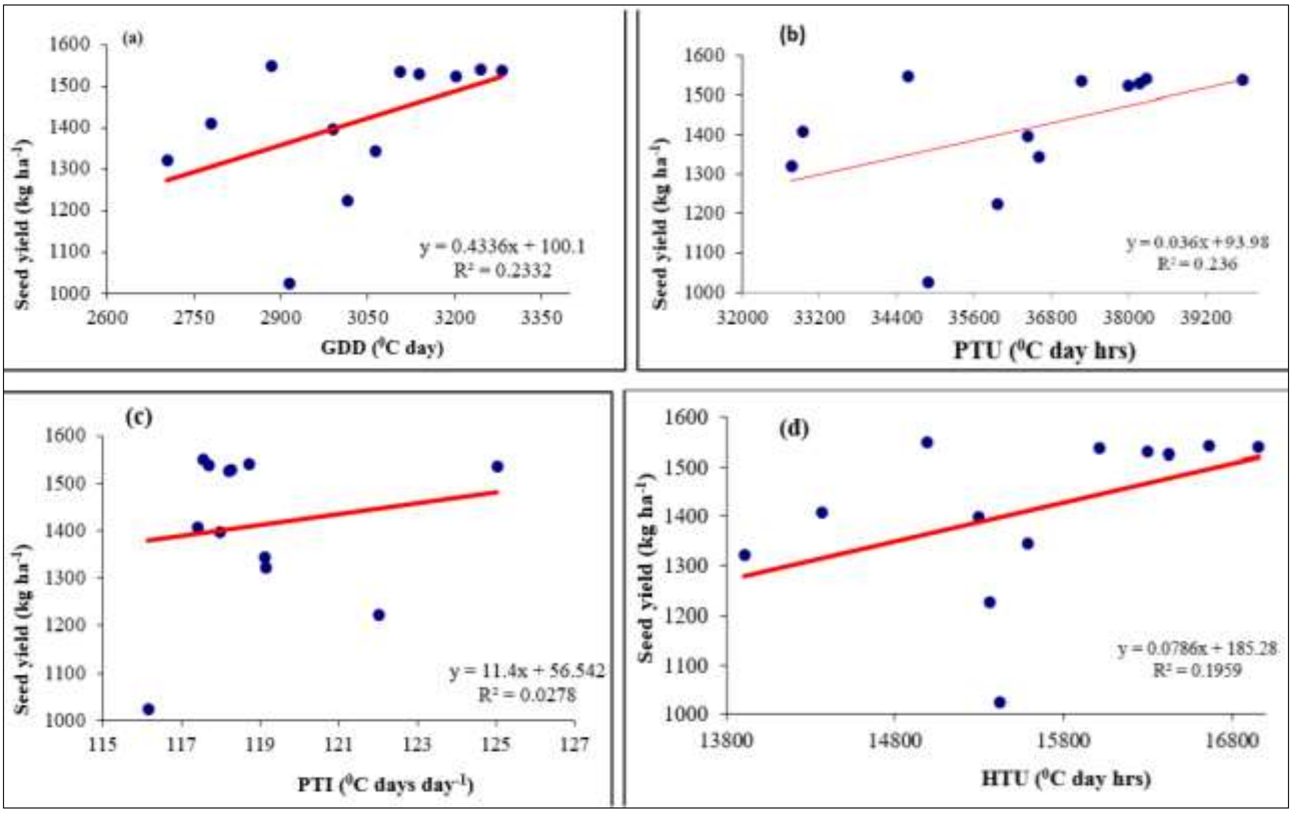


**Fig 3:** Correlation between (a) GDD and seed yield; (b) PTU and seed yield; (c) PTI and seed yield and (d)) HTU and seed yield

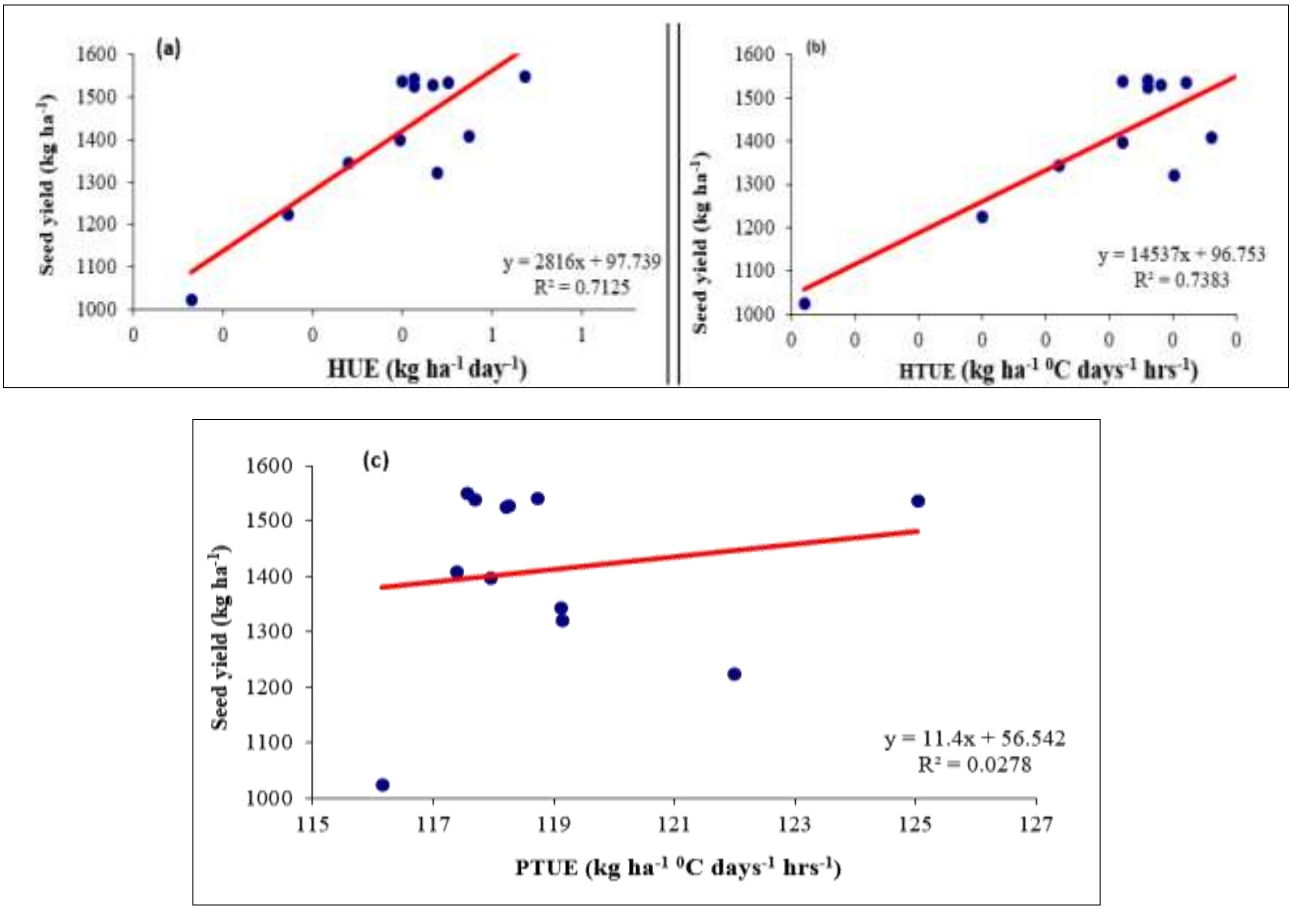


**Fig 4:** Correlation between (a) HUE and seed yield; (b) HTUE and seed yield; (c) PTUE and seed yield

**Table 1:** Combined Analysis of Variance (F values) for agrometeorological indices at different phenophases

| Source of variation | Phenological phases | | | | | | | Accumulated |
|---|---|---|---|---|---|---|---|---|
| | df | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | |
| | GDD | | | | | | | |
| Sowing windows | 3 | 20.25* | 11.59* | 17.02* | 8.77* | 5.35* | 12.53* | 10.8* |
| Genotypes | 2 | 12.47* | 5.42* | 34.77* | 33.2* | 36.1* | 3.66* | 78.66* |
| Sowing windows x Genotypes | 6 | $0.46^{ns}$ | 2.86* | 3.01* | 4.43* | 7* | 3.2* | 2.8* |
| | PTU | | | | | | | |
| Sowing windows | 3 | 16.92* | 5.81* | 4.81* | 6.87* | 4.81* | 4.8* | $1.46^{ns}$ |
| Genotypes | 2 | 5.08* | 7.46* | 3.71* | 3.8* | 3.7* | 3.84* | $2.29^{ns}$ |
| Sowing windows x Genotypes | 6 | 6.73* | 2.8* | 22.6* | 55.12* | 17.45* | 2.81* | 3.79* |
| | HTU | | | | | | | |
| Sowing windows | 3 | 41.84* | 22.15* | 29.12* | 26.09* | 102.58* | 155.81* | 20.79* |
| Genotypes | 2 | 63.18* | 39.24* | 195.97* | 268.92* | 114.54* | 9.45* | 80.08* |
| Sowing windows x Genotypes | 6 | 3.41* | 11.86* | 25.98* | 18.93* | 64.92* | 31.77* | 2.81* |
| | PTI | | | | | | | |
| Sowing windows | 3 | 20.25* | 11.59* | 17.02* | 8.77* | 26.68* | 12.53* | 9.89* |
| Genotypes | 2 | 12.47* | 5.42* | 34.77* | 33.2* | 43.99* | 3.66* | 58.12* |
| Sowing windows x Genotypes | 6 | $0.46^{ns}$ | 2.86* | 3.01* | 4.43* | 2.81* | 3.2* | 2.8* |

* Significant at 0.05 probability level; ns: non-significant; $P_1$: Emergence to initiation of primary branches; $P_2$: Initiation of primary branches to initiation of secondary branches; $P_3$: initiation of secondary branches to flower bud initiation; $P_4$: flower bud initiation to 50% flowering; $P_5$: 50% flowering to 50% podding; $P_6$: 50% podding to physiological maturity; AGDD: Accumulated growing degree day; APTU: Accumulated photo-thermal unit; AHTU: Accumulated helio-thermal unit; APTI: Accumulated photo-thermal index

**Table 2:** Combined Analysis of Variance (F values) for agrometeorological efficiencies

| Source of variation | df | HUE | PTUE | HTUE |
|---|---|---|---|---|
| Sowing windows | 3 | 21.57* | 21.75* | 21.99* |
| Genotypes | 2 | 33.57* | 32.57* | 33.73* |
| Sowing windows x Genotypes | 6 | 3.41* | 4.29* | 3.2* |

HUE: Heat use efficiency; PTUE: Photo-thermal use efficiency; HTUE: Helio-thermal use efficiency; * significant at 5% probability level

**Table 3:** Growing degree day (GDD) of pigeonpea genotypes as influenced by the growing environments at different phenophases

| Treatments | GDD ($^0$C days) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | AGDD |
| **Sowing windows** | | | | | | | |
| $D_1$: First fortnight June | 619.0 | 500.8 | 537.9 | 347.3 | 473.5 | 753.9 | 3209.2 |
| $D_2$: Second fortnight June | 604.9 | 487.3 | 510.0 | 302.0 | 463.5 | 707.3 | 3074.6 |
| $D_3$: First fortnight July | 531.7 | 499.9 | 468.2 | 300.6 | 450.2 | 669.5 | 2943.3 |
| $D_4$: Second fortnight July | 522.9 | 443.8 | 474.2 | 319.4 | 443.3 | 673.5 | 2877.2 |
| **Genotypes** | | | | | | | |
| $G_1$: TS-3R | 542.1 | 467.6 | 456.9 | 289.9 | 423.4 | 688.0 | 2867.8 |
| $G_2$: GRG-152 | 588.7 | 499.1 | 508.2 | 318.8 | 461.1 | 720.0 | 3096.0 |
| $G_3$: GRG-811 | 578.1 | 482.1 | 527.6 | 343.3 | 488.3 | 695.2 | 3114.4 |
| | | | | | | | |
| **LSD (p=0.05)** | | | | | | | |
| *Sowing windows* | 28.7 | 27.2 | 27.4 | 25.4 | 20.2 | 38.2 | 154.9 |
| *Genotypes* | 23.5 | 20.3 | 18.6 | 13.9 | 16.3 | 26.4 | 46.4 |
| *Sowing windows x Genotypes* | 46.9 | 40.7 | 37.1 | 27.8 | 32.5 | 52.8 | 92.9 |

$P_1$: Emergence to initiation of primary branches; $P_2$: Initiation of primary branches to initiation of secondary branches; $P_3$: initiation of secondary branches to flower bud initiation; $P_4$: flower bud initiation to 50% flowering; $P_5$: 50% flowering to 50% podding; $P_6$: 50% podding to physiological maturity; AGDD: Accumulated growing degree day

**Table 4:** Photo-thermal unit (PTU) of pigeonpea genotypes influenced by the growing environments at different phonological stages

| Treatments | PTU ($^0$C day hrs) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | APTU |
| **Sowing windows** | | | | | | | |
| $D_1$: First fortnight June | 7427.8 | 6009.2 | 6454.9 | 4168.1 | 6022.1 | 9047.3 | 38430 |
| $D_2$: Second fortnight June | 7259.2 | 5847.6 | 6120.4 | 3623.4 | 5677.3 | 8487.3 | 36898 |
| $D_3$: First fortnight July | 6380.3 | 5998.2 | 5618.2 | 3607.2 | 5358.7 | 8034.4 | 35320 |
| $D_4$: Second fortnight July | 6275.2 | 5325.8 | 5690.4 | 3832.6 | 4907.8 | 8082.1 | 34526 |
| **Genotypes** | | | | | | | |
| $G_1$: TS-3R | 6505.2 | 5610.8 | 5483.2 | 3478.8 | 5356.7 | 8255.5 | 34373 |
| $G_2$: GRG-152 | 7065.0 | 5989.4 | 6098.4 | 3825.2 | 5514.1 | 8640.5 | 37200 |
| $G_3$: GRG-811 | 6936.7 | 5785.5 | 6331.4 | 4119.6 | 5603.6 | 8342.4 | 37308 |
| **LSD (p=0.05)** | | | | | | | |
| Sowing windows | 344.7 | 326.8 | 328.3 | 305.3 | 317.6 | 458.9 | 1907 |
| Genotypes | 281.5 | 244.1 | 222.8 | 166.9 | 56.5 | 316.6 | 654 |
| Sowing windows x Genotypes | 563.1 | 488.2 | 445.6 | 333.8 | 113.0 | 633.3 | 1309 |

$P_1$: Emergence to initiation of primary branches; $P_2$: Initiation of primary branches to initiation of secondary branches; $P_3$: initiation of secondary branches to flower bud initiation; $P_4$: flower bud initiation to 50% flowering; $P_5$: 50% flowering to 50% podding; $P_6$: 50% podding to physiological maturity; APTU: Accumulated photo-thermal unit

**Table 5:** Photo-thermal index (PTI) of pigeonpea genotypes as influenced by the growing environments at different phonological stages

| Treatments | PTI ($^0$C days day$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | APTI |
| **Sowing windows** | | | | | | | |
| $D_1$: First fortnight June | 20.42 | 19.53 | 19.25 | 19.75 | 20.74 | 20.77 | 120.47 |
| $D_2$: Second fortnight June | 19.21 | 19.49 | 18.88 | 18.86 | 21.70 | 19.84 | 117.99 |
| $D_3$: First fortnight July | 18.54 | 19.48 | 18.97 | 19.99 | 21.85 | 19.31 | 118.14 |
| $D_4$: Second fortnight July | 19.13 | 18.00 | 19.47 | 21.71 | 20.79 | 19.99 | 119.09 |
| **Genotypes** | | | | | | | |
| $G_1$: TS-3R | 19.60 | 19.48 | 19.21 | 19.96 | 21.17 | 20.36 | 119.77 |
| $G_2$: GRG-152 | 19.63 | 19.39 | 19.01 | 20.00 | 21.19 | 20.01 | 119.22 |
| $G_3$: GRG-811 | 18.75 | 18.53 | 19.21 | 20.28 | 21.45 | 19.57 | 117.78 |
| | | | | | | | |
| LSD (*p=0.05*) | | | | | | | |
| Sowing windows | 0.75 | 1.08 | 0.43 | 1.57 | 0.92 | 0.95 | NS |
| Genotypes | 0.72 | 0.58 | 0.18 | 0.26 | 0.25 | 0.61 | NS |
| Sowing windows x Genotypes | 1.43 | 1.15 | 0.37 | 0.52 | 0.50 | 1.22 | 4.08 |

$P_1$: Emergence to initiation of primary branches; $P_2$: Initiation of primary branches to initiation of secondary branches; $P_3$: initiation of secondary branches to flower bud initiation; $P_4$: flower bud initiation to 50% flowering; $P_5$: 50% flowering to 50% podding; $P_6$: 50% podding to physiological maturity; APTI: Accumulated photo-thermal index

**Table 6:** Helio-thermal unit (HTU) of pigeonpea genotypes influenced by the growing environments at different phonological stages

| Treatments | HTU ($^0$C day hrs) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | AHTU |
| **Sowing windows** | | | | | | | |
| $D_1$: First fortnight June | 2133 | 2127 | 2120 | 1951 | 2751 | 5458 | 16540 |
| $D_2$: Second fortnight June | 2024 | 2310 | 1769 | 1815 | 3113 | 4869 | 15901 |
| $D_3$: First fortnight July | 1414 | 2639 | 1722 | 1728 | 3371 | 4207 | 15081 |
| $D_4$: Second fortnight July | 1593 | 2151 | 1871 | 1783 | 3506 | 3989 | 14893 |
| **Genotypes** | | | | | | | |
| $G_1$: TS-3R | 1704 | 2195 | 1748 | 1640 | 2906 | 4625 | 14817 |
| $G_2$: GRG-152 | 1838 | 2397 | 1889 | 1841 | 3191 | 4744 | 15900 |
| $G_3$: GRG-811 | 1831 | 2329 | 1975 | 1977 | 3460 | 4523 | 16095 |
| **LSD (p=0.05)** | | | | | | | |
| Sowing windows | 104 | 134 | 103 | 142 | 152 | 245 | 815 |
| *Genotypes* | 77 | 95 | 70 | 79 | 109 | 173 | 169 |
| *Sowing windows x Genotypes* | 154 | 190 | 139 | 157 | 219 | 345 | 338 |

$P_1$: Emergence to initiation of primary branches; $P_2$: Initiation of primary branches to initiation of secondary branches; $P_3$: initiation of secondary branches to flower bud initiation; $P_4$: flower bud initiation to 50% flowering; $P_5$: 50% flowering to 50% podding; $P_6$: 50% podding to physiological maturity; AHTU: Accumulated helio-thermal unit

**Table 7:** Heat use efficiency (HUE), helio-thermal use efficiency (HTUE) and photo-thermal use efficiency (PTUE) of pigeonpea genotypes influenced by the growing environments at different phonological stages

| Treatments | HUE (kg ha$^{-1}$ $^0$C day) | HTUE (kg ha$^{-1}$ $^0$C days$^{-1}$ hrs$^{-1}$) | PTUE (kg ha$^{-1}$ $^0$C days$^{-1}$ hrs$^{-1}$) |
|---|---|---|---|
| **Sowing windows** | | | |
| $D_1$: First fortnight June | 0.480 | 0.093 | 0.040 |
| $D_2$: Second fortnight June | 0.500 | 0.097 | 0.042 |
| $D_3$: First fortnight July | 0.472 | 0.092 | 0.039 |
| $D_4$: Second fortnight July | 0.416 | 0.080 | 0.035 |
| **Genotypes** | | | |
| $G_1$: TS-3R | 0.507 | 0.098 | 0.042 |
| $G_2$: GRG-152 | 0.459 | 0.089 | 0.038 |
| $G_3$: GRG-811 | 0.434 | 0.084 | 0.036 |
| **LSD (p=0.05)** | | | |
| Sowing windows | 0.027 | 0.005 | 0.002 |
| Genotypes | 0.019 | 0.004 | 0.002 |
| Sowing windows x Genotypes | 0.038 | 0.007 | 0.003 |

**Table 8:** Correlation coefficients of agrometeorological indices and efficiencies with seed yield and biological yield

| Parameters | Seed yield | Biological yield |
|---|---|---|
| GDD | 0.483 ns | 0.735** |
| PTU | 0.487ns | 0.734** |
| PTI | 0.168 ns | 0.171 ns |
| HTU | 0.443 ns | 0.726** |
| HUE | 0.844** | 0.583* |
| HTUE | 0.859** | 0.592* |
| PTUE | 0.846** | 0.587* |

*Significant at 5% probability level; **Significant at 1% probability level; ns: non-significant; HUE: Heat use efficiency; PTUE: Photo-thermal use efficiency; HTUE: Helio-thermal use efficiency

## Conclusion

The significant impact of sowing windows is a major factor for higher production of rainfed pigeonpea. Early sowing pigeonpea accumulated higher agrometeorological indices and efficiency than delayed one. Among the genotypes GRG-811 accumulated higher GDD than other two genotypes. The best period for sowing of pigeonpea crop was first and second fortnight of June, while any delayed sowing may cause yield loss and lesser accumulation of heat units. Hence, sowing windows and selection of genotypes are found to be the critical factors for pigeonpea production.

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