



RESEARCH ARTICLE

# Thermal utilization of finger millet [*Eleusine coracana* (L.) Gaertn.] cultivars under different sowing dates

S R Swain, B Patra\*, J K Nayak, S Mallick, T Audhya, A N Nayak, A Mishra & S Nayak

Department of Agronomy, Faculty of Agricultural Sciences (FAS), Siksha 'O' Anusandhan Deemed to be University (SOADU), Bhubaneswar 751 003, Odisha, India

\*Correspondence email - [bishnupriyapatra@soa.ac.in](mailto:bishnupriyapatra@soa.ac.in)

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## Abstract

A field study was carried out at the Agricultural Research Station (ARS), Binjhagiri, Chhatabar, SOADU, Bhubaneswar, during the kharif season. The experiment consisted of 3 dates of sowing with 15-day interval allocated to the main plots and 4 finger millet varieties i.e., Arjuna, Kalua, Bhairabi, Shreeratna in sub plots under split-plot design with 3 replications. The 24 June sown finger millet crop showed minimum days for achieving phenology, robust growth with a higher leaf area index (LAI) (4.55) at 60 DAS while maximum number of tillers per hill (9.3) was recorded in 24 July sown crop in 90 DAS. The 24 June sown crop gave maximum grain yield (2193 kg/ha), straw yield (3672 kg/ha), total uptake (41.9, 11.1, 66.7 N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O kg/ha), GDD (2125.4 °C day), net return (₹57230/ha) and B.C. ratio (1.9). Number of tillers per hill (10.1), LAI (4.42) at 60 DAS and days to maturity (112.4 days) recorded maximum in Shreeratna variety and lowest growth parameters were observed in Kalua variety. Grain yield (2182 kg/ha), straw yield (3587 kg/ha), total uptake, HUE, GDD (2104.9 °C day), net return (₹56585/ha) and B.C ratio (1.8) were significantly higher in Shreeratna variety. The Shreeratna variety sown on 24 June produced significantly maximum yield (2569 kg/ha & 4040 kg/ha in grain and straw respectively), nutrient uptake (47.9, 12.5, 73.6 N, P<sub>2</sub>O<sub>5</sub>, K<sub>2</sub>O kg/ha) and a net return of ₹71737/ha.

**Keywords:** B:C ratio; date of sowing; finger millet; GDD; grain yield; HTU; HUE; net returns; PTI; PTU

## Introduction

Agriculture is considered the world's primary food source, introduced around 9500 BC. Over half of India's population makes their living either directly or indirectly from the agricultural industry. Any kind of fluctuations in the agricultural sector can have a grave impact on the whole economy. Weather plays a prominent role in the planning of agricultural activities. Since agriculture is very sensitive to weather conditions, agro-meteorological information is essential in crop production planning. Weather parameters like temperature, humidity, sunshine, wind and rainfall play a major role in controlling most key biological processes in plants, like photosynthesis, respiration and transpiration. Nutri-cereals have gained attention due to their inherent quality of early maturity, capacity to yield even under poor soil, drought and low management conditions. The combined potential of the millets as both resilient crops for resource-constrained farmers and as a nutritious foodstuff for growing populations made them to be considered as nutri-cereals in the world of an escalating malnutrition population and play a major role in the nutritional security. Among the different millets, finger millet is reported to have the highest productivity of 1591 kg/ha, followed by pearl millet with 1130 kg/ha (1). Finger millet is a small-seeded, self-pollinated, robust, tufted and tillering annual cereal crop. The crop is also adapted to a wide range of tropical soils, ranging from red lateritic to sandy loams and black heavy vertisols. It is cultivated in more than 25 countries in the world.

With an estimated global annual planting area of 4–4.5 million hectares and a total production of 5 million tonnes of grains, finger millet plays a pivotal role in ensuring food security and sustenance for millions of people (2). In India, finger millet is primarily grown in the states of Karnataka, Andhra Pradesh, Tamil Nadu, Kerala, Telangana, Uttarakhand, Maharashtra, Odisha, Jharkhand, Madhya Pradesh and Haryana. According to a recent report, in India, finger millet's production is about 85 % amongst all other millets and is cultivated on an acreage of 1.19 million hectares accounting for about 2.2 million tonnes of total production and productivity of 1.6 t/ha while Africa follows closely, producing about 2 million tonnes (2, 3). Finger millet can withstand 3 challenges i.e., warming stress, water stress and nutritional stress so it is called a climate change compliant crop. Although it prefers fertile, easily drained sandy to sandy loam soils with a pH between 5 and 7, it can adapt to a wide range of environmental variables and is well known for its ability to endure drought. It is a crucial crop in areas that are prone to drought because of its exceptional capacity to tolerate unfavourable weather conditions (4). The nutritional value of finger millet are very high compared to most of the other cereals. It indeed plays a vital role in providing quality nutrition to the human race. The protein of ragi is "biologically complete". It is equivalent to rice in terms of protein (6–8 %) and fat (1–2 %), but it outperforms rice and wheat in terms of mineral and micronutrient levels (5). Finger millet has a calcium content of 344 mg/100 g, which is the highest among all cereals (6). Isoleucine, leucine, methionine and phenylalanine are

the main amino acids found in these small millets and are lacking in other starchy foods. Its polyphenol and dietary fibre concentrations are primarily responsible for its numerous health advantages, which include anti-diabetic, anti-tumorigenic, atherosclerogenic and antioxidant properties (7). Finger millet is the most important among millets grown in Odisha. Ragi cultivation in Odisha covered 1.14 lakh hectares in 2017–18 and this area has expanded to 1.79 lakh hectares in 2022–23 and ragi production in Odisha increased from 127.8 thousand tonnes in 2018–19 to 150.56, 159.76 and 226 thousand tonnes in 2019–20, 2020–21 and 2022–23, respectively. The productivity of finger millet in Odisha increased from 880 kg/ha in 2017–18 to 1268 kg/ha in 2022–23. Odisha ranked 2<sup>nd</sup> among Indian states in terms of area of ragi cultivation and production after Karnataka (8). Among millets, finger millet ranks the 1<sup>st</sup> in area and production (9). However, a major problem in different regions of India is determining the optimum date of sowing. A crop that is seeded on time benefits from favorable climatic circumstances throughout its phenological phases, which enhances crop production. This in turn is closely associated with soil preparation, which has a critical effect on seed germination, moisture and nutrient availability. Through a comprehensive analysis of agronomic practices and climate variability, this research seeks to provide valuable insights for policymakers, farmers and stakeholders in enhancing the sustainability of finger millet cultivation in the kharif season. A key element in raising millets' production is the choice of an appropriate variety. To obtain sustainable yields, it is crucial to grow cultivars that are short-duration, moderate in height, drought-resistant and have an exceptional producing capability. The effect of interaction between the weather parameters (photoperiodic effect in terms of sowing date) and finger millet varieties remains unexplored in terms of growth and yield, hence the present study was taken up, to assess the thermal utilization efficiency of different finger millet [*Eleusine coracana* (L.) Gaertn.] cultivars under varying sowing dates and to determine how temperature-based indices (GDD, HTU, PTU, etc.) influence their phenology, growth and yield.

## Materials and Methods

### Study site description

The present experiment was laid out at the ARS, Faculty of Agricultural Sciences, SOADU, Binjhagiri, Chhatabar, Khordha, Odisha, during the kharif season of 2023. The climate of the site is characterized by a hot, humid and sub-humid climate with a hot summer. During the cropping period, the maximum temperature of 37.7 °C was recorded in the 25<sup>th</sup> SMW (19<sup>th</sup> June 2023–25<sup>th</sup> June 2023) and the minimum temperature of 20.4 °C was recorded in 46<sup>th</sup> SMW (13<sup>th</sup> November 2023–19<sup>th</sup> November 2023) (Fig. 1). The data indicated that the maximum rainfall of 301.7 mm was recorded during the 31<sup>st</sup> SMW (31<sup>st</sup> July 2023–6<sup>th</sup> August 2023), whereas no rainfall was received in several weeks. The sandy loam soil at the experimental location had an EC value of 0.015 dS/m, was acidic in reaction (pH value: 5.45), moderate in organic carbon (0.61 %) and had a modest amount of available N (203.04 kg/ha), available P (21.1 kg/ha) and available K (178 kg/ha).

### Experimental details and management

The experiment consisted of 12 treatment combinations, which consisted of 3 dates of sowing, viz., D<sub>1</sub>- 24 June, D<sub>2</sub>-9 July, D<sub>3</sub>- 24 July, allocated to the main plots and 4 finger millet varieties i.e., V<sub>1</sub>-Arjuna, V<sub>2</sub>-Kalua, V<sub>3</sub>-Bhairabi, V<sub>4</sub>-Shreeratna in sub plots under split-plot design with 3 replications. Direct sowing of different cultivars of finger millet was done on 24 June, 9 July and 24 July 2023, with an interval of 15 days. Finger millet is known for climate resilience; varying sowing dates help identify genotypes that perform best under delayed or erratic rainfall, a key adaptation strategy. Sowing was done as per the treatments and after 10–15 DAS, thinning and gap filling were done to maintain a spacing of 22.5 cm x 10 cm. The recommended dose of 60 kg N/ha, 30 kg P<sub>2</sub>O<sub>5</sub>/ha, 30 kg K<sub>2</sub>O/ha was applied. Full P<sub>2</sub>O<sub>5</sub> and 75 % K<sub>2</sub>O were applied as a basal dose in the form of single super phosphate and muriate of potash; another 25 % K<sub>2</sub>O was applied at the PI stage. Nitrogen was applied as urea in 2 equal splits, i.e., half at the time of sowing and the remaining half in two top dressings 20–25 DAS (after weeding). Pre-emergence application of weedicide Pendimethalin was done at 0.75 kg/ha a.i.

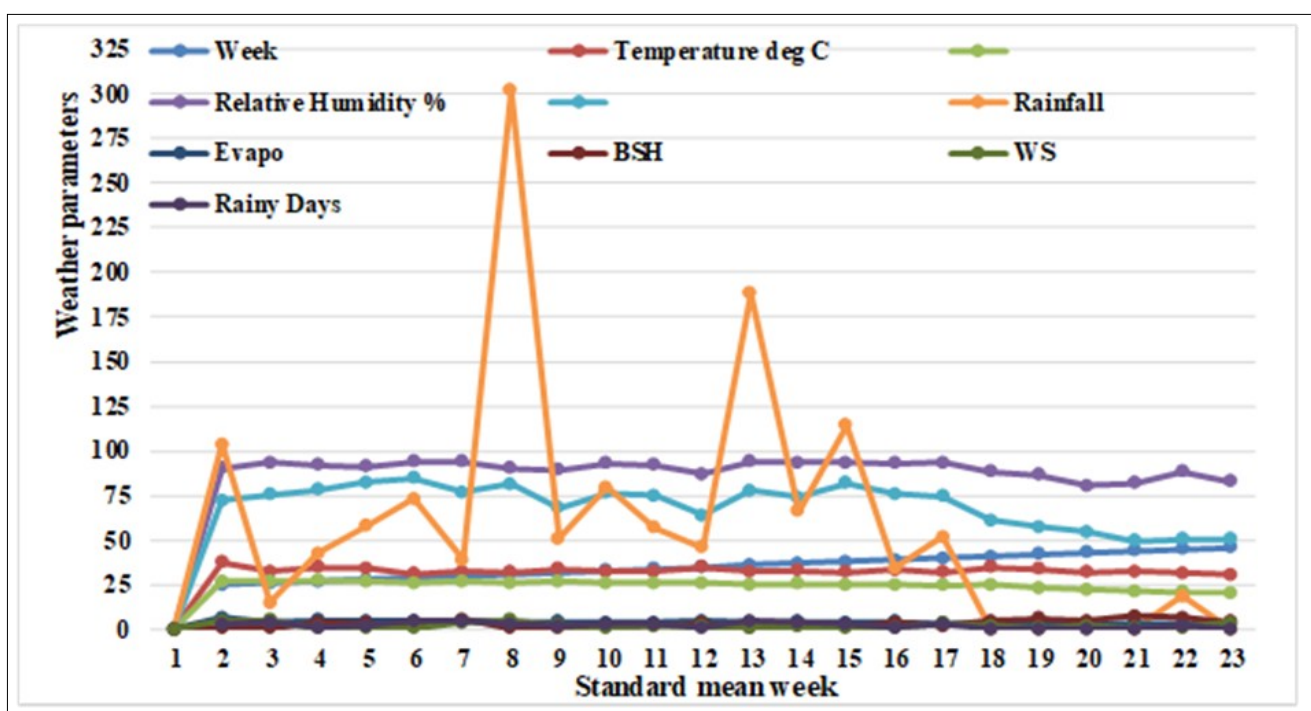


Fig. 1. Standard meteorological week weather data during the crop growing season (kharif, 2023).

at 2 DAS to effectively control the emerging weeds, at 20–25 days after sowing, one hand weeding was carried out. Need-based irrigation was provided during prolonged dry spells.

### Plant sampling and analysis

Data on several phenological parameters, growth parameters, thermal indices and yield parameters were recorded at various stages of the crop. Phenological stages were observed visually and the days taken to reach the phenological stages were calculated. The plant height of tagged plants was measured from the ground surface to the tip of the panicle periodically. Plants from one hill (finger millet) per plot, representing the whole plot, were pulled from the ground. After separating the leaf blades from the shoot, the whole area was determined manually, then LAI, which is also the ratio of the area of the surface of green leaves to the area of the ground covered, was calculated.

The crop was harvested with the attainment of maturity as per the respective dates of sowing. After threshing work, the grain yield was measured for each net plot area. Then it was converted into kg/ha. The harvest index for each plot was calculated by dividing the total grain yield (economic yield) by the total biological yield (grain + straw) and multiplying by 100 as given below (10).

$$\text{Harvest index} = \frac{\text{Economical yield}}{\text{Biological yield}} \times 100$$

Meteorological data, viz., rainfall (mm), maximum and minimum relative humidity (%), maximum and minimum temperature (°C), duration of bright sunshine (hr), wind speed (km/hr), etc., during the crop season were recorded in the meteorological observatory of OUAT, Bhubaneswar. The following agro-meteorological indices were computed using the daily meteorological data:-

### Growing degree days (GDD)

The daily mean temperature above the base temperature was added up and represented in degree days to calculate average GDD. This was determined by using the following formula (11, 12).

$$\text{GDD} = \sum \frac{(T_{\max} + T_{\min})}{2} - T_{\text{base}}$$

Where,

$T_{\text{base}}$  = Minimum threshold/base temperature (°C),

$T_{\max}$  = Daily maximum temperature (°C),

$T_{\min}$  = Daily minimum temperature (°C)

### Helio-thermal units (HTU), degree day hr

The sum of HTU for particular phenophases of interest was determined according to the equation:

$$\text{HTU} = \sum \{\text{GDD} \times \text{BSS} (n)\}$$

Where,

GDD = growing degree days, BSS (n) = bright sunshine hours (hr)

### Photothermal units (PTU), degree day hr

This can be mathematically represented using the following formula:

$$\text{PTU} = \sum (\text{GDD} \times N)$$

Where,

GDD = Growing degree days, N = Maximum possible sunshine hours or day length (hr)

### Heat use efficiency (HUE)

Heat use efficiency indicates the amount of dry matter produced per unit of GDD or thermal time. This was computed by using the following formula:

$$\text{HUE} (\text{g/m}^2/\text{°C day}) = \text{Biomass} (\text{g/m}^2) / \text{GDD} (\text{°C day})$$

### Phenothermal index (PTI)

The GDD attained per day needed to reach that specific phenological stage is represented by the pheno-thermal index of phenological indices according to the equation:

$$\text{Pheno-thermal index (PTI)} = \sum (\text{GDD} \div \text{Growth days})$$

### Statistical analysis

The experimental data for various parameters were statistically analyzed by the methods of analysis of variance (ANOVA) (13). The significance of treatment effects was computed with the help of the 'F' (variance ratio) test and to judge the significance of differences between means of two treatments, critical differences (CD) were worked out as described by (14):

$$\text{CD} = \sqrt{(\text{EMS} \times 2) \div n} \times t - \text{value for error d.f at 5\% level of significance}$$

Where,

CD = Critical difference

n = Number of observations of that factor for which CD is to be calculated.

t = Value of Fisher's table for the error degree of freedom at 5 % level of significance.

## Results and Discussion

### Phenological parameters

Phenological parameters help to optimize crop production and predict when to plant, fertilize, critical stages of irrigation and weed management and finally harvest the crop.

Phenological observations of finger millet recorded at 5 stages of growth, viz., days to germination, active tillering, earhead emergence, 50 % flowering and maturity were significantly influenced by different dates of sowing and varieties (Table 1).

Among the dates of sowing, the 24 June sown finger millet crop took minimum days for emergence (2.5 days), active tillering stage (45 days), earhead emergence (56 days), while 50 % flowering (84 days) and maturity (112 days) are achieved late, rather than other dates of sowing. This might be because sowing occurs when temperature is cooler, the crop accumulates heat units slowly leading to longer vegetative and reproductive phases. Flowering and maturity (107 days) were achieved early by the 9 July sown crop. The reason behind the 9 July sown crop showing earlier 50 % flowering (79 days) might be due to faster heat unit accumulation crop develop faster, probably due to more variation in day and night temperatures during the early vegetative stage and a reduced number of tillers and promoted early panicle initiation, thereby reducing growing season length (shortening stages like tillering, flowering and grain filling) and causing a reduction in finger millet yields. The reason behind the difference in duration of different

**Table 1.** Phenological parameters of finger millet at different growth stages as influenced by different dates of sowing and varieties (DAS)

Treatment	Emergence	Active tillering stage	Earhead emergence	50 % flowering	Maturity
<b>Date of sowing</b>					
24 June	2.5	44.8	56.1	83.7	111.7
9 July	3.8	45.4	62.0	79.3	107.0
24 July	3.3	44.9	60.3	82.2	110.2
SEm (+)	0.13	0.46	0.56	0.33	0.38
CD at 5 %	0.5	NS	2.2	1.3	1.5
<b>Variety</b>					
Arjuna	2.9	44.0	57.4	82.1	108.7
Kalua	3.8	46.7	63.3	80.7	110.0
Bhairabi	3.3	44.3	59.1	80.9	107.3
Shreeratna	2.7	45.1	58.0	83.2	112.4
SEm (+)	0.21	0.51	0.58	0.47	0.41
CD at 5%	0.6	1.5	1.7	1.4	1.2

NS: Non significant; SEm ( $\pm$ ): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

phenological stages might be that the weather or environmental conditions experienced by the crop planted on different dates, especially in terms of temperature, photoperiod, solar radiation and moisture were not the same. These conditions directly influence the rate of physiological and phenological development, leading to variations in the duration of each growth stage. Similar findings were previously reported (4, 15–17).

Among the cultivars, Shreeratna took the maximum days to mature (112.4 days) followed by Kalua (110 days). Shreeratna followed by Arjuna achieved early earhead emergence (avg. 57 days) and an average of 25 days gap between earhead emergence to 50 % flowering while other varieties have a minimum difference between earhead emergence to 50 % flowering. The difference in days to earhead emergence, days to 50 % flowering and days to maturity among the cultivars might be due to the genotypic characters, physiological factors, GDD and their adaptability to agro-climatic conditions. Similar results were also reported (18–22).

### Growth parameters

#### Tillers per hill

The number of tillers per hill of finger millet was significantly influenced by different dates of sowing and varieties (Table 2).

The average number of tillers per hill was 3.73 and 8.53 at 60 and 90 DAS respectively. Tillers count per hill were found to be more at 24 July sown crops (9.3) at 90 DAS, followed by 24 June crop (8.5) and the least number of tillers was found on 9 July sowing condition (7.8). Average rate of increase in number of tillers per hill of finger millet at 90 DAS was 19.2 % in the 24 July sown crop over the 9 July sown condition. This may be due to the climatic conditions during

**Table 2.** Number of tillers per hill of finger millet as influenced by different dates of sowing and varieties

Treatment	60 DAS	90 DAS
<b>Date of sowing</b>		
24 June	4.3	8.5
9 July	3.4	7.8
24 July	3.5	9.3
SEm (+)	0.09	0.13
CD at 5%	0.4	0.5
<b>Variety</b>		
Arjuna	3.7	9.1
Kalua	4.0	7.7
Bhairabi	3.3	7.3
Shreeratna	3.9	10.1
SEm (+)	0.15	0.24
CD at 5%	0.4	0.7

SEm ( $\pm$ ): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

the vegetative growth with proper availability of moisture as well as microenvironment which may result in more nutrient absorption by the roots for the synthesis of protoplasm responsible for rapid cell division; thereby, it may result in an increase in the plant shape and size and ultimately the production of tillers. Similar results were also reported (4, 23–25).

Among the varieties, the highest number of tillers per hill of finger millet was observed in the case of Shreeratna variety (10.1), followed by Arjuna (9.1) and the least number of tillers was found in Bhairabi variety (7.3). The average rate of increase in the number of tillers per hill by Shreeratna was 38.3 % over the Bhairabi variety. Integrated effect of cultivar and date of sowing on the number of tillers at 90 DAS showed that Shreeratna variety with 24 July date of sowing produced the maximum number of tillers, followed by Arjuna with 24 July date of sowing; both are similar to each other but significantly better over other varieties in combination with different dates of sowing (Table 3). This may be due to the genetic competency of the Shreeratna variety over other varieties respectively. These results were in line with earlier reports (4, 16, 18,

**Table 3.** Number of tillers per hill of finger millet as influenced by integrated effect of dates of sowing and varieties

Treatment	Arjuna	Kalua	Bhairabi	Shreeratna
<b>Date of sowing</b>				
24 June	8.83	7.47	7.17	10.60
9 July	8.00	7.53	7.20	8.37
24 July	10.37	8.10	7.50	11.23
SEm ( $\pm$ )	0.398			
CD at 5 %	1.23			

SEm ( $\pm$ ): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

19, 26 & 27).

#### Leaf area index

LAI of finger millet at different stages of growth was significantly influenced by different dates of sowing and varieties (Table 4).

The LAI of finger millet increased with the advancement of crop age, reaching a peak value at 60 DAS and decreased thereafter till maturity. This might be due to the increase in leaf expansion from initial to mid growth stages of plant growth, thereafter, due to tiller mortality, LAI decreased (28). Average LAI was 0.70, 4.14, 3.05, 2.07 at 30, 60, 90 DAS and at the maturity stage respectively. LAI in 24 June sown crop (4.55) at 60 DAS was found to be significantly higher than other dates of sowing, followed by 24 July crop (4.14) and the lowest LAI was observed on 9 July sown condition (3.74). 24 June sown crop gave a 21.7 % increase in LAI over the 9 July crop. The reason behind

**Table 4.** LAI of finger millet as influenced by different dates of sowing and varieties

Treatment	30 DAS	60 DAS	90 DAS	Maturity
<b>Date of sowing</b>				
24 June	0.78	4.55	3.18	2.19
9 July	0.63	3.74	2.94	1.91
24 July	0.71	4.14	3.03	2.13
SEm (+)	0.013	0.088	0.020	0.022
CD at 5 %	0.05	0.34	0.08	0.09
<b>Variety</b>				
Arjuna	0.73	4.20	3.22	2.27
Kalua	0.61	3.90	2.55	1.56
Bhairabi	0.69	4.06	3.00	2.01
Shreeratna	0.79	4.42	3.43	2.46
SEm (+)	0.013	0.053	0.012	0.017
CD at 5 %	0.04	0.16	0.04	0.05

SEm ( $\pm$ ): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

24 June sown crop having higher LAI might be due to favourable climatic conditions viz., temperature and availability of moisture resulted in more leaf area indicating higher chlorophyll area improving photosynthetic efficiency of the plant, for synthesis of growth favouring constituents in the plant system which induced tiller and leaves formation, which increased the number of leaves per unit area and ultimately LAI. Similar findings were reported earlier (4, 23-25, 28 & 29).

Among varieties, the LAI of Shreeratna variety (4.42) at 60 DAS was found to be significantly higher than other varieties followed by Arjuna and Bhairabi. The lowest LAI was observed in the Kalua variety (3.90). Average rate of increase in LAI by Shreeratna was 13.3 % over Kalua variety. The finger millet being a  $C_4$  crop has a higher photosynthetic rate and it is not a limitation in this variety as the tiller producing ability of this variety is more. The reason could be that the better ability of the Shreeratna variety in the uptake of nutrients as well as photosynthetic efficiency leads to a high number of tillers and expansion of more leaves, as a result of which a higher LAI is recorded. Similar findings were previously reported (1, 4, 19, 24, 30).

## Yield

### Grain and straw yield

Grain and straw yield of finger millet was significantly influenced by different dates of sowing and varieties (Table 5). The 24 June sown

**Table 5.** Yield and Economics of finger millet is influenced by different dates of sowing and varieties

Treatment	Grain yield (kg/ha)	Straw yield (kg/ha)	Net returns (Rs/ha)	B:C ratio
<b>Date of sowing</b>				
24 June	2193	3672	57230	1.9
9 July	1325	2642	23793	0.8
24 July	1861	3293	44592	1.5
SEm (+)	56.2	106.9	2084.0	0.06
CD at 5 %	221	419	8182	0.2
<b>Variety</b>				
Arjuna	2054	3297	51810	1.7
Kalua	1258	2801	21552	0.7
Bhairabi	1678	3124	37541	1.2
Shreeratna	2182	3587	56585	1.8
SEm (+)	67.2	108.6	2436.6	0.07
CD at 5 %	200	322	7239	0.2

SEm ( $\pm$ ): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

crop gave highest grain yield (2193 kg/ha) and straw yield (3672 kg/ha) which was significantly higher than other date of sowing followed by 24 July sown crop (1861 kg/ha, 3293 kg/ha). The lowest grain yield was obtained by 9 July sown condition (1325 kg/ha). The 24 June sown crops gave 65.5 and 38.9 % more grain yield over the 9 July crop. Lower yield in the 9 July sown crop as compared to 24 June and 24 July might be due to the changes in weather and soil conditions, especially, in temperature at the time of flowering and pollination that are enough to cause an adverse effect on the development of spikelets due to direct effect of intense solar radiation on the experimental field as well as late germination and crop stand, leaf area and dry matter accumulation in the field. The crop that was sown on June 24 may have benefited from favourable weather circumstances with a longer photoperiod, which caused more assimilates to move towards the panicle and increased grain output. Similar findings were also reported (4, 18, 31-33).

Among varieties, the Shreeratna variety gave the highest grain yield (2182 kg/ha) and straw yield (3587 kg/ha), which was significantly higher than other varieties, followed by Arjuna (2054, 3297, 3124 kg/ha), followed by Bhairabi (1678 kg/ha). The rate of increase in grain and straw yield was 73.4 %, 63.2 %, 33.3 % and 28 %, 17.7 %, 11.5 % by Shreeratna, Arjuna, Bhairabi over Kalua variety respectively (Fig. 2). The genetic ability of the different varieties to use and carry photosynthates from source to sink is responsible for the variation in yields between them. Superiority of the variety Shreeratna for generating a higher number of tillers per plant had a good influence on the final yield of finger millet. The results of the present investigation agreed with previous findings (4, 21, 34-37). Integrated effect of Shreeratna with 24 June sowing gave a higher grain yield of 2569 kg/ha and straw yield accumulation (4040 kg/ha), followed by Arjuna sown on 24 June (2486 and 3873 kg/ha) (Fig. 3).

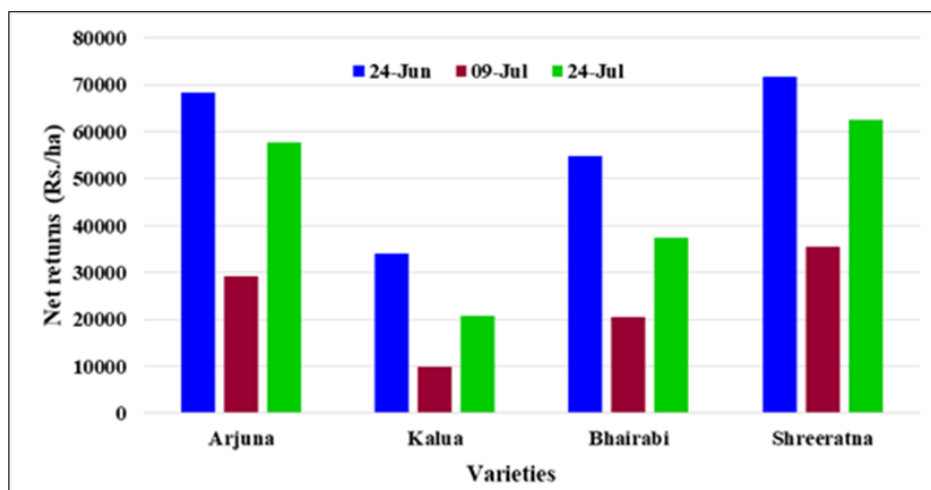
## Agro-meteorological indices

### Growing degree days ( $^{\circ}\text{C day}$ )

GDD required for different phenological stages of finger millet were significantly influenced by different dates of sowing and varieties (Table 6).

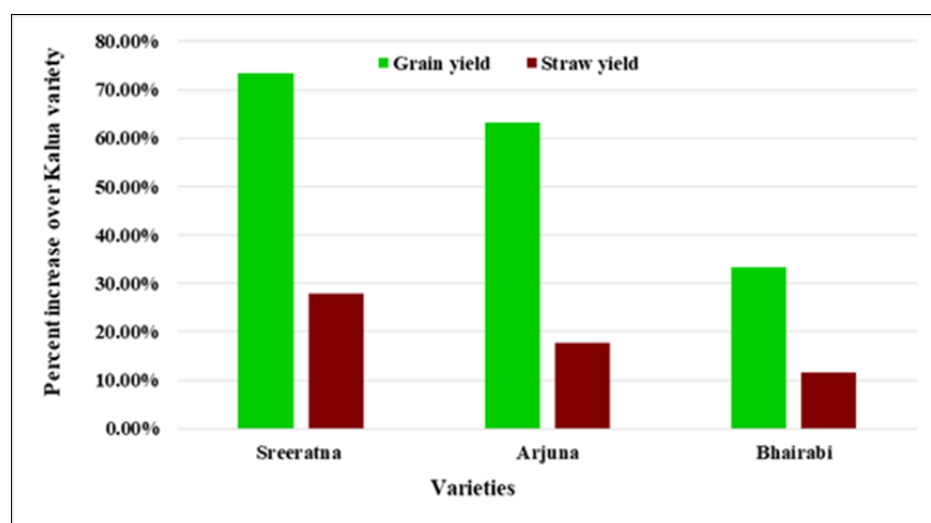
Based on the table, the lowest heat unit (GDD) requirement was observed at the emergence stage; thereafter, the accumulation of heat unit progressively increased up to maturity. This describes clearly the effect of temperature on different phenological stages. More heat units were utilized by the 9 July sown crop till earhead emergence, while from earhead emergence to maturity 24 June sown finger millet crop utilized more heat units. This indicates that there is a decrease in the mean heat load with a delay in sowing dates of finger millet (9 July). GDD is directly related to the duration and temperature observed within the time period of the crop and the crop with prolonged growth periods resulted in higher GDD. This might be a reason that compared to other crops, the early-planted crop on June 24 utilized more degree days to reach maturity. Moisture stress and higher temperatures during flowering decreased the period for grain filling and hastened plant senescence in late-planted crops (38, 39).

Among the varieties, Kalua utilised higher heat units till earhead emergence while Shreeratna utilised more heat units thereafter. This can be a reason that the Shreeratna variety, with a longer crop duration (117 days) was exposed to more temperature variation and registered the highest GDD among the other varieties.



**Fig. 2.** Integrated effect of date of sowing and varieties on net returns of finger millet.

X axis – Different varieties of finger millet sown on different dates, Y axis - Net returns (Rs/ha)



**Fig. 3.** Percent increase in grain yield and straw yield by different improved varieties over Kalua variety.

X axis - Different improved finger millet varieties over Kalua variety; Y axis - Percent increase in grain and straw yield over Kalua variety.

**Table 6.** GDD (°C day) of different phenological parameters of finger millet as influenced by different dates of sowing and varieties

Treatment	Emergence	Active tillering stage	Earhead emergence	50 % flowering	Maturity
<b>Date of sowing</b>					
24 June	42.0	850.1	1069.6	1589.3	2125.4
9 July	68.2	862.5	1179.0	1506.1	2026.9
24 July	61.1	826.9	1151.1	1574.2	2038.6
SEm (+)	2.51	7.81	10.74	6.71	5.66
CD at 5 %	9.8	30.6	42.1	26.3	22.2
<b>Variety</b>					
Arjuna	51.7	830.8	1095.0	1563.9	2049.5
Kalua	69.0	875.7	1205.1	1536.9	2073.1
Bhairabi	60.2	832.5	1126.8	1540.6	2027.1
Shreeratna	47.6	846.9	1105.9	1584.8	2104.9
SEm (+)	3.92	8.73	11.04	9.12	6.84
CD at 5 %	11.6	25.9	32.8	27.1	20.3

SEm (±): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

Similar results were previously recorded (8, 39–43).

#### Helio-thermal units (degree day hours)

HTU for various phenological stages in finger millet were significantly influenced by different dates of sowing and varieties (Table 7).

In general, the accumulation of HTU increased till the maturity of the crop. In the active tillering stage, the 24 June sown crop showed higher HTU, while till days to earhead emergence on 9 July showed higher HTU utilisation. However, 50 % flowering and

maturity resulted in higher HTU utilization by the 24 July sown crop. Requirement of HTU was 23.6 % less for maturity phases under 24 July sown crop as compared to 24 June sown condition. This might be due to the higher bright sunshine hours experienced during the maturity phases of the 24 July sown crop than the 24 June sown finger millet (44). Also, less HTU by the crops sown on July 9 might be due to the lower air temperature and fewer bright sunshine hours for a greater number of days prevailing under late sown conditions (39).

**Table 7.** HTU, PTU (degree day hours) of different phenological parameters of finger millet as influenced by different dates of sowing and varieties

Treatment	Helio-thermal unit (HTU)					Photo-thermal unit (PTU)				
	Emergence	Active tillering stage	Earhead emergence	50 % flowering	Maturity	Emergence	Active tillering stage	Earhead emergence	50 % flowering	Maturity
<b>Date of sowing</b>										
24 June	50.4	2163.1	2410.4	3676.1	5237.2	560.7	11220.2	14039.6	20543.0	26968.7
9 July	227.3	1974.0	2796.5	3569.1	5721.2	905.0	11232.7	15198.7	19194.8	25336.6
24 July	336.1	1988.8	2687.1	4031.9	6858.1	802.2	10603.0	14585.1	19628.2	24956.9
SEm (+)	9.36	12.74	22.20	27.75	28.49	33.32	99.97	129.56	79.90	65.71
CD at 5 %	36.7	50.0	87.1	108.9	111.8	130.8	392.5	508.6	313.6	257.9
<b>Variety</b>										
Arjuna	185.6	2007.7	2559.9	3778.5	5868.9	684.9	10819.9	14133.5	19879.0	25590.2
Kalua	251.7	2091.9	2778.5	3684.6	5987.8	912.3	11389.3	15501.2	19551.2	25865.6
Bhairabi	213.3	2025.7	2608.4	3697.8	5740.1	796.4	10841.0	14528.7	19597.4	25331.9
Shreeratna	167.7	2042.6	2578.5	3875.1	6158.5	630.2	11024.5	14267.7	20127.0	26228.6
SEm (+)	12.29	17.87	24.12	37.12	36.11	52.12	110.02	136.34	109.4	79.00
CD at 5 %	36.5	53.0	71.6	110.2	107.2	154.8	326.8	405.0	325.0	234.6

SEm ( $\pm$ ): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

Among the varieties, Kalua utilised higher HTU till earhead emergence while Shreeratna utilized more HTU from 50 % flowering to maturity. This might be due to a longer crop duration during which temperature fluctuation, along with bright sunshine hours, were found to be higher during maturity phases. The result is in line with those of earlier works (8, 39, 42, 43).

#### Photo-thermal unit (degree day hours)

Accumulation of PTU in different phenological stages of finger millet was significantly influenced by different dates of sowing and varieties (Table 7).

In general, the lowest value of PTU was observed in the emergence stage; thereafter, it increased with the advancement of crop growth stages and reached the maximum value at maturity. Accumulation of PTU was found to be higher in the 9 July sown finger millet crop till earhead emergence due to higher day length as well as extended phenophases during that period, while 50 % flowering to maturity showed higher accumulation of PTU in the 24 June sown finger millet crop, followed by 9 July sown crop. This might be due to a reduction in day length during maturity (October–November months) as well as fluctuation in temperature, which reduced PTU in the 9 July sown crop (44, 45).

Among the varieties, Kalua utilised higher PTU till earhead emergence, while Shreeratna utilised more PTU from 50 % flowering to maturity. Differences in the maturity dates of the different varieties might be the reason for variation in photothermal unit accumulated

values. PTU recorded in the study narrated the relationship between GDD and day length, where the Shreeratna variety had high PTU due to extended phenophases because of its genetic makeup and registered superior performance during 50 % flowering and maturing; thus the higher day length observed led to high PTU. Similar findings were previously reported (8, 39, 42, 43).

#### Phenothermal index (PTI)

PTI in different phenological stages of finger millet were significantly influenced by different dates of sowing and varieties (Table 8).

In general, PTI increased till earhead emergence. PTI was significantly higher at the emergence stage by 24 July sown crop while in all other stages 24 June finger millet crop showed higher PTI which was similar to that of 24 July sown crop. This might be due to reduced growth days to achieve a particular phenophase recorded with early sowing and the incidence of higher temperature during the vegetative stage and moderate temperature during the grain filling stage of the crop (46, 47).

Among the varieties, at emergence stage, Kalua observed higher PTI, while in all other stages, all 4 varieties showed a slight variation in PTI among each other. PTI recorded in the study narrated the relationship between GDD and growth days required to achieve particular phenological stages, where the Shreeratna variety, having extended phenophases showed less PTI and Kalua having less duration, observed high PTI. Similar findings were reported in previous works (8, 39, 42, 43).

#### Heat use efficiency (kg/ha°C/day) (HUE)

**Table 8.** PTI of different phenological parameters and HUE (kg/ha°C/day) of finger millet as influenced by different dates of sowing and varieties

Treatment	Phenothermal index					Heat use efficiency	
	Emergence	Active tillering stage	Earhead emergence	50 % flowering	Maturity	Biological yield	Grain yield
<b>Date of sowing</b>							
24 June	16.80	19.00	19.07	19.00	19.08	2.76	1.03
9 July	18.11	18.99	19.02	18.98	18.94	1.95	0.65
24 July	18.78	18.42	19.08	19.16	18.52	2.53	0.91
SEm (+)	0.049	0.041	0.004	0.004	0.008	0.077	0.029
CD at 5 %	0.19	0.15	0.01	0.01	0.03	0.30	0.11
<b>Variety</b>							
Arjuna	17.81	18.89	19.06	19.05	18.86	2.60	1.00
Kalua	18.08	18.76	19.03	19.05	18.85	1.95	0.60
Bhairabi	17.92	18.78	19.06	19.04	18.89	2.36	0.83
Shreeratna	17.77	18.77	19.07	19.04	18.79	2.73	1.03
SEm (+)	0.060	0.048	0.007	0.003	0.012	0.070	0.032
CD at 5 %	0.17	0.14	0.02	0.01	0.03	0.20	0.09

SEm ( $\pm$ ): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

HUE of finger millet was significantly influenced by different dates of sowing and varieties (Table 8).

Higher heat use efficiency was observed in the 24 June sown finger millet crop (2.76, 1.03 kg/ha °C/ day: biological, grain yield respectively) and the least was observed in the 9 July sown crop. Late-sown finger millet accumulated fewer heat units and grain yield as they were exposed to the suboptimal thermal regime, which led to a decrease in heat use efficiency. These are in line with earlier findings (38, 48).

Variety has a significant effect on HUE and Shreeratna showed higher HUE (2.73, 1.03 kg/ha °C/ day: biological and grain yield respectively) followed by Arjuna and both are statistically at par with each other. The magnitude of increase in HUE was 40 %, and 71.7 % through biological and grain yield respectively over the Kalua variety. Higher HUE indicates effective dry matter partitioning to different plant sections. HUE is the ability to convert heat energy into dry matter and is dependent on favourable climate conditions at sowing time, crop variety and genetic variables. As Shreeratna variety achieved higher grain yield in comparison to GDD higher HUE was achieved. Similar results were previously reported (38, 49).

### Nutrient uptake by plant

#### Nitrogen

Nitrogen uptake (kg/ha) in grain and straw of finger millet were significantly influenced by different dates of sowing and varieties (Table 9).

Nitrogen uptake in 24 June sown finger millet crop (41.9 kg/ha) showed maximum compared to the other two dates of sowing. The 24 June sown crop gives 50.7 % higher total N uptake than the 9 July sown crop.

Among the varieties, Shreeratna recorded maximum nitrogen uptake (41.5 kg/ha) followed by Arjuna (38.9 kg/ha), while there was no significant disparity among themselves. Since, uptake of nutrients in finger millet is a function of grain and straw yield and their nutrient content, the improvement in the content of the nutrient coupled with significantly increased grain and straw yield, increased the uptake of nutrients. The result resembles the earlier findings (50, 51). Shreeratna recorded 47.7 % higher total N uptake than the Kalua variety. The reason behind this is nutrient uptake is the resultant of greater dry matter buildup at various phases of crop growth, along with increased grain and straw output, which in turn caused the crop to absorb nitrogen at a substantially greater rate. These findings corroborate with previous works (25, 52, 53).

#### Phosphorus

Phosphorus uptake was found to be significantly higher in the 24 June sown crop (11.1 kg/ha) (Table 9). The reason behind this is the optimum time of sowing and favourable weather conditions, which might have led to a proportionate increase in growth parameters like dry-matter production, LAI and number of tillers/plants, resulting in more nutrient concentration and nutrient availability in the root zone. These results are similar to the findings of earlier works (25, 53, 54).

Among varieties, Shreeratna recorded higher P uptake (10.9 kg/ha) followed by Arjuna (10.3 kg/ha) in grain, straw and total uptake respectively. However, both varieties are mostly similar to each other. Shreeratna recorded a 49.3 % increase in total P uptake over the Kalua variety. The difference in P uptake among the genotypes showed the diversity in efficiency with which plants can

**Table 9.** Nutrient uptake (kg/ha) of finger millet as influenced by different dates of sowing and varieties

Treatment	N	P	K
<b>Date of sowing</b>			
24 June	41.9	11.1	66.7
9 July	27.8	7.2	47.3
24 July	37.2	9.8	59.5
SEm (±)	0.89	0.26	1.87
CD at 5 %	3.4	1.0	7.3
<b>Variety</b>			
Arjuna	38.9	10.3	60.2
Kalua	28.1	7.3	49.7
Bhairabi	34.1	9.0	56.3
Shreeratna	41.5	10.9	65.2
SEm (±)	1.18	0.30	1.88
CD at 5 %	3.5	0.9	5.5

SEm (±): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

absorb P from soils with varying P availability. The results resemble the findings of earlier results (25, 50, 51, 53, 54).

#### Potassium

The 24 June sown crop recorded the maximum K uptake (66.7 kg/ha) (Table 9). There was a 41 % increase in total K uptake by the 24 June sown crop over 9 July sown crop. Higher nutrient content in the produce and higher biomass production of crops might be the pertinent reason for higher uptake of K. The result resembles the findings of previous works (50, 51).

Shreeratna recorded higher K uptake (65.2 kg/ha) followed by Arjuna and both were similar to each other, while significantly better over Bhairabi and Kalua. There is a 31.2 % increase in total K uptake by Shreeratna over the Kalua variety. The higher potassium uptake by grain, straw and total in Shreeratna variety might be due to the increased growth parameters and yield parameters, due to favorable environment and nutrient availability throughout the root zone, which helped to uptake more nutrients. Similar findings were previously reported (25, 51, 53, 54).

#### Protein content (%) and protein yield (kg/ha)

Protein content in grain as affected by different dates of sowing and varieties was found to be non-significant (Table 10).

However, numerically higher protein content was observed in the 24 July sown crop (7.49 %) and in the Kalua variety (7.52 %). This might be due to higher N content in the grain of 24 July sown crop (7) as well as in the Kalua variety (50). The 24 June sown crop recorded higher protein yield of 161.89 kg/ha which was significantly higher over 24 July crop (139.50 kg/ha). Lowest protein yield was

**Table 10.** Protein content (%) and protein yield (kg/ha) as influenced by different dates of sowing and varieties

Treatment	Protein content	Protein yield
<b>Date of sowing</b>		
24 June	7.39	161.89
9 July	7.40	97.68
24 July	7.49	139.50
SEm (+)	0.026	3.911
CD at 5 %	NS	15.35
<b>Variety</b>		
Arjuna	7.38	151.81
Kalua	7.52	94.82
Bhairabi	7.47	125.24
Shreeratna	7.34	160.22
SEm (+)	0.086	5.583
CD at 5 %	NS	16.58

NS: Non significant; SEm (±): Standard error of mean; CD (5 %): Critical difference at 5 % level of significance

recorded in 9 July sowing condition (97.68 kg/ha). The 24 June sown crop gives 65.7 % more protein yield over 9 July crop. This is due to optimum time of sowing and favourable weather conditions, which led to proportionate increase in growth parameters, yield and nutrient content resulting in more protein concentration in the grain and finally protein yield per hectare. These results are in accordance with earlier findings (53, 54).

Among varieties, the Shreeratna variety recorded significantly higher protein yield (160.22 kg/ha) than Arjuna (151.81 kg/ha) and Bhairabi (125.24 kg/ha). However, the lowest protein yield was observed in the Kalua variety (94.82 kg/ha). Shreeratna variety shows a 68.9 % increase in protein yield over the Kalua variety. This is because of the higher protein content in the produce and higher grain yield of the Shreeratna variety, which might be the pertinent reason for higher protein yield. Similar findings were previously reported (25, 53, 54).

### Correlation and regression analysis

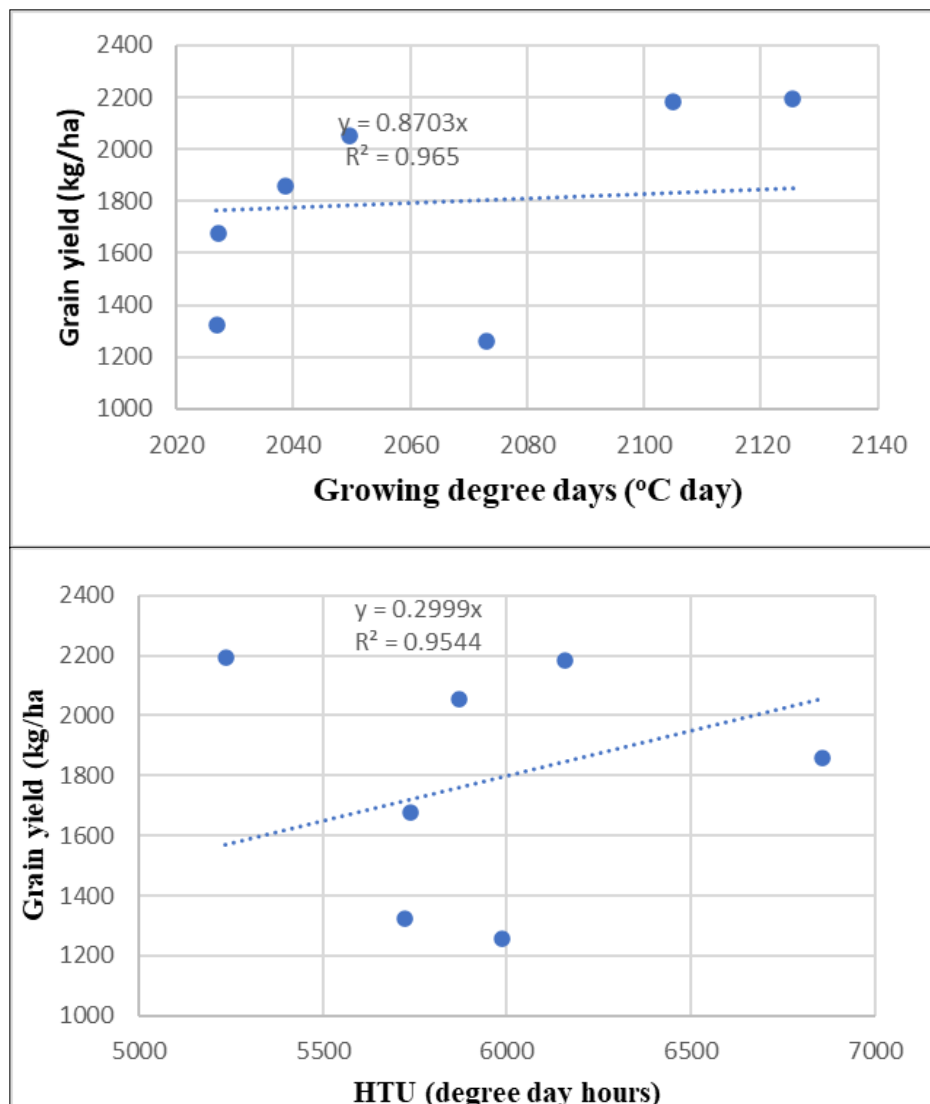
A correlation coefficient of 0.965 between grain yield and GDD in finger millet indicates a very strong positive linear relationship (Fig. 4). As GDD increases, grain yield also increases significantly. This suggests that longer or warmer growing periods (accumulating more GDDs) are highly favourable for maximising grain yield in finger millet. This high correlation of 0.9544 indicates that as HTUs increase, grain yield also increases significantly. It emphasises the importance of both temperature and solar radiation in determining finger millet productivity. Regions or seasons with more cumulative heat and

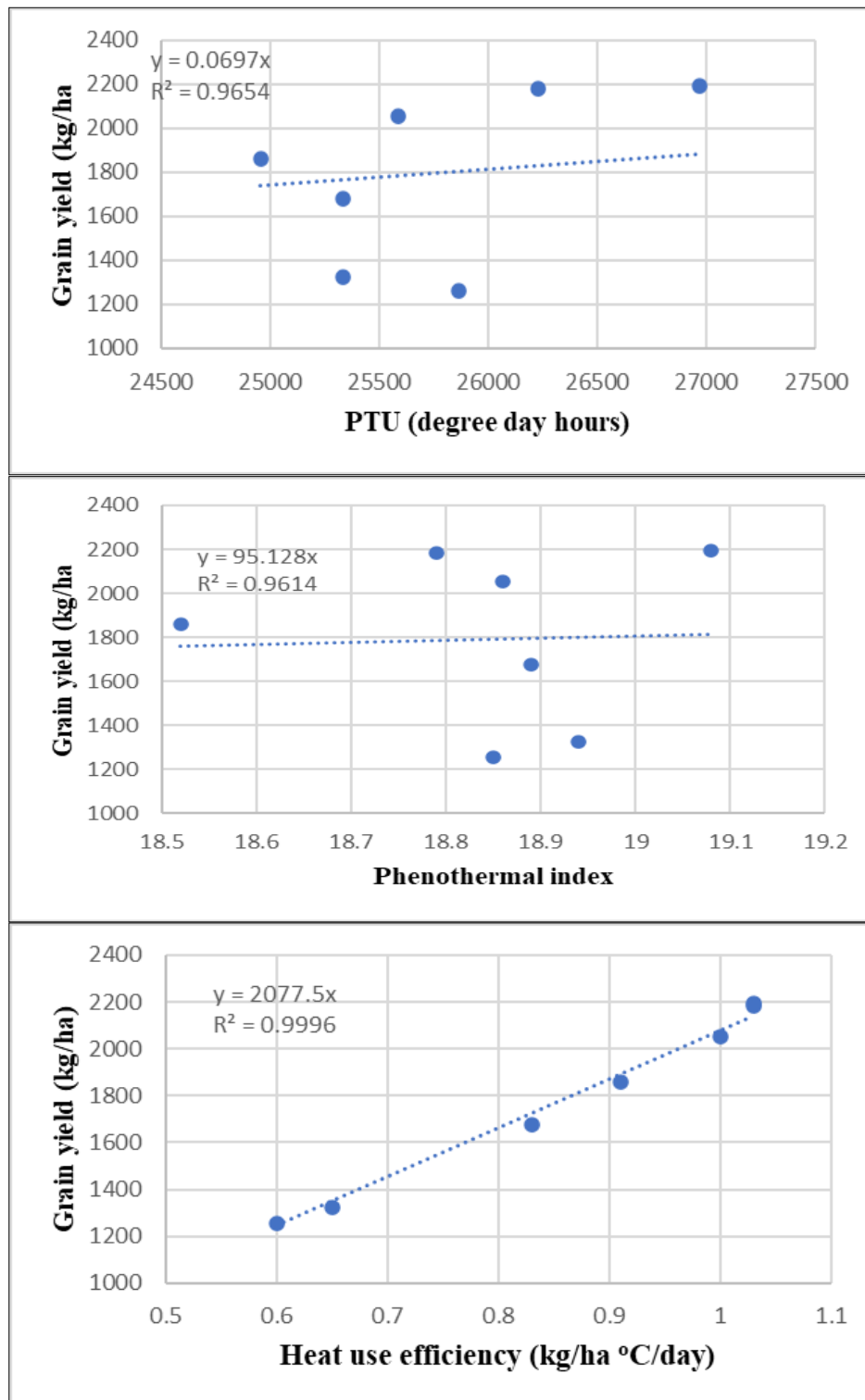
sunlight are likely to support higher yields.  $R^2$  (coefficient of determination) = 0.9654. This means that 96.54 % of the variation in grain yield can be explained by the variation in photothermal units (PTU). Simply, PTU is an excellent predictor of grain yield in finger millet under the conditions of the study. An  $R^2$  value of 0.9614 between grain yield and the PTI in finger millet indicates a very strong linear relationship - suggesting that 96.14 % of the variability in grain yield is explained by changes in PTI. It also indicates a strong influence of temperature conditions during specific phenological stages (e.g., vegetative, flowering and grain filling) on yield outcomes. An  $R^2$  value of 0.9996 between grain yield and HUE in finger millet is exceptionally high, indicating an almost perfect linear relationship. This implies that HUE is the single most accurate predictor of yield among all the thermal indices mentioned so far.

### Economics

Gross returns, net returns and B:C ratio from finger millet production were significantly influenced by different dates of sowing and varieties (Table 5).

The 24 June sown crop recorded significantly higher net return (Rs.57230/ha) and B:C ratio (1.9) followed by the 24 July crop (₹44592/ha, 1.5 :: net return, B:C ratio) and 9 July crop (₹23793/ha, 0.8 :: net return, B:C ratio) respectively. The additional net return obtained was ₹33437/ha by the 24 June sown crop with an additional investment of only ₹933/ha over the 9 July crop. The increased net returns and B:C ratio were mainly due to increased grain and straw yield as well as higher minimum support price in the





**Fig. 4.** Correlation between grain yield and thermal utilization of energy in finger millet.

24 June sown finger millet crop as compared to 24 July and 9 July. Similar results were also previously reported (55–57).

Among varieties, the Shreeratna variety recorded significantly increased net return (₹56585/ha) and B:C ratio (1.8) as compared to Arjuna (₹51810/ha, 1.7 :: net return, B:C ratio) respectively. The increase in net return with Shreeratna, Arjuna, Bhairabi variety was ₹35033/ha, ₹30258/ha and ₹15989/ha more as compared to the Kalua variety respectively with an initial investment of ₹1225/ha, ₹817/ha and ₹467/ha. There is a 52 % increase in net return in the Shreeratna variety than the Kalua variety. This is due to improved grain and straw production in Shreeratna variety, which was the primary factor in the increased gross returns, net returns and B:C ratio as compared to other varieties. Similar results were also

previously reported (48, 55–57). Integrated effect of Shreeratna variety sown on the 24 June gave the highest net return (Fig. 2).

### Conclusion

Thermal utilization of finger millet was maximized when the crop was sown at the last week of June (24 June), ensuring efficient use of accumulated heat units i.e., GDD (2125.4 °C day), PTU at 50 % flowering (20543 degree-day hours) and at maturity (26968.7 degree-day hours), PTI at maturity (19.08) and HUE (1.03 kg/ha °C/day), for improved growth and productivity; grain yield (2193 kg/ha) and straw yield (3672 kg/ha), while delayed sowing reduced thermal efficiency and crop performance.

Among the cultivars, Shreeratna performed significantly better than the others, producing higher grain yield (2182 kg/ha), straw yield (3587 kg/ha), nutrient uptake (41.5:10.9:65.2 kg/ha of N: P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O), GDD (2104.9 °C day), HTU at 50 % flowering (3875.1 degree-day hours) and at maturity (6158.5 degree-day hours), PTU at 50 % flowering (20127 degree-day hours) and at maturity (26228.6 degree-day hours), HUE (1.03 kg/ha °C/day) and net returns (Rs. 56585/ha). Heat use efficiency showed the strongest correlation with yield, indicating it is a reliable indicator for evaluating crop performance under variable thermal environments.

Overall, the combination of Shreeratna sown on 24 June during the kharif season produced the highest growth, favourable agro-meteorological indices, maximum yield (2569 kg/ha) and net returns (₹71737/ha), followed by the same variety sown on 24 July. Thus, Shreeratna demonstrates strong potential for adaptation across varying climatic conditions. Additionally, the high R<sup>2</sup> values observed in the study confirm the strong predictive capability of thermal indices in determining the growth and productivity of finger millet.

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## Authors' contributions

Conceptualization and design were done by BP and SRS. SRS prepared the methodology and investigation. Data analysis was performed by BP, SRS and JKN. All authors participated in writing the original draft, review and editing. Resources were collected by BP. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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