Optimizing sowing time and weather conditions for enhanced growth and seed yield of chia (*Salvia hispanica* L.) in semi-arid regions

CB Harisha[1*], KM Boraiah[1*], PS Basavaraj[1], Hanamant M. Halli[1], RN Singh[1], Jagadish Rane[1,2], K Sammi Reddy[1], GR Halagundegowda[3], Amresh Chaudhary[1,4], Arvind Kumar Verma[5], Y Ravi[5], Honnappa Asangi[6], E Senthamil[7]

[1] Scientist, ICAR-National Institute of Abiotic Stress Management, Baramati, Pune- 413 115, Maharashtra, India

[2] ICAR-Central Institute of Arid Horticulture, Bichhwal-334006, Bikaner-334006, Rajasthan, India

[3] Central Silk Board, Bangalore 560035, India

[4] ICAR-Central soil Salinity Research Institute, Karnal- 132001, Haryana, India

[5] ICAR-National Research Centre on Seed Spices, Ajmer- 305006, Rajasthan, India

[6] ICAR-Indian Institute of Spice Research, RS Appangala- 571201, Karnataka, India

[7] Ph.D. Scholar, University of Agricultural Sciences, Dharwad- 580005, Karnataka, India

Correspondence to:
Scientist, ICAR-National Institute of Abiotic Stress Management, Pune-413115, India.
Email address: Harisha.B@icar.gov.in (CB Harisha); hmhalli4700@gmail.com (Hanamant M. Halli)
*equal first author

ABSTRACT

Background: Climate change-influenced weather events, especially during the flowering, grain filling, and maturity stages, can adversely influence crop yield and quality. Therefore, understanding how the phenological behavior and yield potential of new crops, such as chia, are influenced by weather and sowing dates is crucial for maximizing crop yield. This study aimed to assess the impact of sowing dates on the flowering behavior and yield attributes of chia morphotypes, as well as to identify optimal weather conditions for achieving higher yields.

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Methods: The study was conducted during 2021-22 and 2022-23 and consisted of fifteen sowing windows from 1st July to 1st February (at 15 days interval), with two chia morphotypes (white and black seed) arranged in a replicated split-plot design. Phenological events, flowering characters, and seed yield traits were recorded regularly. Weather parameters at the experimental location (Maharashtra, India) were recorded.

Results: The results revealed that weather conditions such as higher relative humidity (RH) and rainfall favoured the flowering phenology, yield attributes, and seed yield of chia, whereas maximum temperature (T_{max}), bright sunshine hours, and accumulated growing degree days had negative effects. Chia seed yield was significantly influenced by weather parameters during the cropping period: RH (positive, R^2=86.1%), T_{max} (negative, R^2=67.4%), rainfall (positive, R^2=52.9%), and diurnal temperature range (negative, R^2=74.9%). Black-seeded chia morphotypes consistently produced higher seed yields (10.8% greater) and better yield-contributing traits compared to white types across various sowing dates. The maximum chia seed yield (811–793.1 kg ha–1) was achieved with sowing dates between August 1st and September 1st in this semi-arid region of India. The performance of chia was good under congenial weather conditions, including relative humidity (~67–72%), maximum temperature (~30–31°C), day length (<12.0 hours), rainfall (~200–350 mm), and accumulated growing degree days (~1521–1891). The present study findings can help identify the best suitable regions for chia cultivation by revealing relationships between the performance chia morphotypes and weather conditions.

Keywords: Chia, flowering phenology, sowing dates, weather parameters, growing degree days, temperature, yield attributes.

Introduction

Climate change-induced weather events adversely influence the yield and quality of oilseeds by altering crop-growing conditions at both regional and national levels (*Attia et al., 2021*). The global average yield of major oilseed crops such as sunflower, soybean, and canola have plateaued over the last several years (*Attia et al., 2021*; *Ray et al., 2019*). In the last few decades, the import of oilseeds has increased tremendously in the Indian subcontinent due to decreased productivity of major oilseed crops (*Brassicaceae*) (*Jingar et al., 2023*). An average healthy adult intake about 20–35% of their calories through oil and fats. The human body is unable to synthesize two essential fatty acids: alpha-linolenic and linoleic acids (*Saini and Keum, 2018*). Thus, causing ever-increasing pressure on global food

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and nutritional security and determining the Sustainable Development Goals (SDG-2, zero hunger) (*Halli et al., 2024*). Therefore, these two essential fatty acids must be directly obtained from healthy sources like fish and oilseed crops such as chia to reduce the risk of cardiovascular diseases and high blood pressure (*Kris-Etherton and Krauss, 2020*).

In this context, chia (*Salvia hispanica* L.) is an important crop belonging to the *Lamiaceae* family with high nutritional and medicinal values, thriving well in tropical and subtropical climates (*Capitani et al., 2013*). Besides, chia oil can also be used for industrial purposes such as a stabilizer and binder in food processing (*Felisberto et al., 2015; Pathak et al., 2015*), and as an anti-corrosive agent. Apart from its higher protein content, chia seeds contain a notable amount of fixed oil (20.3% to 38.6%), prominently featuring α–linolenic acid (55%) and linoleic acid (19%) (*Attia et al., 2023; Ayerza and Coates, 2011*). The well-balanced profile of essential amino acids makes chia a preferred ingredient for the development of health-oriented products, hence it is often referred to as a "superfood" (*Fernandes et al., 2020*). Accordingly, the consumer tendency to choose food crops like chia, nutri-millets, and grain amaranth is increasing due to multiple health benefits and to combat malnutrition. Consequently, in India, chia cultivation extends across many central and southern states to meet the increasing demand for balanced edible oil and industrial applications. In 2023, the global market for chia was valued at US$ 203 million, and further market insights anticipate a cumulative growth rate of at least 7%, reaching US$ 390 million by 2033 (*Chia Seed Market, 2024*). Because of its suitability under resource-scarce conditions (water, poor soils, and nutrients) of tropical and subtropical regions, the area under chia cultivation is gradually increasing in many states of the country (*Harisha et al., 2023*). However, limited technical information is available on cultivation practices, such as optimum sowing time, weather relation with flowering behavior and yield traits in semi-arid regions (*Attia et al., 2023*; *Jingar et al., 2023*).

In recent years, deviated weather events such as rainfall, temperature, and relative humidity have altered crop performances, prompted the farmers to adopt sowing windows that may not be optimum for crop performance in general. Similarly, in the case of chia, varied sowing windows from July–August to mid-winter December–January result in dwindling responses in terms of flowering, maturity, seed yield, and oil quality (*Karim et al., 2015; Ram et al., 2024*). Chia seed yield is highly responsive to sowing dates, yielding 150 kg ha^{-1} in December sowing and 354 kg ha^{-1} in October sowing under Indian conditions (*Guttedar et al., 2023*). These variations could be predominantly credited to the wide range of prevailing weather conditions (temperature, relative humidity, and rainfall), especially in photosensitive crops (*Ayerza and Coates, 2009; Hirich et al., 2014*). Flower induction in chia requires temperatures between 20–30°C, annual rainfall between 500–1000 mm, and a photoperiod of less than 12 hours (*Jamboonsri et al., 2012*). Suboptimal photoperiods can lead to reduced reproductive phases and increased vegetative growth (*Baginsky et al., 2016*). For example, early sowing in June or July encounters high temperatures and long day lengths initially, extending the growth period or accumulating higher heat units, which leads to enhanced vegetative biomass but decreased seed yield and oil content in chia (*Brandan et al., 2022; Benetoli da Silva et al., 2020*). A positive relation was observed between pre-flowering duration and verticilaster flower weight. While, longer duration leads to more flower dry weight and seed yield in chia. However, the study is limited to growing degree days and photoperiod and the effect of weather parameters before and after flowering was not considered to explain the yield related traits *Brandan et al., (2020)*. Similarly, delayed sown chia experiences initial cooler temperatures and shorter days, followed by hot and dry conditions, which lead to premature floral initiation and shorten the vegetative phase. Therefore, timely sowing is a basic requirement to provide ideal weather conditions for determining the growth and yield of chia (*Baginsky et al., 2016*). A favourable day length and weather conditions during flowering and seed setting stages of chia can optimize the yield and oil quality (*Lobo et al., 2011*).

Apart from climate, diverse morphotypes of chia respond differently to environmental conditions and sowing times (*Benetoli da Silva et al., 2020*). Both white and black-seeded chia types differ in their growth, yield, and oil content (33.8% and 32.7%, respectively) as reported by *Suri et al. (2016)*. However, many studies did not explore how chia morphotypes respond to varying sowing dates, photoperiods, temperatures, and relative humidity concerning growth, pre and post-flowering behaviour, and seed development in semi-arid conditions. The growth dynamics and distribution of assimilates in plants is strongly depend on temperature, relative humidity, and moisture availability (*Silva et al., 2017*). Limited previous studies have investigated the performance of either white or black-seeded chia morphotypes under limited sowing dates and overlooked remaining sowing windows. Yet, no studies have clearly deciphered the impact of wider sowing windows (fifteen sowing dates at intervals of 15 days) in a year on flowering phenology and maturity in two chia morphotypes. The lack of knowledge on how chia morphotypes behave in terms of phenology and seed yield in response to prevailing weather parameters limits the ability to maximize seed yield. Therefore, choosing the ideal sowing time to achieve better synchronized flowering and high seed yield is a primary requirement for any grower or plant breeder. Understanding crop phenology and its relationship with weather helps plant breeders in generation advancement and enables growers to assess yield potential. Such information on how sowing dates and weather parameters influence chia seed and oil yield is crucial for characterizing photoperiod sensitivity and guiding the selection of new niches for chia intensification, thereby reducing climate-induced weather uncertainties to meet the increasing market demand for quality vegetable oil and addressing SDG 13 (climate action). Thus, we hypothesize that sowing dates favouring weather conditions influence flowering phenology and yield attributes of chia types, and the interaction of temperature, relative humidity, and rainfall would optimize vegetative and reproductive phases. Therefore, a two-year field study was planned to determine the effect of varied sowing windows and weather conditions on flower phenology, maturity, and seed yield of chia morphotypes, and also to understand the association between key weather parameters in determining the chia seed yield.

Materials and methods

Weather details of the study location

Field trials were conducted for two consecutive years (2021–22 and 2022–23) at ICAR–National Institute of Abiotic Stress Management (NIASM), Baramati, Pune, Maharashtra, India (Supplementary figure 1). The study site is positioned at 18.15850556º N and 74.50085556º E at an elevation of 570 meters above sea level (MSL). This region falls within the hot and semi-arid zone of the Deccan Plateau region, which is known as the water scarcity zone of the state. The mean maximum and minimum temperature of the region was 31.2℃ and 21.9℃ respectively. The region receives an average annual precipitation of 576 mm, a major portion (75%) is received between August and October (*Harisha et al., 2023*). The annual open-pan evaporation rate of the region is 1965 mm, which is three times more than annual rainfall. The detailed weather parameters for the cropping seasons (2021–22 and 2022–23) are outlined in Fig. 1 and Supplementary Table S1. The weather data on maximum temperature (Tmax), minimum temperature (Tmin), bright sunshine hours (BSS), open pan evaporation, rainfall, relative humidity (RH) for the location during the cropping season was obtained from weather observatory of ICAR-NIASM, Baramati.

Soil details of the experimental site

The soil type of the experimental site was shallow basaltic with 81.9% sand, 10.4% silt, and 7.5% clay exhibits low water holding capacity (*Rajagopal et al., 2018*). The chemical properties of the soil were; pH (7.48), an electrical conductivity (0.21 dS m^{-1}), a moderate level of organic carbon (6.5 g kg^{-1}), low available nitrogen (81.2 kg ha^{-1}), phosphorus (3.6 kg ha^{-1} as P_2O_5), and potassium (80.0 kg ha^{-1} as K_2O).

Experimental details and crop management

The experiment consists of two factors; dates of sowing and chia morphotypes were laid out in split-plot design with three replications. Fifteen dates of sowing (S1; 1st July, S2; 15th July, S3; 1st August, S4; 15th August, S5; 1st September, S6; 15th September, S7; 1st October, S8; 15th October, S9; 1st November, S10; 15th November, S11; 1st December, S12; 15th December, S13; 1st January, S14; 15th January, and S15; 1st February) were treated as main factor and two chia types (White and Black) as sub factor. The plots of size 3 m × 2.5 m were prepared for sowing the seeds of chia types (2.5 kg ha^{-1}) after mixing with sand in 60 cm wider rows. Subsequently, excess and weak plants were removed by retaining one healthy, and maintained a uniform distance of 20 cm between plants within rows. Recommended nutrients (N:P_2O_5:K_2O at 90:60:75 kg ha^{-1}) was applied through fertilizers such as urea, di-ammonium phosphate, and muriate of potash (*Harisha et al., 2023*). The full dose of P_2O_5 and K_2O, and 50% of N was applied during field preparation as a basal, whereas the remaining 50% of N (45 kg/ha) was top dressed through urea in three splits at 30 DAS; days after sowing (15 kg/ha), 45 DAS (15 kg/ha), and 60 DAS (15 kg/ha). The urea was applied in band placement 5 cm away from plants and light raking was done to mix with soil. The chia was cultivated under rainfed conditions with supplemental irrigation. During extended dry spells, supplemental irrigation was scheduled based on soil drying and visible crop moisture deficit symptoms during both the rainy and winter seasons, at a depth of 5 cm at weekly interval using drip system. Weeds were controlled by manual hand weeding, however, the crop remained unaffected by pests and diseases during both cropping periods.

Measurement of chia morphological parameters and phenology

Chia growth attributes such as plant height and dry biomass production were recorded at harvest from five randomly selected plants separately in each treatment. Floral characters such as days to flower bud appearance (FBA), completion of flowering, and maturity were recorded from randomly selected five plants as per the procedure outlined by *Brandan et al.*

(2019). A day to 50% flowering was recorded treatment wise when 50% of plants open their first flower. Likewise, growing degree days (GDD) also called heat unit accumulated up to maturity was calculated for each sowing date as suggested by *Nuttonson (1957)*.

$$\mathrm{GDD} = \frac{\mathrm{T_{Max}} + \mathrm{T_{Min}}}{2} - \mathrm{T_{base}}$$

T_{max} is maximum temperature, T_{min} is minimum temperature, T_{base} is base temperature (10℃) *Ayerza and Coates (2009)*.

Likewise, heat use efficiency (HUE) indicates the capacity of a plant to produce yield per unit of heat used. HUE of the chia crop was calculated using the formula suggested by *Singh and Khushu (2012)*.

$$\mathrm{HUE}\left(\mathrm{kg\ ha^{-1}\ ℃^{-1}\ day^{-1}}\right) = \frac{\mathrm{Grain\ yield\ (kg\ ha^{-1})}}{\mathrm{Accumulated\ GDD\ (℃\ day)}}$$

Seed yield and yield attributes of chia

Yield determinants of chia such as the number of spikes per plant, spike length, seed yield per spike and 1000 seed weight were recorded from five randomly selected plants from each treatment (*Harisha et al., 2024*). Then, seed yield was determined by recording the seed weight from fifty plants in the plot of 7.5 m^2 and sun dried for 3–4 days to attain moisture content of 7±0.5% and expressed in kg ha^{-1}. Likewise, plot wise dry biomass yield was determined from randomly selected five plants after sun drying for 2–3 days followed by oven drying at 63 °C for 72 h to attain constant weight and expressed as dry biomass kg ha^{-1}. Later, the harvest index (HI) was calculated based on the seed and biological yield of chia.

$$\mathrm{HI}\ (\%) = \frac{\mathrm{Grain\ yield\ (kg\ ha^{-1})}}{\mathrm{Dry\ Biomass\ (kg\ ha^{-1})}}$$

Later, grain filling duration (GFD) was calculated considering the number of days between 50% flowering and physiological maturity. Similarly, the grain filling rate was calculated by dividing seed yield with grain filling duration as explained by *Sattar et al. (2023)* in wheat.

Statistics

Before conducting an analysis of variance, the data recorded on various growth, phenology, and yield parameters of chia during both years was tested for normality by the Shapiro–Wilk test using the PROC UNIVARIATE procedure in SAS 9.3 (SAS Institute, Inc., Cary, NC, USA). Then, normal data was subjected to analysis of variance (ANOVA) using the mixed model (proc GLIMMMIX in SAS v 9.3). Chia morphotypes, year, and sowing dates were considered as fixed effects and replications as random effects. Post–hoc test was conducted to compare the difference ($\alpha = 0.05$) using Tukey's honest significant difference (HSD) test. Further, Pearson's correlation coefficient was used to describe the association between weather parameters (T_{max}, T_{min}, RH, accumulated GDD, bright sunshine hours, and rainfall), vs grain yield, days to flower bud appearance, flowering duration, and maturity (*Gomez and Gomez, 1984*). To interpret multi-environment (sowing dates × weather parameters × chia types) interaction, PCA biplot analysis was carried out using R software (version 4.2.3) (*Gopinath et al., 2021*).

Results

Chia growth and floral phenology

Growth determinants such as plant height and biomass accumulation in chia morphotypes differed significantly ($p<0.05$) across sowing dates (Fig. 2a-b). Among chia types, black seeded plants were found to be more vigorous with greater height (119.6 cm) and biomass accumulation (2883.9 kg ha^{-1}) over white seeded plants (117.3 cm, and 2662.2 kg ha^{-1} respectively,). Regarding fifteen sowing dates, early sowing (S1: 1st July, S2: 15th July, S3: 1st August) demonstrated the highest plant height (199.1 cm, 195.1 cm, and 185.3 cm respectively,), and biomass production (4294.2–4021.9 kg ha^{-1}) compared to other sowing dates (Fig. 2a-b). Whereas, delayed sowing after S3 up to S15 conspicuously reduced the plant height and biomass accumulation (1735.1–1899.4 kg ha^{-1}) in chia types.

Similarly, floral phenological events such as days to flower bud appearance (FBA), days to 50% flowering, days to completion of flowering, days to maturity and flowering duration have responded ($p<0.05$) to dates of sowing (Table 1 and Supplementary Table S2). Particularly, flowering phenology did not differ among white and black seeded chia morphotypes. Whereas, early sown plants (S1 and S2) took more days to FBA (70.5–78.2), and it was drastically reduced to 35.0 days in late sown conditions (S7: 1st October). Further delay in sowing after S8: 15th October to S15: 1st February gradually delayed the FBA (54.8 days). Similarly, days to 50% flowering, days to complete flowering and days to maturity followed a similar trend as that of FBA (Table 1). The flowering duration was significantly delayed in late sown conditions (S13 to S15; 63.6 to 77.5 days) over other sowing dates. The shortest flowering duration of 47 days was observed in S8 and S9 sowing conditions. Moreover, early sown conditions (S1 to S4) enhanced the grain filling duration (39.8 to 41.8 days) with a decreasing trend up to S11 and a subsequent increase up to S15. Across years of cultivation, the second year (2022–23) noticed maximum plant height (122.4 cm), and biomass accumulation (2934.7 kg ha^{-1}) with delayed flowering duration, grain filling duration and maturity (115.3 days).

Relation between prevailing weather parameters and flowering phenology of chia

Weather conditions during the vegetative phase (germination to bud appearance) strongly influenced the flowering phenology of chia (Fig. 3a). The Pearson's correlation suggested that FBA exhibited a positive correlation with day length (r=0.7), accumulated GDD (r=0.87), T_{min} (r=0.42), and RH (r=0.38). While FBA was negatively related to diurnal temperature difference (T_{diff}) (r=–0.38) and bright sunshine hours (BSS) (r=–0.43). The flowering duration had a positive correlation with day length (r=0.85), T_{max} (r=0.79), T_{min} (r=0.59), and accumulated GDD (r=0.84) prevailed during flowering phase (flower initiation to completion). However, flowering duration was negatively correlated with RH prevailing during the flowering phase (r=–0.64) (Fig. 3b).

Yield attributes and seed yield of chia

Yield attributes of chia morphotypes responded to sowing dates during two years of investigation (Table 2). Black seeded chia types produced more spikes per plant (30.3), spike length (17.99 cm), 1000 seeds weight (1.15 g), HUE (0.37 kg ha^{-1} $°C^{-1}$ day^{-1}), grain filling rate (17.8 kg ha^{-1} day^{-1}), and seed yield (564.6 kg ha^{-1}) compared to white types. While white seeded morphotypes maintained a greater harvest index (21.32%) across sowing dates. Within sowing dates, treatments (S3–S6; 1st August–15th September) maintained a greater number of spikes, spike length (20.1–21.71 cm), 1000 seeds weight (1.15–1.16 g), and seed yield (741.0–811.0 kg ha^{-1}) with greater HUE, grain filling rate, and HI. In contrast, delayed sowing after S7 to S15 adversely influenced the HUE, grain filling rate, and seed yield of chia morphotypes. Regarding year effect, the first year (2021–22) recorded a superior number of spikes, 1000 seed weight, HUE, grain filling rate, and seed yield (579.2 kg ha^{-1}) over 2022–23 (Table 2). Further, the triple interaction between sowing dates, chia types, and year showed the significant effect for seed yield and HUE. In 2021-22 black type chia produced higher seed yield in S3-S6, whereas in 2022-23 it was higher in sowings S3-S4

(Supplementary table 3). Therefore, sowing up to 15th September could favour the seed yield and heat use efficiency of chia morphotypes in semi-arid conditions.

Weather parameters vs yield attributes of chia

Weather parameters across the growing period up to maturity established a significant ($p<0.05$) relation with yield attributes of chia. The seed yield was positively influenced by RH (r=0.93 and R^2=0.856), HUE (r=0.9), and RF (r=0.76 and R^2=0.529), however, T_{max} (r=–0.82 and R^2=0.674), T_{diff} (r=–0.87 and R^2=0.856), accumulated GDD (r=–0.31), BSS (r=–0.84) were negatively influenced the seed yield (Fig. 4 and 5a–d). Besides, T_{max} negatively related to chia yield attributes; seed yield per spike (r=–0.76), spike length (r=–0.65), and 1000 seed weight (r=–0.58) (Fig. 4). Notably, RH during the entire cropping period displayed a strong positive associations with chia yielding traits; (r=0.71 to 0.85). Analysis of diurnal temperature difference revealed a negative correlation with all growth and yield-related traits of chia. Moreover, the relation between seed yield and plant traits was also found significant (Fig. 4). Seed yield exhibited positive correlations with plant height (r=0.73), spike length (r=0.78), number of spikes per plant (r=0.80), number of branches per plant (r=0.76), seed yield per spike (r=0.89), and 1000 seed weight (r=0.74). Conversely, seed yield showed a negative correlation with flowering duration (r=–0.66) and crop duration (r=–0.28). Hence, prevailing weather parameters had a considerable role in determining the growth and yield of chia morphotypes.

Interaction between yield traits and weather parameters due to sowing dates and chia morphotypes

Multivariate analysis was conducted to elucidate the interaction, inter-relationship and variations among various yield traits and weather parameters that prevailed during the entire chia duration and chai types. Principal Component Analysis (PCA) revealed that the first two components (PC1 and PC2) captured 94.1% of the total variability (Fig. 6a). In PC1, traits such as seed yield, spike length, number of spikes, seed weight per spike, plant height, and biomass production demonstrated strong positive associations as indicated by the narrow angles between their vectors. Similarly, weather parameters RH, RF, and T_{min} showed strong positive associations with seed yield and yield-related traits. These variables explained the maximum total variability as evidenced by the length of their vectors. Conversely, BSS, flowering duration, and T_{max} exhibited negative associations with each other. In PC2, variables such as accumulated GDD, day length, flowering duration, days to 50% flowering, days to maturity, and FBA were positively associated with each other but negatively influenced the seed yield (Fig. 6a). Furthermore, sowing times (S4, S5, and S6) in both black and white seed types were closely related to higher seed yield, and yield traits as favoured by weather parameters like RH and rainfall. Conversely, delayed sowing times (S13, S14, and S15) in both varieties coincided with intense sunshine hours, poor RH, and higher T_{max} resulting in longer flowering duration, and accumulated GDD negatively determined the seed yield and yield traits of chia (Fig. 6b).

Discussion

The deviation in ideal weather conditions due to changing sowing dates notably influences the flowering phenology, maturity, and determines the yield of short day crops like chia. Therefore, this is a kind of first report that exhaustively analysed various dates of sowing and two chia morphotypes, establishing the relationship between weather and yield parameters.

Growth parameters of chia

Black seeded chia morphotype was found more vigorous over white seeded owing to greater plant height and biomass accumulation. This might be due to its superior genetic characteristics and adaptation as described by *Grimes et al. (2018)* and *Guttedar et al. (2023)*. Early sowing during the rainy season (July S1-S2) resulted in higher plant height and biomass accumulation because of long day conditions (average day length; 12.5 hours and accumulated GDD; >2000°C) (Fig. 1c) led to more vegetative growth and delayed reproductive growth over subsequent sowing dates (*Guttedar et al., 2023*). This was also due to the receipt of sufficient rain and the prevailing ideal temperature around ~30°C during the vegetative phase favoured the growth and biomass accumulation in both types of chia, thus increasing the risk of lodging. Our findings corroborate the results of *Goergen et al. (2018)* in chia, where higher GDD and longer photoperiod increase plant height and biomass. Similarly, *Silva et al. (2018)* reported enhanced vegetative growth in chia due to a greater number of branches during early sowing. Whereas, shorter plants with reduced biomass accumulation in case of delayed sowings after December (S11) to February (S15) were attributed to prevailing dry weather (high temperature and low RH) with the least rainfall during active growth stages (Fig. 1a–c). The crop biomass production is closely associated with dominant environmental factors such as temperature, RH, and rainfall together decide crop duration (*Guttedar et al., 2023*). Thus, chia is very sensitive to day length, RH, and temperature, which determines its biomass accumulation and yield.

Flowering phenology and maturity in chia

The delayed FBA in chia during early (S1–S3) and delayed sowings (S14–S15) was possibly due to longer day length conditions (>12.5 hours) compared to intermediate sowings (S4–S13) with shorter day lengths (<12 hours). As a result, flowering duration was extended (56.6 to 77.5 days) owing to more number of days between FBA and completion of flowering. The positive correlation between the flowering duration and T_{max} during flowering phase indicates the potential cause for delayed flower opening due to high temperatures (Fig. 4). It is important to note that hot weather (high temperature; >34 °C, low RH; <50%, and no rainfall; Fig. 1) commencement of long days during flowering phase (March–April) in delayed sowing resulted in delayed FBA and also the conversion of floral structures into vegetative parts in chia (*Guttedar et al., 2023*). Whereas, delayed flowering in early sowing (S1–S2) was probably related to long day condition associated with higher RH, rainfall and accumulated GDD during the vegetative stage. Similarly, *Grimes et al. (2018)* and *Benetoli da Silva et al. (2020)* highlighted that alterations in chia phenology are primarily linked to fluctuations in RH and higher GDD. *Brandan et al. (2020)* also reported more the growing degree days longer than the pre-flowering phase. Therefore, aligning chia flowering with optimal RH and rainfall conditions synchronizes flower opening, and ensuring a shorter flowering duration are crucial for efficient resource utilization and mitigating high temperatures and long days with higher accumulated GDD (*Foulkes et al., 2011; Sylvester-Bradley et al., 2012*).

Days taken for flower opening and its completion decide the duration of crop maturity. In the present study, early sowings as well as delayed sowings extended the chia maturity (125 to 143 days) compared to intermediate sowings (93 to 114 days), mostly due to delayed FBA, and flowering duration in chia. Similarly, *Lobo et al. (2011)* in Tucumán, Argentina and *Baginsky et al., (2016)* in Las Cruces, Chile, demonstrated that January sowing resulted in delayed flowering (105–111 days) and crop maturity (160–170 days respectively). Subsequently, grain filling duration (between 50% flowering and maturity) was extended with early and delayed sowing dates. A similar trend was observed with the completion of flowering (*Jamboonsri et al., 2012; Sattar et al., 2023*). Further, chia maturity was slightly delayed in 2022–23. This delay was likely attributed to increased accumulated GDD, higher

RH and the occurrence of rainfall fostering enhanced vegetative growth. Thus crop has taken more days to complete flowering and extended grain filling duration, as a positive correlation was observed between FBA, RH, rainfall, and day length (Fig. 3a). A similar pattern of extended maturity and grain filling duration was found in lentil (*Jamboonsri et al., 2012; Maphosa et al., 2023*). Both white and black seed chia types did not differ with respect to flowering phenology and maturity. Therefore, chia, being a short-day tropical plant, thrives well under photoperiods of less than 12.5 hours of light.

Seed yield and yield attributes of chia

Black seeded chia morphotypes produced greater (564.6 kg ha^{-1}, 10.8% higher) seed yield over the white type (509.2 kg ha^{-1}). This improvement in seed yield with black types could be attributed to improved biomass accumulation and yield-contributing parameters such as number of spikes, spike length, and 1000 seed weight (1.05 g). Previous researchers have noticed the genetic variation and superiority of black seeded chia types for yielding characters because of their wider adaptability (*Ayerza and Coates, 2009; Guttedar et al., 2023*). In this investigation, the seed yield of chia varied from 47.6 to 811.0 kg ha^{-1} across fifteen sowing dates. The higher seed yield with mid sowing dates (S3–S5) was mainly due to improved yield contributing parameters (Table 2 and Fig. 3b). Similar associations between seed yield and traits such as the number of spikes, spike length, and harvest index have been reported in both black and white types of chia (*Baginsky et al., 2016*). The positive relation between flower dry weight and seed yield in chia was also reported by *Brandan et al. (2020)*. Despite congenial RH, rainfall and temperature, early sowing dates (S1 and S2) produced lower seed yield because the plants produced a lower number of spikes because of more height and canopy spread due to prolonged vegetative phase under long days. This might hinder the production of branches, inflorescences, and subsequent translocation of photosynthates towards seed filling. This concurs with the finding of *Han et al. (2006)* in soybean where overcrowding canopy leads to poor branching with less number of pods. Interestingly, delayed sowing after S5 to S15 drastically reduced the seed yield of chia, ranging between 8.63-94.13% (Table 2). The poor chia seed yield was primarily due to under development of yield governing traits as reported by *Guttedar et al. (2023)* that delayed sowing (October) reduced the seed yield in Indian conditions. Therefore, it is crucial to complete sowing by 1st August (S3) to 1st September (S5) to achieve higher seed yield (790–811 kg ha^{-1}) in chia.

Weather and yield attributes of chia

This study among a few, clearly deciphered the impact of weather parameters in determining the chia yield across various (fifteen) sowing windows in a year. The biplot analysis confirmed that prevalence of optimum temperature (30–31℃), rainfall (200–350 mm), and RH (67–72%) during S3–S5 sowing (1^{st} August to 1^{st} September) resulted in higher seed yield attributes (Fig. 6b). Our findings are in conformity with the results of *Grimes et al. (2018)* and *Benetoli da Silva et al. (2020)* that climatic requirements of moderate to high temperature, minimum temperature (< 10°C) with adequate rainfall enhanced the chia yield in Germany and Brazil. Meanwhile, delayed sowings (S10–S15) reduced the 1000 seed weight of chia, mainly due to higher temperatures during the flowering phase, leading to prolonged flowering and grain-filling durations. This might also affect pollination, resulting in grain shrinkage due to the production of reactive oxygen species, reduced pollen tube development, increased pollen mortality, and grain abortion (*Nawaz et al., 2013; Dubey et al., 2019*). Thus, prolonged flowering and maturity durations negatively influenced the seed yield, owing to non-synchronized flowering, resulting in poor seed setting and seed yield per spike, as evidenced by a negative correlation between seed yield per spike and flowering duration (r=–0.56). Therefore, the increased temperature during the grain filling period increases the percentage of chaffy seed formation, as found in cases of soybean and rice (*Borowska and Prusiński, 2021; Sanwong et al., 2023*).

Similarly, the reduced grain filling rate in chia might be due to increased thermal load, which is manifested in terms of higher accumulation of GDD leading to higher grain filling duration in early (S1–S4) and delayed sowings (S8–S15). These sowing dates also decreased the HUE in chia, despite higher seed yield in S3 and S4, poor HUE was possibly related to more accumulation of GDD. Similar findings were reported in wheat that very early and delayed sowings significantly reduced the thermal use efficiency (*Kaur and Pannu, 2008; Singh et al., 2016*). It's also found that exposing crops to higher temperatures at critical growth phases tends to affect the phenophase duration, HUE and yield (*Parya et al., 2010*). The sowing dates; S4–S6 result in a medium flowering phase (50–51 days), and maturity (98.8–114.4 days), leading to ideal plant height and biomass accumulation in chia over early and delayed sowing dates. Therefore chia sowing from 1^{st} August to 15^{th} September coincides with optimum RH, lower diurnal temperature difference, and rainfall favoured the yield attributes and seed yield of chia in semi-arid conditions.

Conclusions

The study revealed that chia being a short-day plant showed significant response to different sowing windows. Weather conditions during the cropping period played a crucial role in chia's floral phenology, maturity, yield-contributing traits, and overall seed yield. Among chia morphotypes, black seed varieties exhibited greater vigour compared to white types. August 1st and September 1st was found to be optimal sowing time for both the chia types due to favourable weather conditions, including relative humidity (~67–72%), maximum temperature (~30–31°C), day length (<12.0 hours), rainfall (~200–350 mm), and accumulated growing degree days (~1521–1891). This sowing window of 30–45 days between 1st August to mid September in semi-arid regions can assist farmers in aligning chia cultivation with the desirable weather, cropping systems, and resource availability, thereby reducing climate-related risks. Extra-early sowing (July) reduces chia seed yield by 10.35%, moderately delayed sowing (September 15th to November 15th) by 24.1%, and extra-delayed sowing (December 1st to February 1st) resulting in a drastic reduction of 72.7%. Understanding these weather associations can support intensified chia cultivation practices. The findings suggest practical guidance for selecting suitable regions and optimal sowing dates for chia cultivation under evolving climate conditions, thereby contributing to sustainable development goals, particularly SDG 13 (climate action). Enhanced production also presents export opportunities to meet the growing industrial demand for chia seeds.

Authorship contribution statement

CB Harisha: Conceptualization and design of experiment, performed experiments, analysis of data, manuscript preparation. **KM Boraiah**: Conceptualization and design of experiment, performed experiments, manuscript preparation and reviewing. **PS Basavaraj**: Conceptualization and design of experiment, performed experiments, manuscript editing. **HM Halli**: performed experiments, analysis of data, manuscript preparation and editing. **RN Singh**: weather data analysis and manuscript editing. **Jagadish Rane**: Conceptualization and design of experiment, manuscript editing. **Kotha Sammi Reddy**: Supervision, manuscript editing and approved the final draft. **GR Halagunde Gowda**: Analysis of data, preparation of graphs and images, manuscript editing. **A Chaudhary**: data analysis, manuscript editing. **AK Verma**: design of experiment, data analysis, manuscript editing. **Ravi Y**: Analysis of data, preparation of graphs and images. **H Asangi**: data analysis, Preparation of graphs, manuscript editing. **E. Senthamil**: Analysis of data, preparation of graphs, and manuscript editing.

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Declaration of Competing Interest

There are no conflicts involved in the research and submission of this article.

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