



RESEARCH ARTICLE

Influence of sowing windows and genotypes on phenology, thermal indices and yield of chia (*Salvia hispanica* L.)

Usha N^{1*}, Ramachandra C², Anand S R¹, Murali K¹ & Shivanna B³

¹Department of Agronomy, University of Agricultural Sciences, Gandhi Krishi Vigyan Kendra, Bengaluru 560 065, Karnataka, India

²Department of Agronomy, University of Agricultural Sciences, V. C. Farm, Mandya 571 405, Karnataka, India

³Department of Agricultural Entomology, University of Agricultural Sciences, Gandhi Krishi Vigyan Kendra, Bengaluru 560 065, Karnataka, India

*Correspondence email - nusha8166@gmail.com

Received: 15 April 2026; Accepted: 10 June 2026; Available online: Version 1.0: 22 July 2026

Cite this article: Usha N, Ramachandra C, Anand SR, Murali K, Shivanna B. Influence of sowing windows and genotypes on phenology, thermal indices and yield of chia (*Salvia hispanica* L.). Plant Science Today. 2026; 13(sp5): 1-14. <https://doi.org/10.14719/pst.15014>

Abstract

The sowing window and genotype selection play a vital role in optimising the growth, phenology and productivity of chia (*Salvia hispanica* L.) under semi-arid conditions. A field experiment was conducted during the kharif-rabi seasons of 2023 and 2024 at M block, All India Coordinated Research Network (AICRN) on potential crops, University of Agricultural Sciences, Gandhi Krishi Vigyan Kendra, Bengaluru, using 14 treatment combinations arranged in a factorial randomised complete block design (FRCBD) with three replications. Two genotypes (black and white chia) were evaluated across seven sowing windows from the 2nd fortnight (FN) of July to the 2nd FN of October. Black chia recorded significantly higher seed yield (SY) (1217.441 kg ha⁻¹) along with improved seed yield per plant (SYP) (15.614 g), number of inflorescences (NS) per plant (23.098) and inflorescence length (SL) (18.699 cm). Among sowing windows, the 1st FN of August sowing recorded a higher SY (1325.915 kg ha⁻¹), SYP (17.013 g), NS (24.722 plant⁻¹) and SL (20.324 cm). Early sowing extended crop duration, with the 2nd FN of July requiring 132.01 days to reach physiological maturity, whereas delayed sowing during the 2nd FN of October shortened crop duration to 98.27 days, indicating accelerated phenological progression under comparatively lower temperature and shorter photoperiod. The research results indicate that cultivation of black chia during 1st FN of August is the most suitable strategy for achieving higher productivity under the semi-arid conditions of Bangalore.

Keywords: genotypes; phenology; seed yield; sowing windows; thermal indices

Introduction

Chia (*Salvia hispanica* L.) is an ancient oilseed crop belonging to the family Lamiaceae, native to Central and South America, where it was cultivated by the Aztec and Mayan civilisations (1, 2). In recent years, chia has gained global importance because of its high nutritional value, particularly its rich content of α -linolenic acid, dietary fibre, protein, antioxidants and other bioactive compounds (3–6). Increasing demand for functional foods and plant-based omega-3 sources has expanded chia cultivation beyond its traditional regions into North America, Europe, Australia and Asia (1, 7, 8).

Despite its adaptability, chia is highly sensitive to environmental factors, particularly temperature and photoperiod (2, 9). As a short-day plant, chia flowering is strongly regulated by day length, which influences phenological development, biomass accumulation and seed yield (SY) (1, 7). This strong photoperiod sensitivity restricts its cultivation to regions and sowing periods that provide suitable day-length conditions for timely flowering and seed set, thereby limiting its wider commercial adoption across diverse agroclimatic zones. Temperature extremes during reproductive stages can adversely affect grain filling, harvest index (HI) and reproductive success (10–13). Therefore, synchronisation of sowing time with favourable thermal and photoperiodic conditions is essential for optimum crop growth and productivity.

Sowing window is an important agronomic factor influencing crop growth and yield (8, 14). Delayed sowing may expose the crop to suboptimal thermal conditions during flowering and grain filling, resulting in shortened phenological duration and reduced yield, whereas early sowing may prolong vegetative growth and biomass accumulation (9, 10, 15, 16). Thermal accumulation, expressed as growing degree days (GDD), is widely used to quantify crop development and predict phenological stages (11, 12). In chia, thermal accumulation influences flowering initiation, reproductive duration and seed maturation, while excessive radiation load and prolonged sunshine hours (SSH) may adversely affect reproductive development and grain filling (9, 13, 17, 18). Rainfall distribution during critical growth stages also influences biomass production and final SY (14, 19). Genotypic variation further plays an important role in determining growth, phenology and yield stability under varying climatic conditions. Differences between black and white chia genotypes have been reported for vegetative vigour, flowering behaviour and SY, indicating the significance of genotype-environment interactions in crop adaptation and productivity (2, 17, 19). Although these traits are genetically determined, their expression is influenced by environmental factors.

In India, chia cultivation is expanding in semi-arid and sub-humid agroclimatic zones due to its economic potential and climate resilience. However, systematic information on sowing windows and genotypic response under Southern Indian conditions remains limited (17). Although previous studies have examined sowing date effects in temperate and Mediterranean regions (8, 9, 14), information under the agroclimatic conditions of Bengaluru is meagre. Therefore, the present investigation was undertaken to evaluate the influence of different sowing windows and genotypes on growth, phenological behaviour, agrometeorological indices and SY of chia under semi-arid conditions of Bengaluru and to elucidate the relationship between weather variables and crop performance using correlation and principal component analysis (PCA).

Materials and Methods

Experimental site

Field experiments were conducted at M block, All India Coordinated Research Network (AICRN) on potential crops, University of Agricultural Sciences, Gandhi Krishi Vignana Kendra (GKVK), Bengaluru. The site is located at 13°05 'N latitude and 77°33 'E longitude, at an altitude of 924 m above mean sea level. The composite soil samples (0–15 cm depth) were collected randomly from the experimental site before the imposition of treatments and were analysed for physical and chemical properties of the soil. The soil of the experimental site was red sandy loam. The soil was slightly acidic pH (5.71), with an electrical conductivity of 0.26 dS m⁻¹ and an organic carbon content of 0.36 %. The soil was low in available nitrogen (N) (262.64 kg N ha⁻¹), medium in available phosphorus (P) (48.32 kg P₂O₅ ha⁻¹) and medium in available potassium (K) (246.65 K₂O kg ha⁻¹).

Experimental details

The experiment consisted of 14 treatment combinations, including factor-I with genotypes (black and white chia) and factor-II with sowing windows, viz., 2nd fortnight (FN) of July, 1st FN of August, 2nd FN of August, 1st FN of September, 2nd FN of September, 1st FN of October and 2nd FN of October, which were replicated thrice. The field was ploughed once after the harvest of the previous crop and subsequently harrowed to obtain a fine seedbed. The plots were laid out with dimensions of 3.6 m × 3.0 m and the land was further prepared to provide a well-pulverised seedbed before sowing. Staggered sowing of chia was carried out at different sowing windows by mixing the chia seeds with sand to ensure uniform distribution, followed by line sowing. Thinning was subsequently performed to maintain the required spacing of 60 cm between rows and 15 cm between plants within the row, as per the treatments. When 95 % of the inflorescences had reached their mature colour, the crop was deemed mature and harvested. The observations for this study were made at 30 days after sowing (DAS), 60 DAS and at harvest.

Statistical data collection

The data were analysed using a factorial randomised complete block design (FRCBD), with year as Factor I, genotype as Factor II and sowing window as Factor III. Three-way analysis of variance (ANOVA) was performed to evaluate the effects of year, genotype, sowing windows and their interactions. Treatment means were compared using the least significant difference (LSD) test at the 5 % level of significance whenever the *F*-test was significant.

Correlation analysis and PCA were performed using the general R-based analysis platform for experimental statistics, which is powered by R software (20). Pearson's correlation coefficients were computed to assess the associations among growth, yield and agrometeorological parameters and their significance was tested at the 5 % probability level. Principal component analysis was carried out to identify the major sources of variation and to elucidate the multivariate relationships among the studied traits. The results of PCA were visualised using biplots generated through the same platform.

Agrometeorological indices and efficiencies

Agrometeorological indices and efficiencies, derived from various meteorological factors, are documented in the literature to examine crop-weather interactions. The present study utilised indices like GDD, heat use efficiency (HUE), helio thermal use efficiency (HTUE) and photothermal use efficiency (PTUE). By using 10 °C as base temperature (21), thermal and photo-thermal indices were computed for each stage using the appropriate formula suggested by different research workers. The methods of computation of the indices are presented here.

Growing degree days

Growing degree days (GDD) at various phenological phases were computed by summing daily mean temperatures exceeding the base temperature (*T_b* = 10 °C) over the period from sowing to physiological maturity, as proposed (22) and expressed in °C days.

$$\text{GDD (}^{\circ}\text{C days)} = \sum \frac{(T_{\max} + T_{\min})}{2} - T_b \quad (\text{Eqn.1})$$

where, *T_{max}* = maximum temperature; *T_{min}* = minimum temperature; *T_b* = base temperature (21).

Heat use efficiency

The biomass accumulated during the specified period per degree-day is known as HUE, which was also calculated using the following formula to assess the relative performance of chia genotypes under different treatments (23, 24).

$$\text{HUE (kg ha}^{-1}\text{ }^{\circ}\text{C day)} = \frac{\text{Seed yield (Kg ha}^{-1}\text{)}}{\text{Accumulated growing degree day (}^{\circ}\text{C day)}} \quad (\text{Eqn.2})$$

Helio-thermal use efficiency

Helio-thermal use efficiency (HTUE) measures how well a crop makes use of the actual bright SSH that are available and is expressed as yield per degree-day hours. Helio-thermal units (HTU) were calculated by multiplying GDD by the corresponding actual SSH. The HTUE was calculated using the following formula (25)

$$\text{HTUE (kg ha}^{-1}\text{ }^{\circ}\text{C days}^{-1}\text{ hrs}^{-1}\text{)} = \frac{\text{Seed yield (Kg ha}^{-1}\text{)}}{\text{Accumulated HTU (}^{\circ}\text{C day hrs)}} \quad (\text{Eqn.3})$$

Photo-thermal use efficiency

The photo-thermal use efficiency (PTUE) measures how well a crop makes use of the maximum possible bright SSH. Photothermal units were obtained by multiplying GDD by the corresponding day length. The PTUE was computed using the following formula provided (25) and expressed as yield per degree-day hr.

$$\text{PTUE (kg ha}^{-1}\text{ }^{\circ}\text{C days}^{-1}\text{ hr}^{-1}) = \frac{\text{Total seed yield (Kg ha}^{-1})}{\text{Accumulated PTU (}^{\circ}\text{C day hr)}} \quad (\text{Eqn.4})$$

Result and Discussion

Weather conditions

The crop growth period extended from July to January during both the seasons of 2023 and 2024 (Fig. 1). The total rainfall received in 2023 (829.2 mm) was less than the long-term average (941.5 mm), indicating a deficit rainfall year. However, significantly higher rainfall (1436.0 mm) was recorded in 2024, indicating a surplus rainfall year. During the year 2023, higher rainfall was received in the month of September (194.0 mm), followed by May (154.8 mm). In contrast, the highest rainfall in 2024 was recorded during October (585.4 mm), followed by August (261.2 mm) (Fig. 1A). The maximum air temperature ranged from 27.7 °C in December 2023 to 36.0 °C in April 2024 (Fig. 1B). January recorded the lowest air temperature of 13.5 °C in 2023 and 18.3 °C in 2024, indicating cooler conditions for the early phases of crop growth. During the crop growth period, the mean relative humidity (RH) ranged from 81–89 % in 2023 and from 74.0–90.2 % in 2024. In both years, the monsoon months had relatively higher values. Early in the crop's growth, lower RH was typically noted. Bright SSH during the crop growth period were higher during the initial and terminal stages of crop growth and lower during the monsoon months (Fig. 1 C). In 2023, February had the maximum bright SSH (9.6 hr day⁻¹), while July had the minimum (4.5 hr day⁻¹). Similarly, in 2024, February had the higher bright SSH (9.6 hr day⁻¹), while July had the lower (2.3 hr day⁻¹) because of more cloud cover. The seasonal variation in rainfall, temperature, RH and SSH created distinct thermo-moisture environments that influenced crop growth, phenology and productivity of chia under different sowing windows.

Growth parameters

Growth parameters were significantly influenced by both seasons, genotypes and sowing windows (Table 1). Higher vegetative growth was observed during 2023, with plant height (PH) (164.333 cm), number of branches (NB) (19.884 plant⁻¹) and number of leaves (NL) (128.823 plant⁻¹) at harvest exceeding those of 2024 (154.649 cm, 18.811 plant⁻¹ and 116.902 plant⁻¹, respectively). Seasonal variation in vegetative growth may be attributed to differences in temperature and rainfall distribution (Fig. 1). Similar environmental factors influencing chia growth have been reported (14, 15), in which it is demonstrated that sowing time and thermal regime significantly influence biomass accumulation.

Genotypic differences were evident, as G₁-Black chia recorded significantly higher PH (162.071 cm), NB (19.818 plant⁻¹) and NL (124.733 plant⁻¹) at harvest compared to G₂-white chia (156.911 cm, 18.877 plant⁻¹ and 120.993 plant⁻¹, respectively). Genotypic variability in structural traits has been documented under contrasting environments (7, 19), indicating differential adaptability and growth potential. Sowing during the 2nd FN of July (S₁) recorded significantly higher PH (170.438 cm) and NL (146.672 plant⁻¹) at harvest. However, S₂ (1st FN of August) recorded a significantly higher NB (23.483 plant⁻¹), whereas delayed sowing (S₃) reduced PH (148.310 cm), branching (14.555 plant⁻¹) and NL

(91.064) at harvest. Branching appeared to be more responsive to favourable environmental conditions during the vegetative phase, which enhanced axillary bud development, while delayed sowing curtailed the vegetative growth period (9, 26). In contrast, PH is largely influenced by stem elongation and overall vegetative growth, whereas leaf number depends on the duration and rate of leaf initiation. Further, the increase in PH under the 2nd FN of July sowing resulted in greater accumulation of vegetative biomass, which predisposed the crop to lodging under field conditions. Excessive stem elongation coupled with higher biomass production during the 2nd FN of the July sowing window might have reduced the mechanical strength of the stem, thereby increasing susceptibility to lodging, particularly under the relatively favourable moisture and thermal conditions prevailing during the 2nd FN of July. Similar observations on higher PH and branching under favourable environmental conditions were reported (17), which were attributed to extended vegetative growth and improved accumulation of photosynthates.

Yield Parameters and agrometeorological efficiencies

Seed yield and yield attributes were significantly influenced by year, genotype and sowing windows (Table 2). Yield was higher during 2023 (1198.569 kg ha⁻¹) compared to 2024 (1170.028 kg ha⁻¹), corresponding with greater inflorescence length (SL) (19.081 cm) and number of inflorescences (NS) (23.537 plant⁻¹). However, agrometeorological efficiencies varied between years; 2024 recorded higher HUE (0.784 kg ha⁻¹ °C day) and PTUE (0.067 kg ha⁻¹ °C days⁻¹ hr⁻¹), whereas 2023 registered higher HTUE (0.161 kg ha⁻¹ °C days⁻¹ hr⁻¹). This indicates that although absolute yield was higher in 2023, thermal resource utilisation per unit accumulation was relatively more efficient during 2024.

Among genotypes, G₁-black chia recorded higher SY (1217.441 kg ha⁻¹) compared to G₂-white (1151.156 kg ha⁻¹), along with higher seed yield per plant (SYP) (15.614 g), test weight (TW) (1.474 g) and SL (18.699 cm). The higher yield of black chia may be attributed to its superior vegetative vigour, prolonged crop duration and greater assimilate accumulation, which enhanced source-sink balance and reproductive sink development. The longer duration to flowering and physiological maturity in black chia enabled greater thermal accumulation and dry matter production, thereby improving inflorescence development and seed filling. In contrast, G₂-white exhibited higher HUE (0.771 kg ha⁻¹ °C day), HTUE (0.144 kg ha⁻¹ °C days⁻¹ hr⁻¹) and PTUE (0.066 kg ha⁻¹ °C days⁻¹ hr⁻¹), suggesting comparatively better thermal energy conversion efficiency despite lower absolute yield. This apparent contradiction indicates that white chia completed its life cycle within a relatively shorter duration and utilised accumulated thermal units more efficiently per unit biomass produced; however, reduced total biomass and sink capacity ultimately limited final yield. Similar genotypic differences in phenology, biomass accumulation and yield potential were also reported (19).

Among sowing windows, the 1st FN of August sowing recorded significantly higher SY (1325.915 kg ha⁻¹), followed by the 2nd FN of August sowing (1300.880 kg ha⁻¹) and the 1st FN of September sowing (1286.765 kg ha⁻¹). The higher yield under the 1st FN of August sowing was associated with improved yield attributes such as SYP (17.013 g), TW (1.480 g), SL (20.324 cm) and NS per plant (24.722). In contrast, delayed sowing (S₃) resulted in lower SY (1020.002 kg ha⁻¹), SYP (12.781 g plant⁻¹), SL (14.754 cm) and NS

Table 1. Growth parameter of chia as influenced by genotypes and sowing windows

Treatments	Plant height (cm)			Number of branches/ plant			Number of leaves/plant		
	30 DAS	60 DAS	At harvest	30 DAS	60 DAS	At harvest	30 DAS	60 DAS	At harvest
Year (Y)									
2023	23.537 ^a	87.293 ^a	164.333 ^a	8.259 ^a	13.276 ^a	19.884 ^a	19.595 ^a	171.367 ^a	128.823 ^a
2024	21.884 ^b	83.046 ^b	154.649 ^b	6.853 ^b	11.584 ^b	18.811 ^b	17.663 ^b	167.098 ^b	116.902 ^b
LSD ($p = 0.05$ %)	0.464	1.905	3.283	0.162	0.256	0.406	0.396	3.513	2.477
Genotypes (G)									
G ₁ -Black	23.098 ^a	86.579 ^a	162.071 ^a	7.951 ^a	12.635 ^a	19.818 ^a	19.031 ^a	173.074 ^a	124.733 ^a
G ₂ -White	22.324 ^b	83.760 ^b	156.911 ^b	7.161 ^b	12.225 ^b	18.877 ^b	18.226 ^b	165.391 ^b	120.993 ^b
LSD ($p = 0.05$ %)	0.464	1.905	3.283	0.162	0.256	0.406	0.396	3.513	2.477
Sowing windows (S)									
S ₁ -2 nd FN of July	23.413 ^b	91.877 ^a	170.438 ^a	7.855 ^c	12.405 ^c	19.652 ^c	22.087 ^a	188.145 ^a	146.672 ^a
S ₂ -1 st FN of August	24.722 ^a	90.285 ^{ab}	166.950 ^{ab}	9.472 ^a	13.510 ^a	23.483 ^a	21.830 ^{ab}	183.222 ^{ab}	143.057 ^{ab}
S ₃ -2 nd FN of August	24.031 ^{ab}	87.818 ^{bc}	163.282 ^b	9.270 ^{ab}	13.170 ^{ab}	22.418 ^b	21.258 ^b	180.595 ^b	140.697 ^b
S ₄ -1 st FN of September	23.633 ^b	85.350 ^{cd}	161.387 ^{bc}	9.033 ^b	12.930 ^b	22.177 ^b	18.578 ^c	172.743 ^c	125.305 ^c
S ₅ -2 nd FN of September	22.074 ^c	82.802 ^{de}	155.842 ^{cd}	6.303 ^d	12.123 ^{cd}	17.278 ^d	16.952 ^d	165.928 ^d	112.104 ^d
S ₆ -1 st FN of October	20.867 ^d	80.269 ^{ef}	150.227 ^{de}	6.037 ^d	11.662 ^{de}	15.870 ^e	15.207 ^e	151.308 ^e	101.140 ^e
S ₇ -2 nd FN of October	20.235 ^d	77.787 ^f	148.310 ^e	4.923 ^e	11.210 ^e	14.555 ^f	14.490 ^e	142.688 ^f	91.064 ^f
LSD ($p = 0.05$ %)	0.868	3.564	6.143	0.302	0.479	0.760	0.740	6.572	4.633
Interactions									
Y×G	NS	NS	NS	NS	NS	NS	NS	NS	NS
Y×S	NS	NS	NS	0.428	NS	NS	1.046	NS	NS
G×S	NS	NS	NS	0.428	NS	1.075	NS	NS	NS
Y×G×S	NS	NS	NS	NS	NS	NS	NS	NS	NS

DAS: days after sowing; FN: fortnight; NS: non-significant.

Table 2. Yield attributes and agrometeorological efficiencies of chia as influenced by genotypes and sowing windows

Treatments	Seed yield (kg/ha)	Seed yield (g/plant)	Test weight (g)	Inflorescence length (cm)	Number of inflorescence	HUE (kg ha ⁻¹ °C day)	HTUE (kg ha ⁻¹ °C days ⁻¹ hr ⁻¹)	PTUE (kg ha ⁻¹ °C days ⁻¹ hr ⁻¹)
Year (Y)								
2023	1198.569 ^a	15.305 ^a	1.454 ^a	19.081 ^a	23.537 ^a	0.715 ^b	0.161 ^a	0.059 ^b
2024	1170.028 ^b	14.979 ^b	1.421 ^b	17.340 ^b	21.884 ^b	0.784 ^a	0.114 ^b	0.067 ^a
LSD (p = 0.05 %)	23.697	0.312	0.029	0.379	0.464	0.015	0.003	0.001
Genotypes (G)								
G ₁ -Black	1217.441 ^a	15.614 ^a	1.474 ^a	18.699 ^a	23.098 ^a	0.728 ^b	0.132 ^b	0.060 ^b
G ₂ -White	1151.156 ^b	14.670 ^b	1.401 ^b	17.722 ^b	22.324 ^b	0.771 ^a	0.144 ^a	0.066 ^a
LSD (p = 0.05 %)	23.697	0.312	0.029	0.379	0.464	0.015	0.003	0.001
Sowing windows (S)								
S ₁ -2 nd FN of July	1189.710 ^b	15.288 ^c	1.432 ^{ab}	18.723 ^c	23.413 ^b	0.634 ^d	0.118 ^d	0.053 ^e
S ₂ -1 st FN of August	1325.915 ^a	17.013 ^a	1.480 ^a	20.324 ^a	24.722 ^a	0.707 ^c	0.131 ^c	0.059 ^d
S ₃ -2 nd FN of August	1300.880 ^a	16.671 ^{ab}	1.472 ^a	19.614 ^b	24.031 ^{ab}	0.756 ^b	0.142 ^{ab}	0.064 ^c
S ₄ -1 st FN of September	1286.765 ^a	16.230 ^b	1.438 ^{ab}	19.525 ^b	23.633 ^b	0.790 ^a	0.147 ^a	0.068 ^b
S ₅ -2 nd FN of September	1111.035 ^c	14.526 ^d	1.428 ^{ab}	18.242 ^c	22.074 ^c	0.741 ^b	0.138 ^b	0.059 ^d
S ₆ -1 st FN of October	1055.780 ^d	13.483 ^e	1.412 ^b	16.289 ^d	20.867 ^d	0.804 ^a	0.145 ^a	0.068 ^b
S ₇ -2 nd FN of October	1020.002 ^d	12.781 ^f	1.400 ^b	14.754 ^e	20.235 ^d	0.812 ^a	0.144 ^a	0.071 ^a
LSD (p = 0.05 %)	44.332	0.584	0.055	0.710	0.868	0.028	0.005	0.002
Interactions								
Y×G	NS	NS	NS	NS	NS	NS	NS	0.002
Y×S	NS	NS	NS	NS	NS	0.04	NS	0.003
G×S	62.695	0.827	NS	NS	NS	0.04	0.008	0.003
Y×G×S	NS	NS	NS	NS	NS	NS	NS	0.005

FN: fortnight; HTUE: helio thermal use efficiency; HUE: heat use efficiency; NS: non-significant; PTUE: photothermal use efficiency.

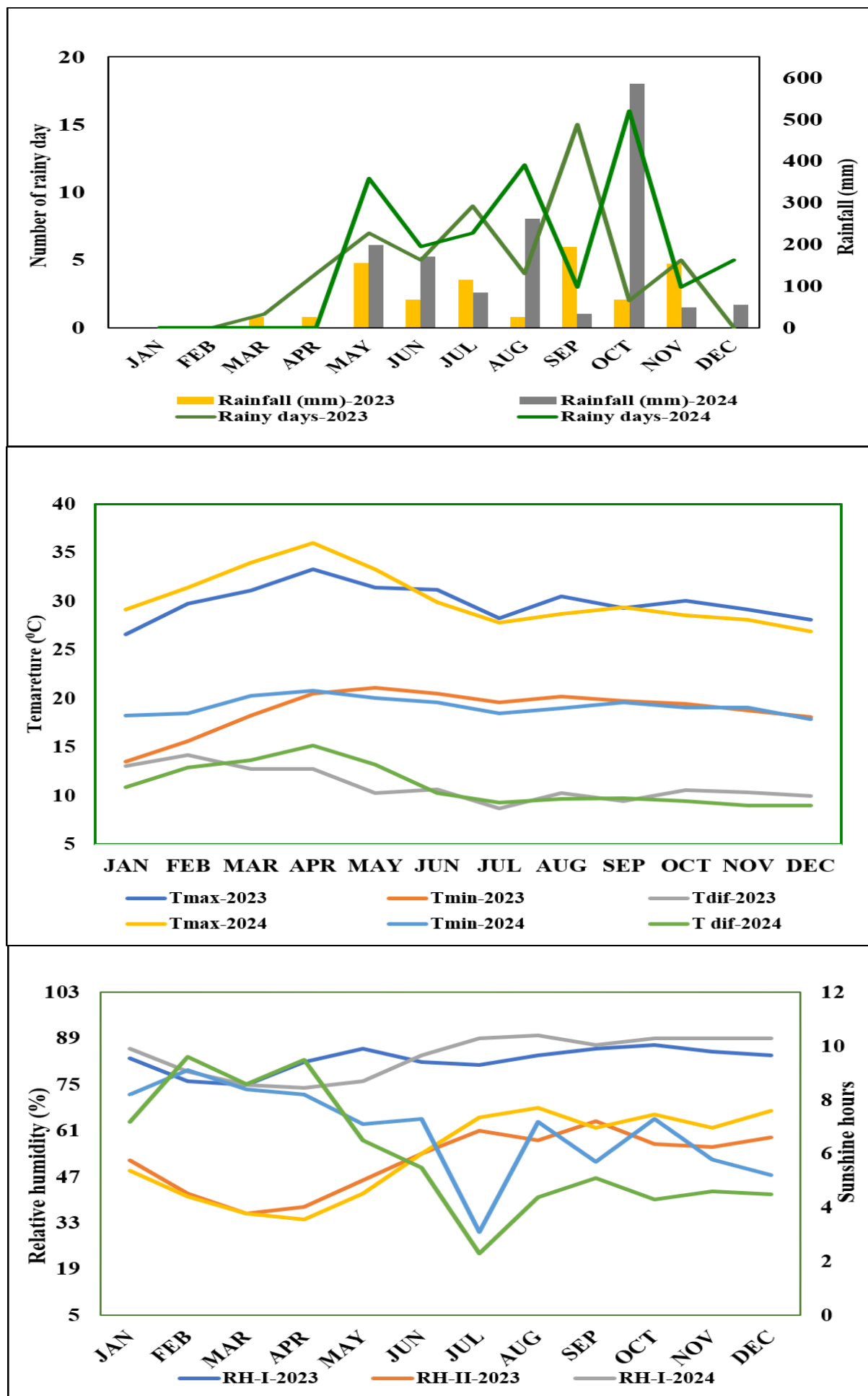


Fig. 1. Weather parameters during the cropping period of chia (Years 2023 and 2024). A) Rainfall and number of rainy days; B) Maximum and minimum temperature and C) Relative humidity and sunshine hours.

(20.235 plant⁻¹). The superior performance of August sowing may be attributed to better synchronisation of vegetative and reproductive phases with favourable thermal and moisture conditions, which enhanced photosynthetic activity, assimilate translocation and grain filling. Delayed sowing exposed the crop to shortened photoperiod and comparatively cooler conditions during reproductive stages, which accelerated phenological progression and reduced the duration available for biomass accumulation and grain filling. Similar observations were reported (9, 14), which observed that optimum sowing periods improved reproductive development and SY in chia.

Agrometeorological efficiencies were markedly influenced by sowing time. Higher HUE was recorded under S_7 (0.812 kg ha⁻¹ °C day) and S_6 (0.804 kg ha⁻¹ °C day), while S_4 registered higher HTUE (0.147 kg ha⁻¹ °C days⁻¹ hr⁻¹) and S_7 recorded higher PTUE (0.071 kg ha⁻¹ °C days⁻¹ hr⁻¹). Conversely, S_1 recorded lower HUE (0.634 kg ha⁻¹ °C day), HTUE (0.118 kg ha⁻¹ °C days⁻¹ hr⁻¹) and PTUE (0.053 kg ha⁻¹ °C days⁻¹ hr⁻¹). Although delayed sowing exhibited relatively higher efficiency indices due to reduced thermal accumulation and shorter crop duration, the absolute yield remained lower. This indicates that efficiency indices alone do not necessarily reflect productivity potential. Under delayed sowing, the crop produced lower biomass but utilised the limited accumulated thermal units more efficiently on a per-unit basis. However, shortened vegetative duration restricted canopy expansion, assimilate production and sink development, thereby reducing final SY. In contrast, early and optimum sowing windows accumulated greater biomass and reproductive structures, even though thermal efficiency indices were comparatively lower. Therefore, optimum synchronisation between temperature, photoperiod and crop phenology during S_2 and S_3 favoured better biomass partitioning and reproductive development, ultimately resulting in higher yield. Further, the excessive vegetative growth observed under the 2nd FN of July sowing increased susceptibility to lodging due to stem elongation and higher biomass accumulation under favourable early-season moisture conditions. Lodging may have adversely affected assimilate translocation, inflorescence orientation and photosynthetic efficiency during reproductive stages, thereby limiting yield despite prolonged crop duration and higher thermal accumulation. This observation indicates that very early sowing may not always be advantageous under semi-arid conditions, particularly when excessive vegetative growth predisposes the crop to lodging stress. Similar enhancement in yield components under optimum sowing periods was documented (9, 14), who emphasised the importance of thermo-photoperiod synchronisation for maximising reproductive development.

Phenology and agrometeorological indices

Phenological progression and thermal accumulation varied significantly among the treatments (Fig. 2, Table 3). The phenological stages, viz., emergence, branching, 50 % flowering and physiological maturity, were attained earlier under delayed sowing (S_6 and S_7), whereas early sowing windows (S_1 and S_2) prolonged the crop duration. The crop sown during the 1st FN of July (S_1) took 78.20 days to 50 % flowering and 132.01 days to physiological maturity, while the 2nd FN of October sowing (S_7) required 58.82 days to 50 % flowering and 98.27 days to physiological maturity. Similarly, the 1st FN of August sowing (S_2) attained 50 % flowering and physiological maturity in 75.77 and 128.13 days, respectively. Total GDD were higher during 2023

(1754.643 °C days) compared to 2024 (1527.718 °C days), which coincided with extended phenophases and improved growth and yield.

Black chia accumulated higher total GDD (1728.064 °C days) compared to G_2 -white chia (1554.296 °C days), indicating a relatively prolonged duration to flowering and maturity. The extended vegetative and reproductive phases in black chia (G_1) may have facilitated greater assimilate accumulation ultimately supporting better sink development and higher SY. The influence of sowing date on phenology and thermal accumulation has been widely documented in chia (2, 15).

Among sowing windows, 1st FN of August and the 2nd FN of July sowing accumulated significantly higher total GDD (1907.800 and 1887.975 °C days, respectively) and exhibited prolonged duration to flowering and maturity (Fig. 02). In contrast, the 2nd FN of October sowing accumulated significantly lower GDD (1277.487 °C days) and reached flowering and physiological maturity earlier, indicating forced phenological advancement due to elevated temperatures during later growth stages. Reduced heat accumulation under delayed sowing shortened both vegetative and reproductive phases, potentially limiting biomass production and assimilate translocation during grain filling. The accelerated phenological progression under late sowing may represent an adaptive response of chia to suboptimal environmental conditions, wherein the crop completes its life cycle rapidly under declining thermal and photoperiodic regimes. However, this reduction in crop duration restricted source development and sink formation, thereby reducing final productivity. Similar photothermal sensitivity of flowering behaviour under different sowing windows was reported (17).

Correlation studies

Correlation analysis revealed a significant positive correlation between SY and growth parameters (Fig. 3). Seed yield showed a significant positive correlation with establishment % ($r = 0.85$), PH at harvest ($r = 0.80$), NB per plant ($r = 0.97$) and NL per plant ($r = 0.83$), total dry matter production (TDMP) (0.84), leaf area (LA) (0.74) and leaf area index (LAI) (0.74). The positive correlation of SY with NL, dry matter accumulation and branching indicates that plants with greater vegetative growth tended to record higher productivity. A higher NL, greater biomass accumulation and increased branching reflect a more vigorous crop growth pattern, which was associated with superior yield performance under the experimental conditions. A similar positive correlation between vegetative growth traits and SY in chia has been reported under different agroclimatic conditions (8, 14).

Seed yield also exhibited a strong positive correlation with yield attributes (Fig. 4). The highest positive correlation was observed between SY and SYP ($r = 0.99$), indicating a close association between per plant productivity and overall yield. Seed yield also showed a strong positive correlation with the NS per plant ($r = 0.96$) and SL ($r = 0.90$), suggesting that increased inflorescence production and longer inflorescences enhanced sink capacity and consequently improved yield. Test weight was moderately and positively correlated with SY ($r = 0.75$), indicating that seed size contributed to yield improvement, though its influence was comparatively lower than inflorescence number and SL. Harvest index (HI) exhibited a very weak negative correlation with SY ($r = -0.05$), suggesting that partitioning

Table 3. Growing degree days (GDD) of chia as influenced by genotypes and the sowing windows at different phenological phases

Treatments	GDD (°C day)					Total
	P ₁	P ₂	P ₃	P ₄	P ₅	
Year (Y)						
2023	273.721 ^a	345.407 ^a	433.950 ^a	470.093 ^a	231.471 ^a	1754.643 ^a
2024	245.307 ^b	322.339 ^b	339.968 ^b	405.650 ^b	214.454 ^b	1527.718 ^b
LSD (p = 0.05 %)	5.404	6.976	8.369	9.235	4.671	34.407
Genotypes (G)						
G ₁ -Black	272.914 ^a	348.029 ^a	406.668 ^a	467.075 ^a	233.379 ^a	1728.064 ^a
G ₂ -White	246.114 ^b	319.718 ^b	367.250 ^b	408.668 ^b	212.546 ^b	1554.296 ^b
LSD (p = 0.05 %)	5.404	6.976	8.369	9.235	4.671	34.407
Sowing windows (S)						
S ₁ -2 nd FN of July	294.575 ^a	377.875 ^a	436.175 ^a	513.125 ^b	266.225 ^a	1887.975 ^a
S ₂ -1 st FN of August	292.300 ^a	364.775 ^b	415.500 ^b	588.675 ^a	246.550 ^b	1907.800 ^a
S ₃ -2 nd FN of August	272.800 ^b	364.750 ^b	393.025 ^c	465.975 ^c	237.300 ^c	1730.825 ^b
S ₄ -1 st FN of September	269.775 ^b	343.975 ^c	373.875 ^d	432.725 ^d	219.188 ^d	1638.125 ^c
S ₅ -2 nd FN of September	258.100 ^c	318.700 ^d	441.925 ^a	373.725 ^e	214.750 ^d	1611.638 ^c
S ₆ -1 st FN of October	220.000 ^d	293.788 ^e	381.738 ^{cd}	351.438 ^f	189.275 ^e	1434.412 ^d
S ₇ -2 nd FN of October	209.050 ^e	273.250 ^f	266.475 ^e	339.438 ^f	187.450 ^e	1277.487 ^e
LSD (p = 0.05 %)	10.110	13.050	15.657	17.278	8.739	64.37
Interactions						
Y×G	NS	NS	NS	13.061	6.606	48.659
Y×S	14.297	NS	22.143	24.435	12.359	91.033
G×S	14.297	18.455	22.143	24.435	12.359	91.033
Y×G×S	20.22	NS	31.315	34.556	17.479	128.741

FN: fortnight; GDD: growing degree days; NS: Non-significant.

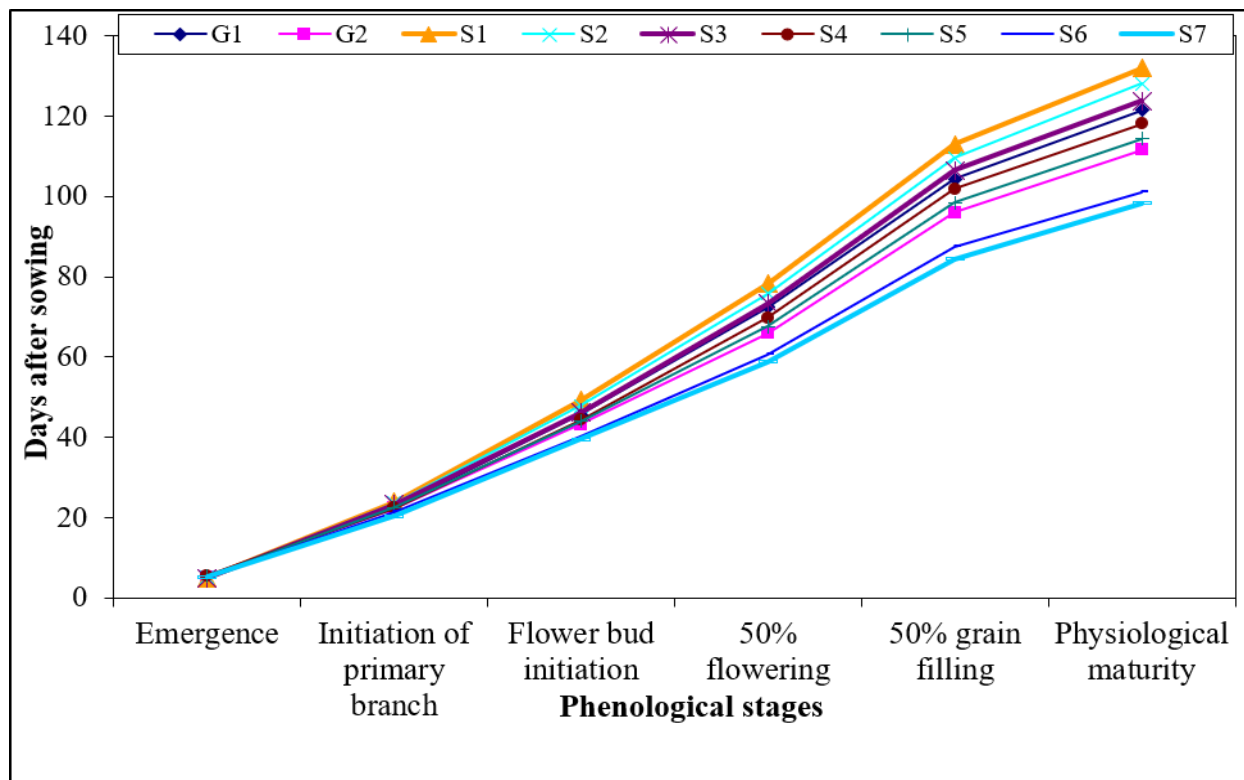


Fig. 2. Phenology of chia as influenced by the genotypes and sowing windows (pooled data of two seasons).

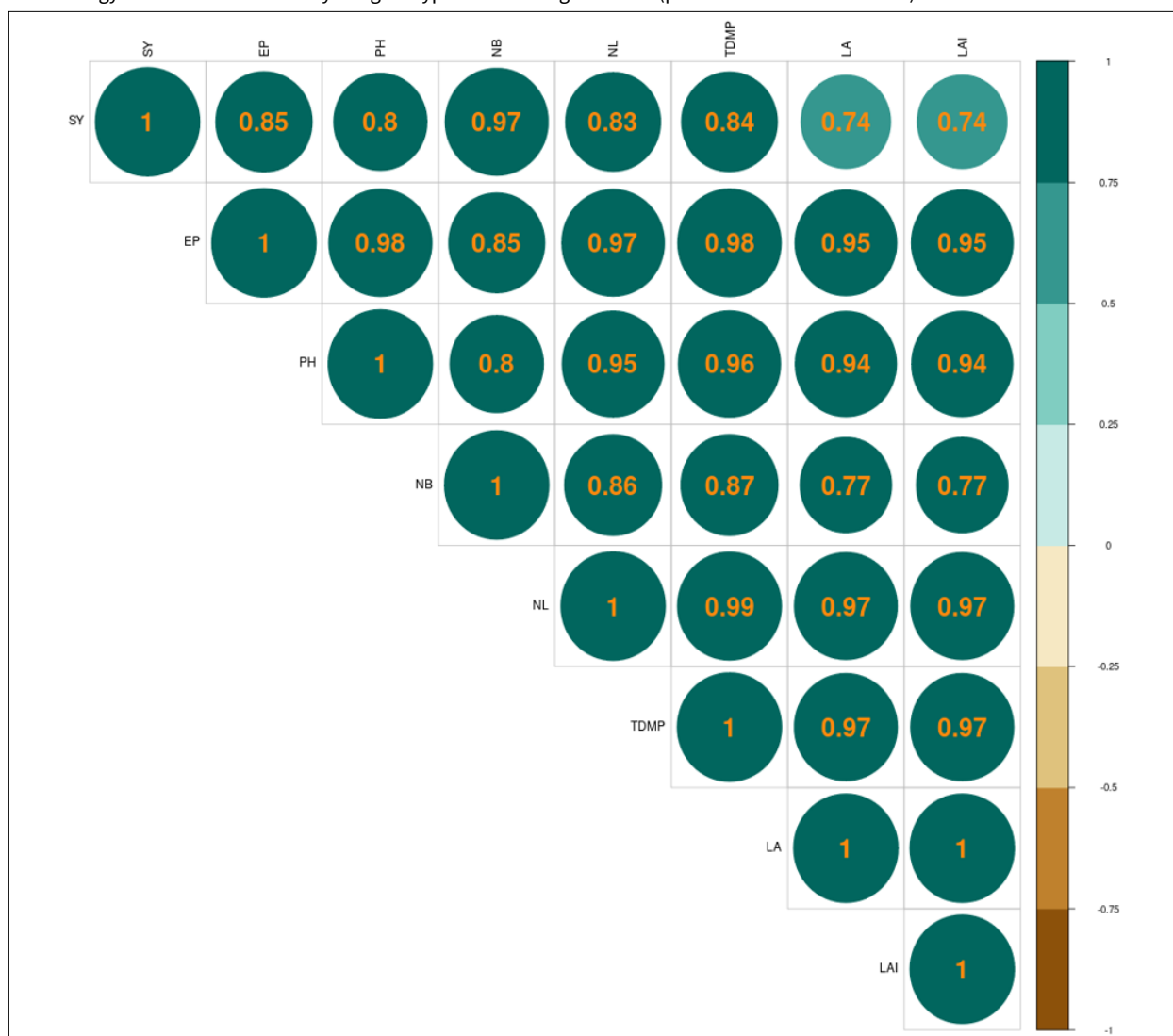


Fig 3. Correlation between seed yield and growth parameters of chia as influenced by genotypes and sowing windows (pooled data of two seasons). SY: seed yield; EP: establishment percent; PH: plant height; NB: number of branches; NL: number of leaves; TDMP: total dry matter production; LA: leaf area; LAI: leaf area index.

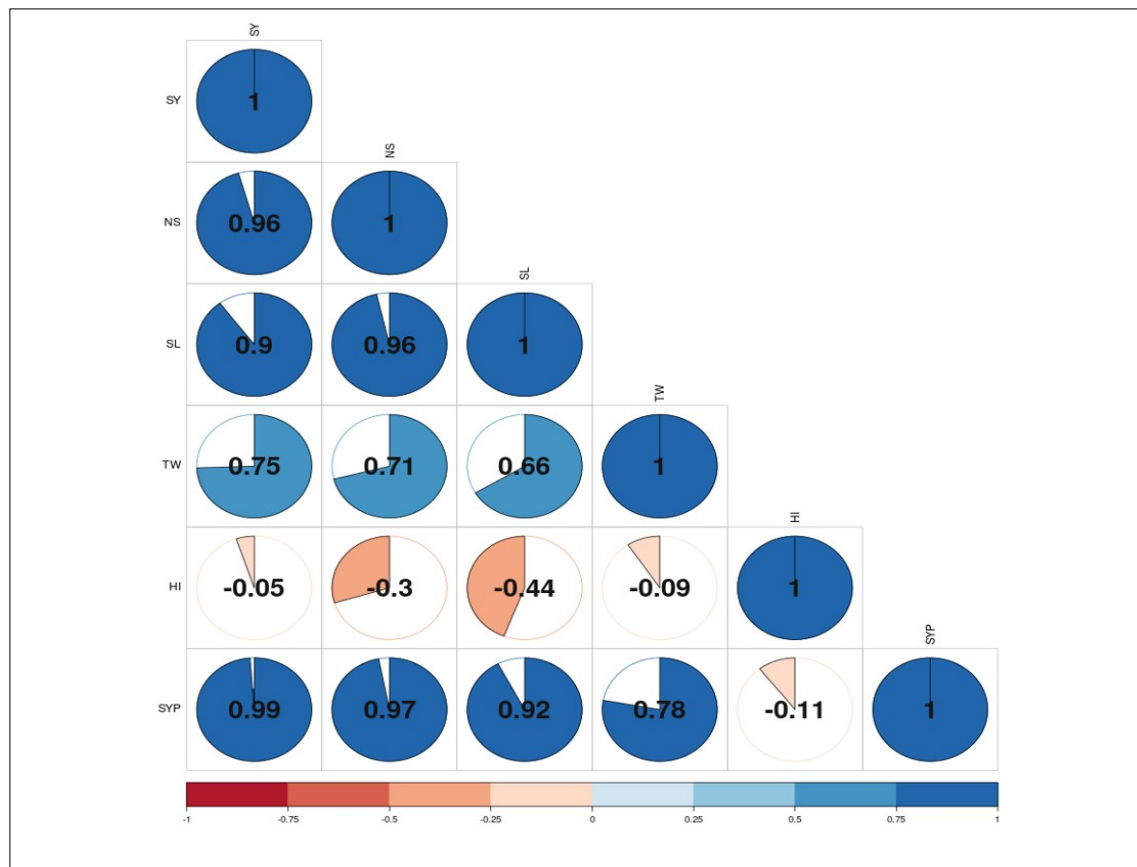


Fig. 4. Correlation between seed yield and yield parameters of chia as influenced by genotypes and sowing windows (pooled data of two seasons). SY: seed yield; NS: number of inflorescences plant⁻¹; SL: inflorescence length plant⁻¹; TW: test weight; HI: harvest index; SYP: seed yield plant⁻¹.

efficiency alone was not a major determinant of yield variation under the present study. This suggests that biomass production and yield components were primary determinants of yield. Similar associations between inflorescence traits and SY have been reported in chia (1, 7). The correlation analysis revealed that both vegetative growth traits and yield attributes were closely associated with SY, highlighting their importance in characterising productivity under the prevailing experimental conditions.

Principal component analysis of weather and growth parameters

Principal component analysis revealed that PC1 accounted for 87.1 % of total variability, while PC2 contributed 7.1 % (Fig. 5). Together, the first two principal components accounted for 94.2 % of the total variation. The predominance of PC1 indicates that a common underlying gradient was responsible for most of the variability among treatments, whereas PC2 captured a comparatively smaller proportion of the variation.

Plant height (PH), NB, NL, TDMP, LA and LAI were strongly and positively loaded along PC1. Establishment percentage (EP) also aligned positively, suggesting that early stand establishment contributed substantially to final vegetative development. Similar strong association between canopy traits (LAI, biomass) and thermal regime have been reported in chia under semi-arid conditions (17). The vegetative biomass and canopy expansion in chia are closely regulated by temperature accumulation and sowing date effects (14).

Among weather variables, maximum temperature (T_{max}), minimum temperature (T_{min}) and mean temperature (T_{mean}) showed strong positive association with growth traits along PC1, confirming that thermal accumulation was the dominant driver of

vegetative expansion. Similar temperature-driven biomass responses in chia have been documented (9, 26) which reported that growth and phenological progression are highly sensitive to thermo-photoperiodic conditions. Previous studies have shown that suitable thermal regimes enhance dry matter accumulation and leaf development under different sowing windows (15).

Rainfall also aligned positively with growth parameters, indicating that adequate moisture availability supported LA development and TDMP. Similar findings were reported (19), which observed improved vegetative growth and canopy development under optimum moisture conditions. In contrast, SSH were positioned in the opposite direction of the growth traits along PC1, indicating a negative association. Excessive sunshine duration may increase evaporative demand and canopy stress, thereby restricting leaf expansion and biomass accumulation. The study reported that higher radiation load combined with thermal stress can adversely influence vegetative growth in chia under arid conditions (18). The PCA clearly demonstrates that vegetative growth of chia was predominantly governed by temperature-driven thermal accumulation supported by adequate rainfall, whereas excessive sunshine exposure exhibited an antagonistic influence. These findings reinforce the importance of synchronising sowing time with favourable thermal regimes to optimise canopy development and biomass production.

Principal component analysis of weather and yield parameters

Principal component analysis revealed that PC1 accounted for the 70.9 % of total variability, while the second principal component (PC2) explained 16.9 %, together contributing 87.8 % of the total variability (Fig. 6). Yield traits including SY, SYP, NS, SL, TW and HI were strongly and positively loaded along PC1, suggesting

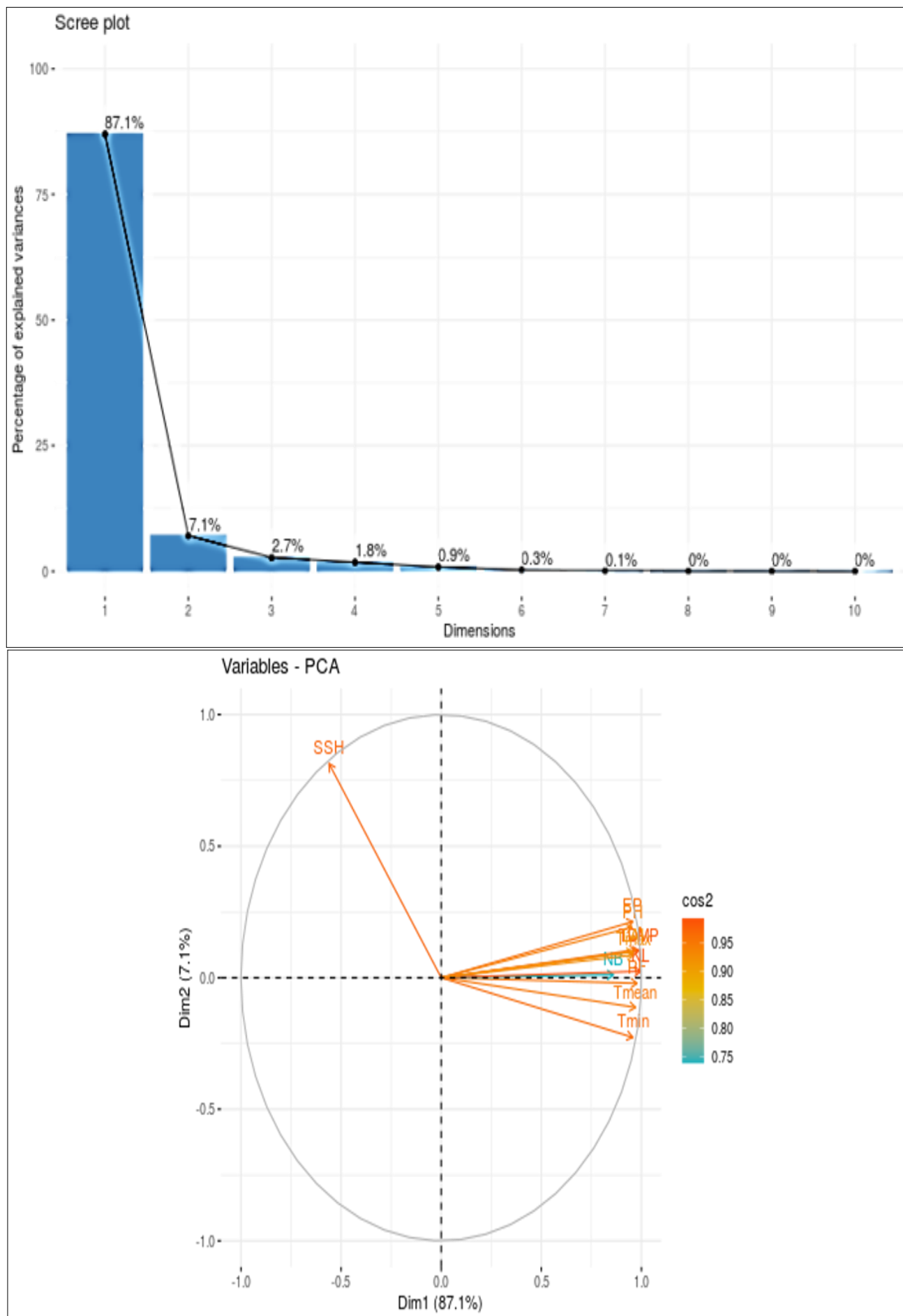


Fig. 5. Variable principal component analysis between weather and growth parameters of chia as influenced by genotypes and sowing windows (pooled data of two seasons). RF: Rainfall; Tmax: maximum temperature; Tmin: minimum temperature; Tmean: mean temperature; SSH: sunshine hours; EP: establishment percent; PH: plant height; NB: number of branches; NL: number of leaves; TDMP: total dry matter production; LA: leaf area, LAI: leaf area index.

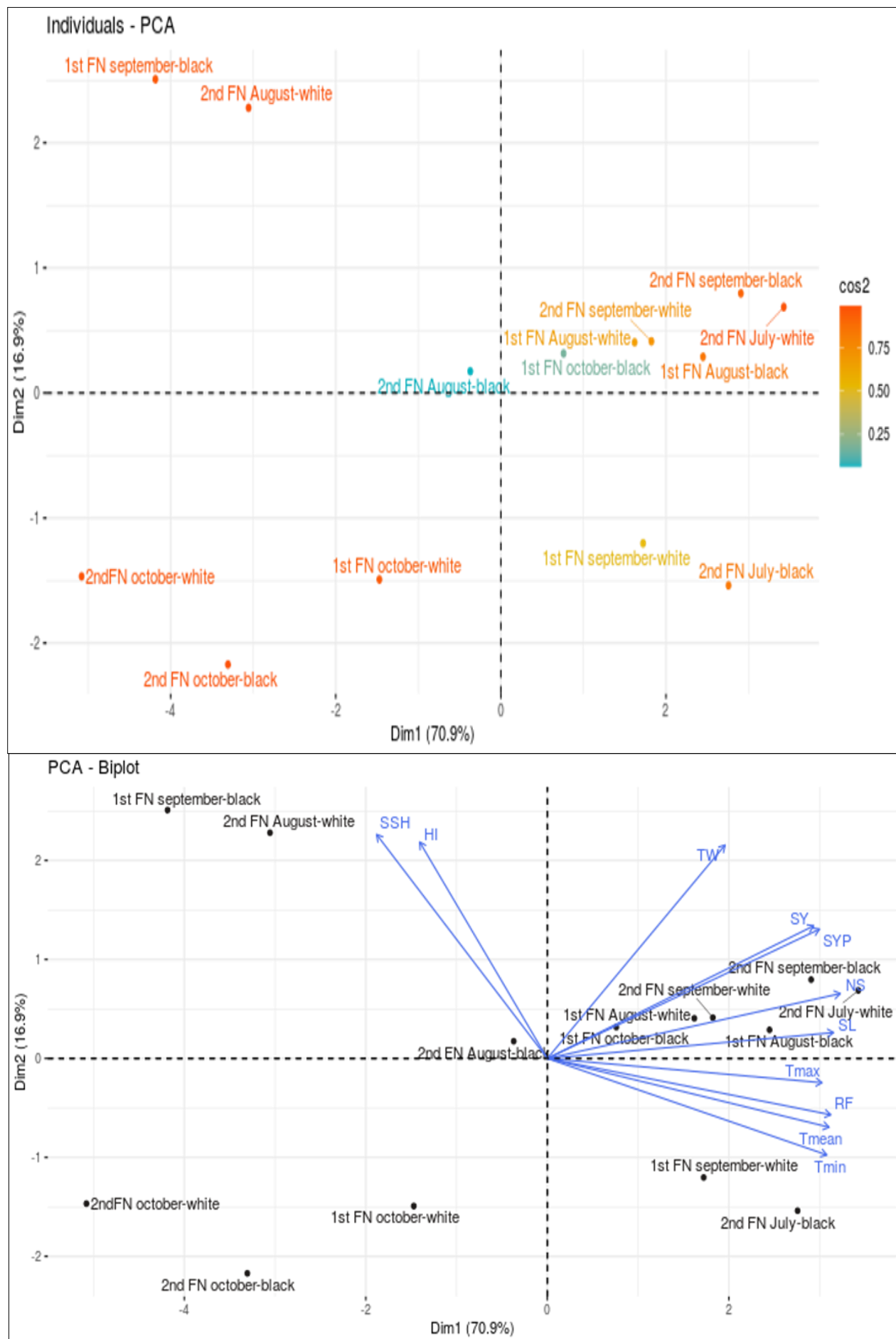


Fig. 6. Principal component analysis between weather parameters and yield parameters of chia as influenced by genotypes and sowing windows (pooled data of two seasons). RF: Rainfall; Tmax: maximum temperature; Tmin: minimum temperature; Tmean: mean temperature; SSH: sunshine hours; SY: Seed yield; SYP: seed yield plant⁻¹; TW: test weight; HI: harvest index; NS: number of inflorescence plant⁻¹; SL: inflorescence length.

coordinated regulation of sink size and grain filling efficiency.

Maximum temperature ($T_{\max}$) and T_{mean} showed strong positive alignment with yield parameters, indicating that favourable thermal regimes during reproductive stages enhanced inflorescence development and assimilate partitioning. Similar temperature-driven responses of reproductive growth have been widely documented in oilseed crops, where optimal thermal conditions promote floret fertility, seed set and grain filling (10, 11). In chia specifically, phenology and yield sensitivity to thermo-photoperiod conditions have also been demonstrated under contrasting environments (1).

Minimum temperature ($T_{\min}$) exhibited moderate positive association with PC1 but contributed to variation along PC2, indicating that night temperature may influence grain filling dynamics. Elevated night temperatures have been reported to alter assimilate partitioning and reduce yield stability in several crops (12), highlighting the importance of a balanced diurnal thermal regime.

Rainfall (RF) also aligned positively with yield traits, suggesting that adequate soil moisture during flowering and grain filling supported inflorescence number and seed weight. Moisture availability during the reproductive phase has been reported to significantly influence HI and final yield in short-duration oilseeds (16). In contrast, SSH and RH were oriented opposite to yield variables, indicating a negative association. Excessive radiation load combined with high evaporative demand may increase canopy temperature and accelerate phenological progression, thereby shortening grain filling duration and reducing seed weight (13). The antagonistic orientation of SSH relative to SY and TW in the present study supports this interpretation.

Treatments corresponding to early-mid August sowing were positioned near the positive PC1 region, reflecting their association with higher SY and improved yield attributes. Late sowing treatments clustered away from the positive yield axis, indicating sub-optimal environmental synchronisation during reproductive development. The PCA indicates that yield performance in chia was predominantly regulated by a favourable temperature regime and adequate moisture availability during reproductive stages, whereas excessive sunshine exposure showed an inverse relationship. These findings emphasise the need to align sowing window with optimal thermal conditions to maximise reproductive efficiency and yield stability.

Conclusion

The study revealed that sowing windows and genotypes significantly influenced growth, phenology and seed yield (SY) of chia under semi-arid conditions of Bengaluru. Black chia recorded higher growth and SY, while sowing during the 1st fortnight (FN) of August provided favourable thermal and moisture conditions for improved productivity, whereas delayed sowing increased thermal use efficiencies but reduced overall yield because of shortened crop duration and lower biomass accumulation. Correlation and principal component analyses indicated that temperature-driven thermal accumulation, supported by adequate rainfall, predominantly governed growth and yield. Hence, sowing black chia during 1st FN of August was found to be suitable for achieving higher productivity in the Eastern dry zone of

Karnataka. Further investigations on physiological mechanisms governing thermal accumulation, assimilate partitioning, genotype and environment interactions and reproductive efficiency under varying thermo-photoperiodic regimes may contribute to the development of climate-resilient and high-yielding chia production systems.

Acknowledgements

We sincerely thank the authorities and staff of M Block, All India Coordinated Research Network (AICRN) on Potential Crops, University of Agricultural Sciences, Gandhi Krishi Vigyan Kendra, Bengaluru, for granting permission to utilise the experimental land and for extending necessary labour support and field infrastructure required for carrying out the present investigation.

Authors' contributions

UN conceptualised and conducted the field experiments, collected and analysed the data and prepared the original manuscript. RC supervised the research work, contributed to the experimental design and critically revised the manuscript. ASR assisted in data interpretation and statistical analysis. MK supported laboratory analysis and technical guidance. SB provided overall guidance, reviewed and approved the final manuscript. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

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

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the Artificial intelligence (AI) tool, ChatGPT, was used solely for language refinement, grammar correction and improving the clarity of the manuscript. The scientific content, data analysis, interpretation of results and conclusions presented in this study are entirely the original work of the authors. No AI tools were used for generating experimental data or altering research outcomes. The authors take full responsibility for the accuracy, integrity and originality of the work.

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