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# Optimizing Sowing Window and Cultivar Selection for Sustainable Foxtail Millet (*Setaria italica* L.) Cultivation in Punjab, India

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***Abstract***: Heat use efficiency plays a vital role in determining the growth and yield performance of foxtail millet under varying thermal regimes. The field investigation was carried out to evaluate the growth, phenology, yield and heat use efficiency of three foxtail millet cultivars (SiA-3156, Punjab Foxtail millet-3, and PFM-2) under six sowing dates (starting end April to mid-July) to expose the crop to a range of temperature conditions. The significant variation in HUE among cultivars and sowing dates, with early-sown crops generally exhibiting higher efficiency due to optimal thermal accumulation during critical growth phases was observed. Early sowing ($S_1$-26$^{th}$ April) significantly improved growth and yield, with the highest grain yield of 1.66 t ha$^{-1}$ while late sowing ($S_6$-11$^{th}$ July) showed reduced grain yield despite higher biological yield. The delayed sowings resulted in shortening grain filling duration, and lowering both biomass accumulation and yield. The $S_1$-26$^{th}$ April sown crop accumulated 1738.8 growing degree days, which was lower than that other treatments, yet exhibited the highest heat use efficiency and grain yield. Among the cultivars, Punjab Foxtail Millet-3 outperformed the others, showing the highest HUE and producing the maximum grain and biological yields, followed by PFM-2. These results highlight the critical role of timely sowing and cultivar selection in optimizing foxtail millet productivity.

***Keywords***: Growth, Yield, Punjab foxtail millet-3, Sowing date, Phenology

Since the green revolution, Punjab's agriculture has become increasingly dominated by wheat and rice, leading to a significant decline in the cultivation of pulses, oilseeds, fibre crops, and millets (Statistical Abstracts of Punjab, 1970-2024). The rice–wheat cropping system has also led to several problems, including a declining water table, deteriorating soil health, and the imbalanced use of fertilizers and agrochemicals (Kang et al., 2015, Singh et al., 2016). Thus, to address the problems associated with the rice–wheat monoculture and the challenges posed by global climate change, crop diversification is necessity (Kaur et al., 2020). Millets are C4 plants that can efficiently utilize elevated atmospheric $CO_2$, enabling more biomass production (Brahmachari et al., 2018), may help in mitigating the impact of global warming. Millets, particularly foxtail millet (*Setaria italica*), are nutrient-dense and highly adaptable to low-fertility soils, requiring minimal inputs (Cui et al., 2022). Despite being the third most important millet after pearl millet (*Pennisetum glaucum*) and finger millet (*Eleusine coracana*), foxtail millet remains underutilized (Zheng et al., 2024). Under conditions of insufficient rainfall or water stressed conditions, foxtail millet (*Setaria italica*) is frequently cultivated as a substitute for sorghum (*Sorghum bicolor*), owing to its superior drought resilience (Jyothi et al., 2016). Typically grown in semi-arid regions, foxtail millet requires minimal water and benefits from a short growth cycle, making it well-suited to areas with limited rainfall. Its resilience and adaptability allow it to be sown in environments where most other crops fail to thrive. The increasingly unpredictable climatic patterns such as delayed monsoons and early cessation of rainfall, optimal sowing time has become critical. Timely planting promotes better root development and efficient resource utilization, leading to higher yields, whereas delayed sowing shortens the growth duration and significantly reduces productivity (Xing et al., 2023, Sharma et al., 2018).

Crop growth and phenology analyses conducted in specific environments are often insufficient for determining the optimal combinations of crop cultivars, environmental conditions, and cultivation practices (Sahoo et al., 2020). Understanding the thermal time requirement of a crop can help estimate both the harvest date and key developmental stages. In addition, the field performance of crop cultivars is largely influenced by interaction effects and random variability among genotypes, environmental conditions, and management practices (Nandini and Sridhara 2019). The interaction and environmental effects account for more than 50% of the variability in varietal performance across different regions and years (Ning et al., 2015, Nandini and Sridhara 2019, Sahoo et al., 2020). Therefore, it is essential to evaluate the performance of various cultivars under different sowing times to ensure sustainable yields. Hence, the present investigation was conducted to find the best sowing time and cultivar for sustainable yield by evaluation their effect on the growth, phenology, heat use efficiency and yield of foxtail millet.

## MATERIAL AND METHODS

**Experimental location:** The study was conducted during 2023 and 2024 at the Regional Research Station of Punjab Agricultural University, Gurdaspur, Punjab. The experimental site is located in the sub-mountainous undulating zone of Punjab, at a latitude of 32.02°N, longitude of 75.22°E, and an elevation of 265.2 meters above sea level. The region receives an average annual rainfall of approximately 1325 mm, 80% of which is usually received during the south western monsoon season and remaining during the winter season. The soil was classified as fine loamy, non-calcareous, mixed, hyperthermic typic Haplustalfs with silt loam texture (41 % sand, 40.5 % silt and 18.5% clay) (Singh and Sharma 2021). The soil has 7.5 pH (1:2 soil), electrical conductivity 0.13 $dSm^{-1}$ (1:2 soil, superannuated solution), organic carbon 0.52 %, available phosphorus 37.5 kg $ha^{-1}$, and available potassium 62.5 kg $ha^{-1}$.

Three cultivars namely SiA-3156, Punjab Foxtail millet-3, and PFM-2 (coded cultivars under testing by Punjab Agricultural University) were sown on six sowing dates namely $S_1$: 26th April, $S_2$: 11th May, $S_3$: 26th May, $S_4$: 10th June, $S_5$: 25th June, $S_6$: 11th July. The experiment was conducted using a factorial randomized complete block design with two factors: date of sowing and cultivar, each replicated three times. The crop management was done as per recommended practices by PAU, Ludhiana.

**Observations recorded:** The maximum plant height, number of tillers, number of days taken to 100% flowering and maturity were recorded from the randomly selected five plants from each plot. The harvesting was done once the crop reached physiological maturity i.e. when grains turned brown. The crop was harvested and left in the field for drying. After 2-3 days of drying the crop was threshed using multicrop thrasher. The grain and straw yield were recorded and expressed in quintals per hectare.

The growing degree days as a measure of thermal time, were calculated by simple arithmetic accumulation of daily mean temperature above the base temperature. The growing degree days for each stage were calculated (Nuttonson 1955):

$$\text{Growing degree days (°C days)} = \sum_{i=1}^{n} T_i - T_b \qquad (1)$$

Where, i is the $i^{th}$ day from sowing, $T_i$ is mean temperature for that day, n is the number of days in the growing season (Ellis et al 1990) and $T_b$ is Base temperature and was taken equal to 10°C. The heat use efficiency was calculated using the following formula:

$$\text{Heat use efficiency (Kg/ha/}^{o}\text{C days)} = \frac{\text{Grain or dry matter yield (Kg/ha)}}{\text{AGDD (}^{o}\text{C day)}} \qquad (2)$$

AGDD is Accumulated growing degree days (°C Day) is sum of growing degree days acquired by crop during life cycle.

The daily maximum and minimum temperatures were recorded at Agrometeorological Observatory, Punjab Agricultural University Regional Research Station, Gurdaspur situated near the experimental site.

**Statistical analysis:** The analysis of variance for factorial randomised complete design was performed using RStudio (R Core Team). The least significant difference (LSD) was used to compare treatment means at 5% level of significance.

## RESULTS AND DISCUSSION

Plant height significantly varies due to change in date of sowing windows (Table 1). Maximum plant height was recorded in $S_1$ (131.4 cm) date of sowing which was at par with $S_3$ and $S_4$ sowing date. Plant height also influenced by different cultivars, the maximum plant height was observed under Pb Foxtail millet-3 (130.7 cm), that was statistically similar to the PFM-2 (130.1 cm). The early sowing i.e. $S_1$ typically offer more favourable environmental conditions such as optimal temperature and photoperiod, which promote better vegetative growth and lead to greater plant height. Delayed sowing ($S_6$) exposes crops to suboptimal growing conditions or stress (e.g., heat, excess water), resulting in shorter plants. Additionally, the delayed sowing date of $S_6$ coincides with monsoon rainfalls, may results in crop lodging due to water logging or storms. The differences in plant height among cultivars are genetically controlled. The cultivars like, Pb Foxtail millet-3 possess traits such as greater internode elongation or longer growth duration, contributing to taller stature.

**Number of tiller/plants:** Among the date of sowings, the highest number of tillers was observed under $S_1$ and among cultivars the maximum number of tillers was observed under Pb Foxtail millet-3 (Table 1). The early sown (26th April) crop resulted in maximum number of tillers per plant. Tillering is sensitive to sowing time; early sowing ($S_1$, $S_2$) allows longer vegetative phases, supporting the formation of more tillers. Late sowing ($S_6$) compresses the vegetative phase and coincide with higher temperatures or water stress, reducing tiller formation. Varietal differences in tillering capacity are typically linked to genetics. The Pb Foxtail millet-3 have higher tillering potential, might be due to better tiller initiation and survival, efficient nutrient use, or more vigorous early growth.

**Phenological stages:** The maximum number of days to attain flowering were acquired taken by $S_1$ sowing date (70.2 days), while $S_2$ and $S_4$ took minimum days to flowering as compare to $S_3$ sowing date. Among the cultivars, SiA-3156 took the longest time to flower, which was significantly higher compared to the other cultivars. The Pb Foxtail-3 variety reached flowering in 67.2 days. Revathi et al. (2017) also reported that with delay in sowing induces earlier flowering, resulting in less vegetative growth and earliness in maturity.

The early sown (26th April) (87.6 days) took the highest number of days to reach maturity, whereas other sowing dates did not significantly affect the time taken to reach physiological maturity (Table1). The SiA-3156 (88.3 days) required significantly higher number of days to reach physiological as compared to Pb Foxtail millet-3 (85.5 days), and PFM-2 (85.1 days). Navya *et al* (2015) also reported that crop variety characteristics directly affect the physiological maturity.

**Grain yield:** The highest grain yields were in the crop sown on $S_1$ (1.66 t ha$^{-1}$) date of sowing that was statistically at par with $S_2$ (1.65 t ha$^{-1}$) (Table 2). Minimum grain yield was observed under $S_6$ sowing dates (1.10 t ha$^{-1}$). Among cultivars, the maximum grain yield was observed under Pb Foxtail millet-3 (1.47 t ha$^{-1}$) foxtail variety, while minimum grain yield was in SiA-3156 variety (1.27 t ha$^{-1}$). The increase in grain yield is mainly attributed to increase in plant height and leaf area, increases the assimilatory surface area per plant might have led to the accumulation of a large quantity of photo assimilates directly affecting the grain yield. The results are in accordance with Munirathnam *et al* (2006).

**Biological yield:** Maximum biological yield of foxtail millet was in $S_6$ (6.78 t ha$^{-1}$), that was statistically at par with sowing date of $S_5$ (6.74 t ha$^{-1}$) (Table 2). The sowing dates of $S_2$, and

**Table 1.** Effect of date of sowing and different cultivars on Growth and yield attributes of foxtail millet

| Treatments | Plant height (cm) | No. of tillers per plant | Days to flowering | Days to physiological maturity |
|---|---|---|---|---|
| $S_1$: 26th April | 131.4 | 5.40 | 70.22 | 87.6 |
| $S_2$: 11th May | 129.4 | 5.27 | 68.44 | 87.0 |
| $S_3$: 26th May | 130.6 | 5.01 | 69.60 | 86.9 |
| $S_4$: 10th June | 130.4 | 4.81 | 68.05 | 85.9 |
| $S_5$: 25th June | 127.9 | 4.45 | 67.07 | 85.6 |
| $S_6$: 11th July | 126.6 | 3.92 | 66.40 | 84.7 |
| LSD (p=0.05) | NS | 0.30 | 1.98 | NS |
| SiA-3156 | 127.5 | 4.66 | 70.65 | 88.3 |
| Pb Foxtail millet-3 | 130.7 | 4.94 | 67.16 | 85.5 |
| PFM-2 | 130.1 | 4.84 | 67.08 | 85.1 |
| LSD (p=0.05) | NS | 0.17 | 1.66 | 1.6 |
| Interactions (S×V) | NS | NS | NS | NS |

**Table 2.** Effect of date of sowing and different cultivars on growth and yield attributes of foxtail millet

| Treatments | Grain yield (t ha$^{-1}$) | Biological yield (t ha$^{-1}$) | AGDD (℃ days) | Heat use efficiency (kg ha$^{-1}$ °C days$^{-1}$) |
|---|---|---|---|---|
| $S_1$: 26th April | 1.66 | 6.11 | 1,738.8 | 0.959 |
| $S_2$: 11th May | 1.65 | 5.90 | 1,763.7 | 0.936 |
| $S_3$: 26th May | 1.48 | 5.92 | 1,761.7 | 0.843 |
| $S_4$: 10th June | 1.21 | 6.37 | 1,775.0 | 0.682 |
| $S_5$: 25th June | 1.10 | 6.74 | 1,724.7 | 0.637 |
| $S_6$: 11th July | 1.09 | 6.78 | 1,673.8 | 0.65 |
| LSD (p=0.05) | 0.16 | 0.38 | 45.9 | 0.076 |
| SiA-3156 | 1.27 | 5.76 | 1,778.6 | 0.711 |
| Pb Foxtail millet-3 | 1.47 | 6.60 | 1,724.6 | 0.853 |
| PFM-2 | 1.35 | 6.54 | 1,715.7 | 0.789 |
| LSD (p=0.05) | 0.08 | 0.33 | 32.5 | 0.054 |
| Interactions (S×V) | NS | NS | NS | NS |

$S_3$ recorded minimum biological yield compare to all other treatments, whereas produced maximum grain yield indicating more harvest index. The foxtail variety influence the biological yield, where Pb Foxtail millet-3 and PFM-2 recorded maximum biological yield of 6.60 and 6.54 t $ha^{-1}$, respectively that was significantly higher than the biological yield observed under SiA-3156 (5.76 t $ha^{-1}$). Early sowing often leads to higher biological yields due to favourable weather conditions that promotes key growth traits (taller plants, larger leaf area, and increased dry-matter accumulation), which in turn enhance biomass production.

**Growing degree days:** The accumulated growing degree days (AGDD) based on date of sowing to maturity under different sowing times and cultivars (Table 2). Different phenological stages of both the cultivars require different heat units till maturity under all dates of sowing. The highest requirement of GDD was d at maturity for all the cultivars. The requirement of heat unit was less for April sown crop and this increased up to June 10 sowing. GDD requirement was maximum in June 10 sown crop followed $S_3$ and $S_2$ sowings. Further delay in sowing beyond June 10 reduced the growing degree day requirement of foxtail cultivars. Among the cultivars, Pb Foxtail millet-3 recorded significantly more heat units as compared to other two cultivars and it was at par with the heat units recorded by PFM-2 cultivar. than late sown crop due to longer period for all the phenological stages in the timely sown crop. The April and late June sowing accumulated lesser heat units due to lower temperatures as compared to May and early June sown crops. The delay in sowing also decreased the duration of maturity period which forced the crop to attain early maturity. The high temperature during vegetative phases and low temperature during reproductive phases lead to lesser heat unit accumulation.

**Heat use efficiency:** The effect of sowing times on heat use efficiency was significant with highest heat use efficiency was obtained in April 26 sowing, which was statistically at par with May 11 sown crop but significantly higher than other sowing dates (Table 2). The normal growing plants produced higher grain yield by using accumulated heat units efficiently. Due to consistently favourable temperatures during the normal growing season, the crop was able to utilize heat more efficiently, which in turn stimulated physiological processes and resulted in higher grain yield. Pb Foxtail millet-3 exhibited significantly higher heat use efficiency as compared to other two cultivars. The interaction effect was not significant among sowing dates and cultivars.

The regression relationship between the grain yield and heat use efficiency shows the high value for coefficient of determination which means 97 percent variation in grain yield is determined by the heat use efficiency (Fig. 1). With

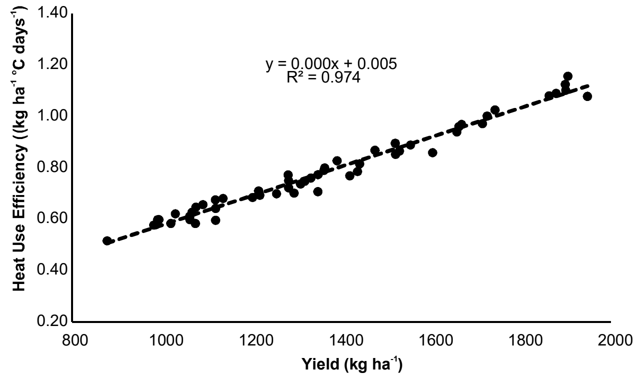


**Fig. 1.** Relationship of foxtail millet yield and heat use efficiency under different sowing times

progressive delay in sowing, HUE declined markedly. Crops sown in later windows (e.g., $S_6$) experienced not only reduced grain yields but also lower heat use efficiency, despite sometimes showing higher biological (vegetative) yield. This reduction arises primarily from shortened grain filling duration and the exposure of sensitive growth stages to higher temperatures, which limits the efficient conversion of heat units into grain due to thermal and potential water stress, resulting in poor grain set and lower harvest indices (Nandini and Sridhara 2019).

## CONCLUSION

The study highlights the significant influence of sowing dates on the accumulation and utilization of heat units, ultimately affecting the growth duration, phenological development, and yield of foxtail millet cultivars. Early sowing ($S_1$-26th April) resulted in better synchronization with favorable thermal regimes, allowing the crop to accumulate optimal growing degree days) and achieve higher heat use efficiency and the highest grain yield) and better growth parameters in foxtail millet. Delayed sowing ($S_{6}$-11th july) reduced GDD accumulation during critical stages leading to reduced grain yield despite higher biological yield. The Pb foxtail millet-3 variety, performed best with the highest grain and biological yield. And required more days to mature but had lower yield performance. Interaction between sowing date and variety was non-significant for all traits.

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