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Field-based assessment of sowing date-induced temperature stress on growth, sensitivity, and yield of four cucurbit species

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Key words: Bottle gourd, cucumber, composite cucurbit growth index (CCGI), *Cucumis sativus*, growing degree days, *Lagenaria siceraria*, *Luffa acutangula*, *Luffa cylindrica*, oxidative stress, ridge gourd, sensitivity index (SI), sponge gourd.

Abstract: Climate-induced thermal stress is a major constraint limiting cucurbit productivity in subtropical agro-ecosystems. This study quantified the impact of sowing date-induced temperature variations (-0.49°C to +1.9°C) across three regimes - optimal (SD1), late (SD2), and very late (SD3) - on phenological, physiological, biochemical, and yield traits of four Cucurbitaceae species (ridge gourd, sponge gourd, bottle gourd, cucumber) over two seasons (summer-spring and kharif) in field experiments at IARI, New Delhi, India. Climatic suitability analysis indicated that summer-spring crops performed best within a temperature deviation of 0 to 0.95°C deviation, while kharif crops showed optimal performance near 0 to -0.2°C. The composite cucurbit growth index (CCGI) and sensitivity index (SI) revealed species-specific thermal responses, with sponge gourd showing maximum sensitivity during summer-spring and ridge gourd during kharif. Mid-season sowing (SD2) favored greater growth stability, as indicated by higher CCGI (0.466 in summer-spring and 0.388 in kharif). Overall, summer-spring provided more stable productivity (CCGI 0.4325; SI -0.0163) than kharif (CCGI 0.3458; SI -0.0899). These results highlight the utility of integrated indices for assessing crop resilience and identify mid-season sowing as an effective strategy to sustain cucurbit productivity under increasing climate variability.

1. Introduction

Global warming, characterized by a persistent rise in atmospheric temperatures, poses a substantial threat to agricultural sustainability by increasing climatic variability and the frequency of extreme weather events (Zandalinas *et al.*, 2017; IPCC, 2019; Seneviratne *et al.*, 2021). Temperature, one of the key environmental parameters altered by climate change, is particularly critical, as it governs plant morphological, anatomical, physiological, and biochemical functions, especially during

sensitive phenophases such as flowering and fruit development (Rehman *et al.*, 2015). In India, anticipated temperature rises could reduce overall agricultural productivity by 4-8%, with worst-case projections estimating up to 25% yield loss by 2050 (Pingali *et al.*, 2019). Horticulture plays a pivotal role in India's food and nutritional security, contributing 30.4% to agricultural GDP while occupying just 13.1% of the total cropped area (Datta, 2013; Ayyogari *et al.*, 2014). In 2021-2022, vegetable production reached 204.63 million tons over 11.28 million hectares (Press Information Bureau, 2022). Among horticultural crops, the Cucurbitaceae family holds particular importance, accounting for approximately 18% of India's total vegetable output (Nagendran *et al.*, 2017). Globally, cucurbits such as watermelon, cucumber, melon, pumpkin, and squash are cultivated across diverse agroecological zones (<http://faostat.fao.org>). In addition to their dietary relevance, cucurbits are valued for medicinal, ceremonial, and industrial applications (Rahman *et al.*, 2008). Despite their broad adaptability and utility, cucurbits are acutely sensitive to climate-induced abiotic stresses, particularly elevated temperatures, water scarcity, and soil acidity, which together can cause productivity losses of up to 10% (Parvathi *et al.*, 2022; Smiti *et al.*, 2025). Most cucurbits thrive in warm-season environments, with optimal growth between 20°C and 30°C. However, temperatures exceeding 32°C disrupt physiological and reproductive functions, manifesting as reduced chlorophyll content, skewed male-to-female flower ratios, oxidative stress from reactive oxygen species (ROS), and impaired fruit development (Verma *et al.*, 2016; Chandra *et al.*, 2023). One of the most widely accepted methods to quantify crop growth under variable thermal conditions is the Growing Degree Days (GDD) approach. GDD calculates the cumulative heat units required for a crop to complete its development stages, offering a reliable metric to model phenology in response to changing temperature regimes (Yang *et al.*, 1995; McMaster and Wilhelm, 1997). Under thermal stress, cucurbits often experience shortened vegetative periods, early senescence, and declines in biomass and yield (Tao *et al.*, 2013; Figueiredo *et al.*, 2015; Wang *et al.*, 2016). These responses are closely linked to temperature-driven disturbances in cellular redox homeostasis, which lead to elevated oxidative damage and compromised resilience (Bisbis *et al.*, 2019; Shah *et al.*, 2024). Given these challenges, the present study

focuses on four cucurbit species: cucumber (*Cucumis sativus*), bottle gourd (*Lagenaria siceraria*), sponge gourd (*Luffa cylindrica*), and ridge gourd (*Luffa acutangula*). The selection was made with the intention of balancing research gaps within the Cucurbitaceae family. Cucumber is the most extensively studied cucurbit under abiotic stress conditions, accounting for nearly 45% of relevant literature (Smiti *et al.*, 2025). On the other end of the spectrum, ridge gourd and sponge gourd remain among the least explored species, despite their substantial agronomic value in tropical and subtropical agro-ecosystems (Karmakar *et al.*, 2013; Sindhu *et al.*, 2021; Dutta *et al.*, 2024). Their inclusion aims to fill critical gaps and broaden the taxonomic scope of cucurbit stress physiology. Bottle gourd, occupying a middle ground in terms of research representation, serves as an ideal intermediary species to evaluate stress response variability. In the context of climate adaptation, adjusting sowing dates is one of the most effective and low-cost agronomic strategies available. Aligning the crop's growth stages with more favorable temperature, rainfall, and humidity conditions can significantly reduce exposure to environmental stress and optimize resource utilization (Qureshi *et al.*, 2007; Kabesh *et al.*, 2009). Extensive research in cereals such as wheat, maize, and rice has demonstrated that aligning phenology with favorable thermal regimes improves resilience and yield stability (Abbas *et al.*, 2017; Huang *et al.*, 2018; Mourtzinis *et al.*, 2019). Comparable research in cucurbits, however, remains limited. Existing studies are often restricted to a single species - commonly cucumber or muskmelon - and emphasize routine yield and physiological traits under delayed sowing (Sawale *et al.*, 2022; Dhakal *et al.*, 2023). Under-utilized but economically valuable cucurbits such as ridge gourd and sponge gourd remain underrepresented, and their sowing responses to temperature shifts are poorly characterized. Moreover, no study to date has attempted to integrate phenological, physiological, biochemical, reproductive, and yield traits into a unified framework for ranking cucurbit resilience across seasons. This lack of comparative and integrative evidence restricts the development of robust, species-specific sowing recommendations for cucurbit growers facing climate variability. The objectives of this study were as follows: 1. Investigate the effects of different sowing dates on phenological development and yield attributes of four cucurbit species e.g., Ridge gourd,

bottle gourd, sponge gourd, and cucumber. 2. To assess their physiological and biochemical responses under stressful conditions. 3. To identify the most tolerant and sensitive cucurbit and most favorable sowing window through integrative indices. The novelty of this research lies in its comparative and integrative approach. Unlike previous cucurbit studies that typically focus on a single species or trait under delayed sowing, this work simultaneously evaluates four cucurbit species across two contrasting seasons, capturing species- and season-specific responses. Furthermore, by developing and applying the composite cucurbit growth index (CCGI) and sensitivity index (SI), the study moves beyond routine phenological and yield observations to provide an integrative decision-support framework. This framework allows the ranking of species and sowing windows for climate resilience, with particular emphasis on under-studied crops such as ridge gourd and sponge gourd. To our knowledge, this is the first attempt to combine multivariate physiological, biochemical, and yield traits into composite indices to guide cucurbit sowing strategies under climate variability.

2. Materials and Methods

Plant material, experimental site and condition, and experimental layout

Seeds of four cucurbit species were obtained from the National seed bank, Indian Agricultural Research Institute, New Delhi (Table 1, Fig. 1 a-p).

The field experiment was carried out during the optimal growing season at the Research Farm of the Indian Agricultural Research Institute (IARI), New Delhi, located at Latitude 28°38'23" N, Longitude 77°09'27" E, at an altitude of 228.61 m above sea level in the subtropical region of Northern Plain Zone of India. The soil pH in the experimental field ranged between 7.5 and 8.5. Soil organic carbon content (0-



Fig. 1 - Habit, Male flower, Female flower, Mature fruit of Ridge gourd (a-d), Bottle gourd (e-h), Sponge gourd (i-l), Cucumber (m-p).

15 cm) was <0.5%, available nitrogen was <280 kg ha⁻¹, available phosphorus ranged between 25 and 50 kg ha⁻¹, available potassium was >280 kg ha⁻¹. Fields were typically prepared with 2 ploughings, incorporating organic matter, such as farmyard manure (FYM). A recommended dose of 10 kg of FYM per pit, along with 100 g of NPK (6:12:12) as basal dose and N at 10 g per pit applied 30 days before sowing, was used. Cucurbits require consistent moisture for optimum growth and productivity; hence drip irrigation was applied at 5-7 day intervals, based on soil moisture. Cucurbit pests (red pumpkin beetle and leaf miner) were managed with insecticide (Ridomil Gold) spray (2 mL L⁻¹, 1 spray per week), while diseases like powdery mildew and downy mildew were typically controlled using fungicides such as Mancozeb.

A split-split plot design was adopted, with season (summer-spring and kharif) as the main plot factor, crop species (Ridge Gourd, Bottle Gourd, Sponge Gourd, and Cucumber) as the sub-plot factor, and temperature stress imposed through three sowing dates as the sub-sub-plot factor. The sowing dates were defined as normal/optimal (SD1), late (SD2; 12-day delay), and very late (SD3; 24-day delay). SD1 corresponded to 16 February and 23 July for the summer-spring and kharif seasons, respectively; SD2 to 28 February and 4 August; and SD3 to 12 March and 16 August (Table 2). Four seeds were sown per mud pit, spaced 50 cm apart on ridges (34-40 m long, 10-15 cm high). Crop species and sowing dates were

Table 1 - Selected cucurbits for the experiment

Cucurbit	Scientific name	Variety
Ridge gourd	<i>Luffa acutangula</i>	Pusa swarna
Bottle gourd	<i>Lagenaria siceraria</i>	Pusa santushti
Sponge gourd	<i>Luffa cylindrica</i>	Pusa sneha
Cucumber	<i>Cucumis sativus</i>	Swarna sheetal

Table 2 - Sowing dates and the average meteorological conditions during the experimental period (sowing date-harvesting date)

Season	Sowing date (SD)	T _{max} (°C)	T _{min} (°C)	T _{avg} (°C)	T. stress (°C)	Rainfall (mm)	Relative humidity (%)	Bright sunshine (hrs.)	Evaporation (mm)
Summer-spring	SD1	36.76	21.19	28.95	Reference	1.80	54.8%	5.72	54.75
Summer-spring	SD2	37.75	22.13	29.9	0.95	1.83	53.8%	5.92	53.80
Summer-spring	SD3	38.67	23.08	30.85	1.9	2.00	52.9%	6.15	52.90
Kharif	SD1	32.56	22.37	27.47	Reference	4.91	73.5%	3.44	73.51
Kharif	SD2	32.48	22.07	27.27	-0.2	4.59	73.1%	3.43	73.14
Kharif	SD3	32.34	21.63	26.98	-0.49	4.48	73.2%	3.37	73.16

randomized independently within each season. All comparisons were made using SD1 as the control i.e., recommended sowing dates for optimum productivity.

Meteorological conditions during the experimental period

Observations of maximum temperature (T_{max}; °C), minimum temperature (T_{min}; °C), average temperature (T_{avg}; °C), and rainfall (mm) (Figs. 2 a, b and 3 a, b) as well as relative humidity (%), bright sunshine hours (hrs), evaporation (mm) were obtained for the entire experimental period from the meteorological monitoring database system, Division of Agricultural Physics, New Delhi (Table 2, Table S1, supplementary materials - SM). The temperature stress (T. stress) associated with each sowing date was calculated using the following formula:

$$[T_{avg} \cdot (\text{Sowing-Harvesting}) - T_{avg} \cdot (\text{Sowing-Harvesting})]$$

Optimal sowing].

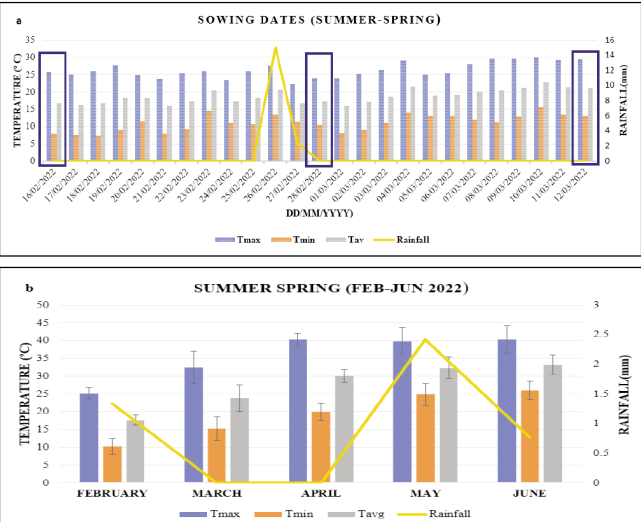


Fig. 2 - Temperature and rainfall profile during the (a) sowing period in summer-spring season (b) complete experimental period in summer-spring season.

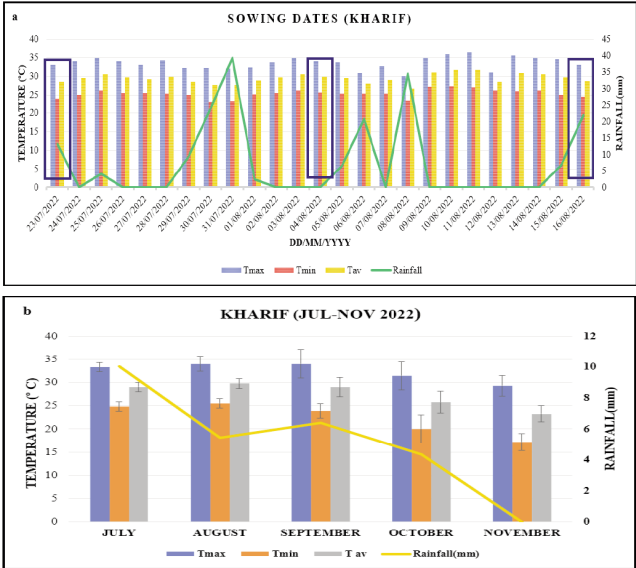


Fig. 3 - Temperature and rainfall profile during the (a) sowing period in kharif season (b) complete experimental period in kharif season.

Phenology and growing degree days (GDD)

The following five major phenological stages of each selected cucurbits were observed weekly during the experimental period: (i) emergence (Stage 1); (ii) complete unfolding of cotyledons (Stage 2); (iii) appearance of first flower on the plant (Stage 3); (iv) appearance of first fruit on the plant (Stage 4); (v) maturation stage (Stage 5); The number of days required to reach each phenological stage and their respective growing degree day (GDD) requirements were calculated using the following formulae:

$$GDD = \sum(T_{max} + T_{min})/2 - T_b \tag{Eq. 1}$$

T_{avg} = Average shift in temperature across the season
N= Number of days in the growing season
Where, GDD - growing degree days, T_{min} - daily minimum air temperature (°C), T_{max} - daily maximum air temperature (°C), Tb - base temperature below

which the crop cannot grow ($^{\circ}\text{C}$) with ridge gourd, cucumber having T_b of 15.5°C and bottle gourd, sponge gourd having T_b of 15.5°C (Doijode, 2012).

Physiological and biochemical parameters

Leaf samples were collected 50 days after sowing (DAS) to assess the physiological attributes namely, relative water content (RWC), total chlorophyll (T.CHL) content and the biochemical attributes namely, lipid peroxidation which is measured by malonaldehyde (MDA) content, antioxidant enzymes e.g., superoxide dismutase (SOD), catalase (CAT), peroxidase (POX).

The method outlined by Rajagopal *et al.*, 1977 was used to calculate the RWC using the formula:

$$\text{RWC} = (\text{FW}-\text{DW})/(\text{TW}-\text{DW}) \times 100$$

where FW=sample fresh weight, DW=sample dry weight, and TW=sample turgid weight. The total chlorophyll content was determined by the DMSO method as described by Hiscox and Israelstam (1979). For determination of leaf extract pH, 5 g of fresh leaf tissue were homogenized in 50 mL of deionized water and measured using a pH meter. MDA content was determined as per the method prescribed by Heath and Packer (1968). SOD activity was determined by the method given by Dhindsa *et al.* (1982). The catalase (CAT) enzyme activity was assayed by method given by Aebi (1984). POX activity was assayed as an increase in optical density due to the oxidation of guaiacol to tetra-guaiacol as described by Castillo *et al.* (1984).

Reproductive and biomass parameters

The number of male and female flowers per plant was recorded weekly between 45-50 days after sowing (DAS) and the male-to-female flower ratio (M:F) was calculated. Total plant biomass (TB) was determined by measuring the fresh weight of aboveground and belowground parts at harvest.

Yield and yield indices

Mature fruits were collected from each plant and then yield traits (number of fruits per plant (Y) and the weight of fruits per plant (FW) were measured prior to final plant harvest. To quantify the effects of temperature stress resulting from shift in sowing dates, the following yield indices were used:

(i) the tolerance index (TOL), defined as the difference between yield under normal and stress

conditions; (ii) the mean productivity index (MP), defined as the average yield under normal (Y_p) and stress conditions (Y_s); (iii) the yield stability index (YSI), calculated as the ratio between the yield under stress and normal conditions. Higher values of MP, YSI, along with lower values of TOL, indicate greater tolerance to temperature stress.

$$\text{TOL} = Y_p - Y_s \quad (\text{Eq. 2})$$

Mean productivity (MP) (Rosielle and Hamblin, 1981) was calculated as follow:

$$\text{MP} = (Y_p + Y_s)/2 \quad (\text{Eq. 3})$$

Yield stability index (YSI) (Bouslama and Schapaugh, 1984) was calculated as:

$$\text{YSI} = Y_s/Y_p \quad (\text{Eq. 4})$$

where Y_p and Y_s are the yield performance under normal and temperature stress conditions, respectively.

Statistical analysis and index development

Data from each sowing date were subjected to analysis of variance (ANOVA) at a significance level of $p = 0.05$, using MINITAB 19 software. Principal Component Analysis (PCA) was performed on all the selected variables in MINITAB 19 ensuring standardization of the variables. Temperature stress and season were excluded as variables but used only as labels for grouping observations. CCGI values were calculated across replicates for each temperature stress-season combination and ranked to identify optimal sowing strategies. Principal components (PCs) with eigenvalues greater than 1 were chosen, as they explain the variance at least as much as an original standardized variable according to Kaiser's rule. Parameters with loading values within 10% of the maximum loading within each PC were chosen for the minimum data set MDS. When more than one variable was retained within a PC, the correlation sum was examined. The variable with the highest correlation sum was chosen as the indicator parameter (Rezaei *et al.*, 2006). Normalization of selected MDS indicator parameters was done using the linear scoring (Andrews *et al.*, 2002).

$$\text{Weightage of each PC was calculated (Wi)} = \frac{\text{Individual variance}}{\text{Total Variance}}$$

Normalization followed by Scoring (S_i) was done by

using the following formula:

Indicator score (More is better): $(X - X_{\min}) / (X_{\max} - X_{\min})$

Indicator score (Less is better): $(1 - (X - X_{\min}) / (X_{\max} - X_{\min}))$

$Si = (X - X_{\min}) / (X_{\max} - X_{\min})$ or $(1 - (X - X_{\min}) / (X_{\max} - X_{\min}))$

Composite Cucurbit growth Index = $\sum Wi \times Si$

Sensitivity Index compares the composite scores across different sowing conditions:

Sensitivity Index = $\frac{\text{Composite score (Late/very late sowing)} - \text{Composite score (Optimal sowing)}}{\text{Composite score (Optimal sowing)}}$

3. Results

Meteorological conditions

During the summer-spring season (February-June), $T_{\max}$ ranged from 25.2°C to 40.4°C, $T_{\min}$ from 10.1°C to 26.0°C, and T_{avg} from 18.0°C to 33.1°C (Fig. 2). In the kharif season (July-October) $T_{\max}$ range was 31.5-33.3°C, $T_{\min}$ range was 20.0-24.8°C, and T_{avg} range was 26-29.0°C (Fig. 3). Table 2 summarizes the meteorological parameters for the three sowing regimes, while Table S1 presents the monthly meteorological variations. The elevated temperature peaks recorded during these periods led to visible heat injury symptoms across the investigated crops, including leaf scorching, floral burning, and fruit deformation (Fig. 4).

Phenological growth stages and growing degree day requirements (GDD)

Delayed sowing significantly shortened the

duration of all major phenological stages across cucurbit crops in both experimental seasons, with the strongest effects observed under very late sowing. The reduction was consistently greater during the summer-spring season, indicating higher sensitivity to elevated temperature conditions. Early growth stages were most responsive; emergence and cotyledon unfolding durations declined by more than 50% in several crops under very late sowing, whereas reductions in later stages such as flowering, fruit initiation, and harvesting were generally below 20% (Tables S2 and S3). Despite shorter phenological duration, crops accumulated significantly higher thermal units under delayed sowing. In the summer-spring season, GDD requirement for emergence increased by more than 900% in some crops, while increases during flowering, fruit initiation, and harvesting remained comparatively modest ($\leq 21\%$). During the kharif season, GDD accumulation also increased under delayed sowing, though the magnitude was lower than in summer-spring, reflecting seasonal moderation of heat stress (Tables S4 and S5).

Physiological and biochemical parameters

Delayed sowing caused pronounced and statistically significant changes in plant water status, photosynthetic pigments, and oxidative stress responses, with distinct crop- and season-specific patterns (Table 3). RWC declined substantially in ridge gourd and cucumber, with maximum reductions exceeding 60% under very late sowing during summer-spring, indicating severe dehydration stress. In contrast, bottle gourd maintained higher RWC, showing significant increases of up to ~48% under late sowing, suggesting superior water status regulation. T.CHL content declined significantly under delayed sowing in most crops, particularly during summer-spring. In ridge gourd and sponge gourd, T.CHL reduction exceeded 50% under very late sowing, whereas bottle gourd showed a significant increase in T.CHL content (approximately 55-62%) during kharif, indicating enhanced photosynthetic stability under moderate stress. Oxidative damage, as indicated by lipid peroxidation (MDA content), increased sharply under delayed sowing. During summer-spring, MDA levels increased by more than 7000% in ridge gourd, confirming severe membrane damage under high thermal stress. In contrast, cucumber exhibited comparatively smaller or



Fig. 4 - (a) Burnt leaves of Ridge gourd (b) Burnt leaf Cucumber (c) Yellow leaves of sponge gourd (d) Burnt flower of bottle gourd (e) Scald on bottle gourd fruit (f) Scald on sponge gourd fruit (g) Deformed cucumber fruit due to increased temperature stress

Table 3 - Three-way ANOVA (p values <0.05) for physiological, biochemical, reproductive, biomass, and yield attributes

Source of variation	DF	RWC (%)	T. CHL (mg/g)	MDA (nmol/cm)	CAT (Units/g)	POX (Units/g)	SOD (Units/g)	M: F	Yield (Fruit/plant)	FW (g)	TB (g)
Season	1	***	***	NS	NS	***	NS	NS	NS	NS	**
Temperature Stress (TS)	2	***	***	***	***	NS	NS	NS	***	***	**
Crop	3	***	***	***	NS	***	***	***	***	NS	***
Season × TS	2	***	***	***	**	***	***	NS	NS	NS	NS
Season × Crop	3	***	***	***	*	***	NS	*	NS	NS	**
TS × Crop	6	***	***	***	NS	**	NS	NS	***	*	**
Season × TS × Crop	6	***	***	***	NS	***	***	*	*	NS	NS
Error	48										
Total	71										

Where, NS= p>0.05, * = p≤0.05, **= p ≤ 0.01, *** = p≤0.001.

declining changes in MDA, suggesting greater oxidative tolerance. Antioxidant enzyme activities responded strongly to sowing delays. CAT activity increased significantly under very late sowing, particularly in ridge gourd, where it increased by more than 600% during summer-spring. POX activity also increased across most crops and seasons, whereas SOD showed variable responses, with marked stimulation under late sowing but partial suppression under very late sowing in some crops, especially during kharif (Fig. S1 a-f; Fig. S2 a-f).

Reproductive and biomass parameters

Delayed sowing significantly altered reproductive traits and biomass accumulation (Table 3). In the summer-spring season, the M:F increased by more than 100% in ridge gourd and bottle gourd under very late sowing, indicating a stress-induced shift toward male flower dominance. Sponge gourd exhibited a contrasting response under severe sowing delay, showing a reduction in male dominance. During kharif, reproductive responses were more variable and crop-specific. TB declined significantly under delayed sowing in ridge gourd and cucumber across both seasons, with reductions exceeding 70% under very late sowing, particularly during summer-spring. Bottle gourd showed partial tolerance, with a ~59% increase in TB under late sowing, but declined under very late sowing. In contrast, sponge gourd accumulated substantially higher TB during kharif, showing increases exceeding 600% under delayed sowing, suggesting strong vegetative compensation under favorable moisture conditions (Fig. S1 g-h; Fig. S2 g-h). Mean values and variability are presented in Table S6.

Yield parameters and yield indices

Y and FW were significantly influenced by sowing date, crop species, and their interactions with season (Table 3), confirming the strong effect of temperature stress induced by delayed sowing. Yield responses differed markedly between the summer-spring and kharif seasons. During the summer-spring season, Y generally declined under delayed sowing, with very late sowing causing the strongest reductions. Ridge gourd showed severe yield penalties, with Y declining by up to 100%, while sponge gourd also exhibited substantial reductions. Bottle gourd displayed partial tolerance under late sowing, with Y increases of about 50%, but declined under very late sowing. Cucumber maintained Y under late sowing but it declined sharply under very late sowing. FW followed a similar pattern: under late sowing, some crops showed compensatory increases (up to ~115%), whereas very late sowing resulted in consistent reductions across all cucurbits (approximately 20-80%). In the kharif season, Y was comparatively more stable under late sowing. Ridge gourd and bottle gourd showed moderate Y increases (approximately 12-66%) under late sowing, whereas very late sowing caused strong Y losses, particularly in cucumber (up to ~75%). Sponge gourd maintained relatively stable Y across all the sowing windows. FW responses mirrored these trends, with increases under late sowing in ridge gourd and bottle gourd, but consistent declines under very late sowing. Yield indices further highlighted seasonal differences in stress tolerance. In the summer-spring season, very late sowing was associated with high tolerance index (TOL) values and low yield stability index (YSI), as observed in ridge gourd (YSI ≈ 0.0) and bottle gourd

(YSI $\approx$ 0.5), indicating poor yield stability under severe stress. In contrast, during the kharif season, several crops exhibited negative TOL values and higher YSI (>1.0 -1.6) under late sowing, reflecting improved tolerance under milder temperatures ($T_{avg} \approx 27^\circ\text{C}$). Nevertheless, very late sowing remained detrimental across seasons, particularly for cucumber (YSI $\approx$ 0.25 in kharif). Overall, high mean productivity (MP) and YSI values combined with low or negative TOL consistently identified crops with greater tolerance to temperature stress, with summer-spring conditions amplifying yield penalties, while the kharif season allowed better yield buffering. Figure S1 i-j and figure S2 i-j represent heat maps for yield parameters of each crop in summer-spring and kharif seasons respectively. Table S6 and Table S7 represent the mean and standard error values of yield parameters and yield index values respectively.

Correlation

The two correlograms, representing season 1 (summer-spring) and season 2 (kharif), illustrate the correlation between physiological and yield-related parameters (e.g., RWC, T.CHL, MDA, CAT, POX, SOD, TB, M: F, Y, and FW) and environmental factors, including temperature stress, with correlation coefficients ranging from -0.5 (strong negative) to 0.5 (strong positive). In summer-spring (Season 1), T. stress, ranging from 0.95°C to 1.9°C above the reference, showed a significant negative correlation with RWC (-0.54) and FW (-0.36), indicating that elevated temperature stress reduced water retention and fruit size. Conversely, positive correlations with CAT (0.52) and POX (0.56) suggested that temperature stress enhances antioxidant enzyme activity, aiding in mitigating oxidative damage. Temperature stress also showed a negative correlation with Y (-0.29) (Fig. 5 a). In kharif (Season 2), T. stress was negative (-0.49°C to -0.2°C below the reference, with T_{avg} of 26.98 - 27.47°C), correlating negatively with CAT (-0.59) and MDA (-0.45), indicating reduced antioxidant enzyme activity and MDA under cooler conditions. Positive correlations with TB (0.22), Y (0.34) and FW (0.29) indicate that the cooler and wetter kharif environment supported vegetative growth and yield, despite oxidative challenges (Fig. 5 b).

Composite cucurbit growth index and sensitivity index

The principal component analysis (PCA) reduced the variability among the measured traits into a

smaller number of independent dimensions, with the first four principal components explaining 63.0% of the total variance. The first two components (PC1 = 19.5%, PC2 = 18.2%) together accounted for 37.7% of the overall variation and were thus used for biplot visualization. PC1 was largely defined by a contrast between productivity-related traits such as FW, Y, and TB, which loaded negatively, and stress-associated traits, including MDA, CAT, and RWC, which loaded positively. This pattern indicates that PC1 represents a trade-off between stress response and productivity. PC2 separated samples based on positive associations with Y, RWC, and SOD, in contrast to negative associations with CAT and POX. This PCA loading plot highlights the relationships among yield, physiological, and stress-related traits under different conditions. Y, FW, T.CHL, RWC, and SOD clustered closely and loaded positively on PC2, showing that these traits are positively associated and represent key indicators of productivity and stress tolerance. In contrast MDA was positioned away from Y, suggesting that higher stress damage is negatively linked with productivity. Antioxidant enzymes such as CAT and POX also loaded in the

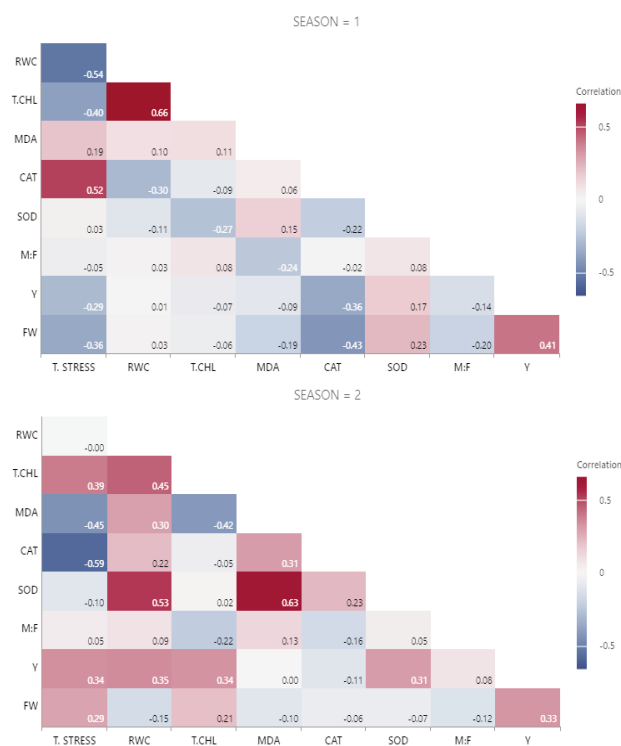


Fig. 5 - Correlogram representing the relationship between sowing date (SD) and the observed parameters of the selected cucurbits during (a) season 1 (summer-spring) and (b) season 2 (kharif).

opposite direction to Y, indicating that although their activity increases under stress, they do not directly contribute to enhanced productivity. TB loaded separately, reflecting variability not strongly connected to yield-related traits. Overall, the analysis reveals that yield performance is best explained by high RWC, T.CHL, SOD activity, and FW, whereas high MDA and antioxidant enzyme activity reflect stress responses that are less favorable for Y (Fig. 6). The composite cucurbit growth index (CCGI) was developed to quantitatively evaluate the optimality of sowing dates for ridge gourd, bottle gourd, sponge gourd, and cucumber cultivation under T. stress conditions. It integrates key phenological, physiological, and biochemical parameters into a single score to assess plant performance across different temporal planting windows. The following equation was used to calculate the CCGI values:

$$0.202 \times [\text{MDA (nmol/cm)}] + \text{TB (g)} + \text{FW (g)} + 0.188 \times [\text{RWC (\%)} + (\text{SOD (Unit/g)}) + 0.144 \times [\text{T.CHL (mg/g)}] + 0.117 \times [\text{M:F}].$$

A higher mean index value indicates more favorable composite physiological and yield performances, while the sensitivity index quantifies crop response to delayed sowing, with more negative value indicating increased sensitivity, and positive values denoting tolerance. The PCA-derived mean index values, reflecting plant health and growth parameters, showed distinct performance trends for the four crops across three sowing dates in summer-spring and kharif seasons. Table 4 and 5 compare the performance of four cucurbit crops across two seasons, summer-spring and Kharif, using average sensitivity index values (indicating sensitivity to

Table 4 - Crop-wise sensitivity index (SI) to sowing date shifts

Crop species	Average SI	
	Summer-spring	Kharif
Ridge gourd	-0.021	-0.337
Bottle gourd	-0.106	0.027
Sponge gourd	-0.172	-0.085
Cucumber	0.135	0.037

Table 5 - CCGI response to sowing date-induced temperature deviations

Sowing date	Temperature shift from optimum sowing date (°C)		Average CCGI	
	Summer-Spring	Kharif	Summer-Spring	Kharif
1 (Optimum)	0.0	0.0	0.448	0.368
2	0.95	-0.20	0.466	0.388
3	1.90	-0.49	0.382	0.273

sowing date shifts relative to a baseline) and average CCGI values (reflecting overall growth performance). In summer-spring, sponge gourd was the most sensitive crop with an average sensitivity index of -0.172, indicating significant growth reduction under delayed sowing, while cucumber was the most tolerant at 0.135, showing improved performance. In kharif season, ridge gourd exhibited the highest sensitivity (-0.337), while cucumber again showed tolerance (0.037). For identifying the most suitable sowing date corresponding to the optimal temperature regime, sowing date 2 consistently produced the highest average CCGI in both seasons (0.466 for summer-spring, 0.388 for kharif), making it the most suitable regime for sowing of cucurbits, while sowing date 3 resulted in the worst CCGI values (0.382 for summer-spring and 0.273 for kharif, respectively). Seasonal comparison revealed that summer-spring was the more favorable season, with a higher average CCGI (0.4325 vs. 0.3458) and a less negative average sensitivity index (-0.0163 vs. -0.0899), indicating superior and more stable growth performance across crops and sowing dates compared to kharif, where crops generally exhibit greater sensitivity to sowing date shifts (Table 6, Table S8). In summer-spring, cucumber proved to be the most tolerant crop, followed by ridge gourd and

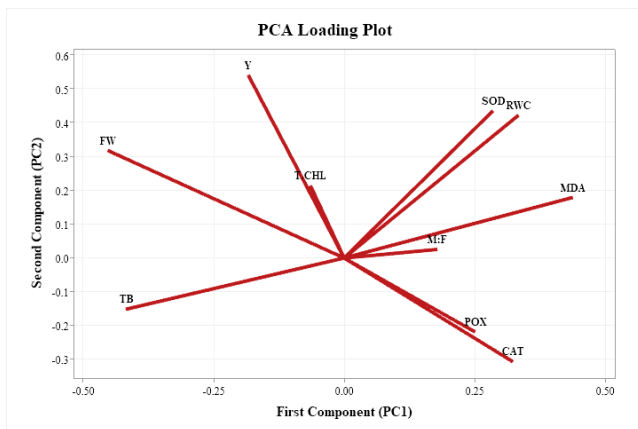


Fig. 6 - PCA loading plot representing the spread of parameters across two major principal components (PCs).

Table 6 - Overall seasonal performance

Season	Average CCGI	Average SI
Summer–spring	0.4325	-0.0163
Kharif	0.3458	-0.0899

bottle gourd, with sponge gourd being the most sensitive. In the kharif season, cucumber again demonstrated the highest tolerance, followed closely by bottle gourd, while ridge gourd was the most sensitive. Climatic suitability analysis reveals that summer-spring crops perform best within a 0°C to +0.95°C shift from the optimal sowing date, while in kharif, the ideal conditions occur under a temperature shift ranging from 0°C and -0.2°C. Overall, summer-spring conditions provided higher climatic growth potential and reduced sensitivity to sowing date shifts compared to kharif, making them more favorable for cultivation.

4. Discussion and Conclusions

Alterations in crop phenology serve as a critical indicator of climate change impacts and are a potential adaptation strategy aimed at yield maximization (Wolkovich *et al.*, 2012; Muleke *et al.*, 2022). Consistent with prior research (Phelan *et al.*, 2018; Liu *et al.*, 2021), our study demonstrates that sowing time profoundly influences plant phenology (Parya *et al.*, 2010). Delayed sowing generally shortens the vegetative growth phase, likely due to higher minimum temperatures accelerating developmental processes (Guo *et al.*, 2023). The shortening of critical phenological phases, which regulate photoperiod sensitivity and crop productivity, may explain the poor performance under delayed sowing (Ferrise *et al.*, 2010). Delayed sowing increases the possibility of crops being exposed to high temperatures during the fruit formation stage, which is harmful to leaf photosynthesis, flowering, and final yield formation. (Garg *et al.*, 2013). High values of GDD under late sowing can be mainly attributed to the higher daily and cumulative temperatures (Aslam *et al.*, 2017). Increased accumulation of heat over time accelerates the phenology and introduces trade-offs in plants, such as reduced capacity of vegetative structures to acquire resources and disruptions in source-sink

relationships, limiting assimilate allocation to reproductive organs (Jeffrey *et al.*, 2025; Wingler and Soualiou, 2025). RWC is a well-established marker of plant water status and stress resilience, reflecting both osmotic adjustment and cellular hydration (Rajagopal *et al.*, 1977; Hasanuzzaman *et al.*, 2021). Declines in RWC under delayed sowing indicate compromised protoplasmic stability and a reduced capacity to sustain photosynthesis during temperature stress (Raja *et al.*, 2020). Variability among cucurbits suggests species-specific plasticity: some maintain RWC through osmotic adjustment and stomatal regulation, while others show sharp declines linked to membrane instability and oxidative injury (Hasanuzzaman *et al.*, 2013). High humidity conditions may further reduce effective RWC by limiting transpiration and weakening osmotic gradients (Hasanuzzaman *et al.*, 2013). Chlorophyll content provides an equally critical indicator of stress adaptation, as pigment degradation directly compromises photosynthetic efficiency. High temperature and excessive rainfall accelerate chlorophyllase activity, destabilize thylakoid membranes, and suppress pigment biosynthesis (Camejo *et al.*, 2005; Zhou *et al.*, 2017). In some species, moderate stress associated with intermediate sowing dates triggers acclimatory adjustments such as altered membrane lipid composition or protective protein synthesis, sustaining or temporarily increasing chlorophyll levels (Tang *et al.*, 2018; Zhao *et al.*, 2020). Under prolonged stress, however, electron transport disruption and inhibition of biosynthetic enzymes dominate, leading to chlorophyll decline (Purnama *et al.*, 2018). These dynamics reinforce that RWC and chlorophyll are interlinked determinants of stress tolerance, sensitive to both thermal load and moisture regimes (Amin *et al.*, 2024). Delayed sowing intensified oxidative stress, as evidenced by enhanced production of reactive oxygen species (ROS) such as singlet oxygen, superoxide radicals, hydrogen peroxide, and hydroxyl radicals (Liu *et al.*, 2020; El-Remaly, 2023). Excess ROS destabilize membranes, oxidize proteins, and induce lipid peroxidation, reflected in elevated malondialdehyde (MDA) accumulation (Hasanuzzaman *et al.*, 2020). Increases in MDA observed under high temperature stress are consistent with oxidative damage reported across crops including chickpea, turfgrass, and cucumber (Wilson *et al.*, 2014; Verma *et al.*, 2016; Nagar *et al.*, 2021). Plants counteract ROS damage

primarily via enzymatic defense systems. Catalase (CAT) decomposes hydrogen peroxide but its activity often fluctuates: declines have been attributed to high temperature-induced inhibition of new protein synthesis (Dat *et al.*, 1998), while recovery under prolonged stress indicates compensatory scavenging activity (Almeselmani *et al.*, 2006; Mustafa *et al.*, 2021). Peroxidase (POX) also scavenges hydrogen peroxide and is often linked with hormonal regulation, showing induction under moderate stress but suppression when stress overwhelms cellular capacity (Prerostova *et al.*, 2020; Aydogan *et al.*, 2021). Superoxide dismutase (SOD) catalyzes the conversion of superoxide radicals into hydrogen peroxide and oxygen, with increased activity generally reflecting stress adaptation (Gosavi *et al.*, 2014; Raja *et al.*, 2020). Declines in SOD observed under severe stress suggest enzyme inactivation or insufficient induction (Zhao *et al.*, 2018; Zhou *et al.*, 2017). Temperature stress strongly influenced reproductive allocation, as reflected in altered male-to-female flower ratios. Elevated temperatures during delayed sowing increased the proportion of male flowers, a response mediated by ethylene biosynthesis, hormonal signaling, and photoperiod sensitivity (Daba *et al.*, 2016; Gao *et al.*, 2021; Liu *et al.*, 2021). While this strategy conserves resources, it reduces fruit set and yield potential, consistent with previous findings in cucumber under temperature stress (Schultheis *et al.*, 2016). Male gametophyte formation is generally more sensitive to stress than female reproductive development (Lohani *et al.*, 2020). This explains why male flower abundance increased under moderate stress, but collapsed under extreme late sowing in some species, reflecting disrupted pollen development. Seasonal variability also contributed, with water deficits and high evaporative demand compounding reproductive imbalance under kharif conditions (Sawan, 2018). Biomass accumulation, a central indicator of resource capture and energy storage, was constrained under delayed sowing by shortened vegetative phases that reduced light interception and temperature utilization (Westoby *et al.*, 2002; Liu *et al.*, 2016; Chandra *et al.*, 2023). Ridge gourd and cucumber showed marked biomass declines, reflecting chlorophyll loss, photosystem II damage, and redox imbalance (Hasanuzzaman *et al.*, 2013). Sponge gourd, however, maintained stability in kharif, potentially linked to temperature-induced

acclimation involving abscisic acid accumulation, apoplastic hydrogen peroxide, RBOH transcripts, and HSP70 expression (Li *et al.*, 2014). Bottle gourd exhibited a hormetic response, gaining biomass under moderate stress through the activation of basic helix-loop-helix (bHLH) transcription factor families that regulate stress adaptation (Wang *et al.*, 2024), but declining sharply under extreme stress and rainfall-induced root damage (Agathokleous *et al.*, 2019; Manghwar *et al.*, 2024). Ridge gourd was consistently sensitive, in agreement with earlier findings of reduced flower initiation and fruit set under delayed sowing (Singh *et al.*, 2020). Bottle gourd and cucumber displayed partial resilience, with yield maintenance under moderate delays but sharp losses under severe stress. Sponge gourd exhibited recovery under very late Summer-spring sowing, suggesting delayed acclimation. Fruit weight trends confirmed that moderate delays occasionally aligned fruiting with favorable microclimates (Jaksunarno and Akali Sema, 2001; Kishor *et al.*, 2010; Singh *et al.*, 2020), but very late sowing universally reduced fruit size across species due to limited assimilate supply (Ball *et al.*, 2000). Multivariate analyses clarified how physiological and reproductive traits interact under stress. PCA and correlogram results revealed strong positive associations among RWC, chlorophyll stability, and biomass, consistent with their central role in sustaining productivity under stress (Kalaji *et al.*, 2018; Hamawi *et al.*, 2023). In contrast, oxidative stress markers such as MDA clustered inversely with yield parameters, underscoring lipid peroxidation as a key determinant of growth penalties (Hasanuzzaman *et al.*, 2020). Antioxidant enzymes exhibited variable associations, with moderate increases linked to effective ROS detoxification and tolerance, but extreme induction indicating overcompensation and oxidative injury (Dat *et al.*, 1998; Zhao *et al.*, 2018; Mustafa *et al.*, 2021). Reproductive shifts, particularly altered male-to-female flower ratios, were also aligned with stress markers, pointing to an integrated regulatory network involving ethylene biosynthesis, ROS signaling via RBOH, and heat shock responses (Li *et al.*, 2014; Lohani *et al.*, 2020; Gao *et al.*, 2021). The Composite Cucurbit Growth Index (CCGI) integrates physiological, biochemical, reproductive, and yield traits into a single cumulative measure, while the sensitivity index (SI) identifies sowing windows that optimize resilience under variable environments.

Together with PCA, these indices revealed a fundamental trade-off: productivity-related traits such as yield, fruit weight, chlorophyll content, superoxide dismutase activity, and relative water content declined as stress indicators like MDA, catalase, and peroxidase increased. This underscores that enhanced antioxidant activity alone does not guarantee yield stability; resilience must be defined by the combined capacity to tolerate stress and sustain productivity. In summer-spring, sponge gourd was most vulnerable, showing sharp growth reductions with delayed sowing, whereas cucumber-maintained tolerance, reflecting its ability to preserve chlorophyll levels and water status under heat stress. In kharif, ridge gourd emerged as the most sensitive due to its narrow thermal and water tolerance, while cucumber again demonstrated resilience. Across both seasons, sowing date 2 (12-day delay) consistently achieved the highest CCGI values, confirming it as the most favorable window for balancing acclimation with yield stability. Seasonal comparisons further indicated that summer-spring conditions supported higher resilience and growth potential than kharif, where excessive rainfall and humidity amplified sensitivity to temperature stress due to shifts in sowing dates. These results validate the utility of CCGI and SI as multidimensional tools that integrate stress physiology with agronomic outcomes, enabling practical identification of optimal sowing schedules. Early planting under cooler conditions (<30°C) promotes assimilate distribution, delays senescence, and boosts yield potential (Gomez-Macpherson and Richards, 1995; Hatfield and Prueger, 2015). By contrast, delayed sowing intensifies oxidative stress, disturbs reproductive balance, and reduces stability, highlighting the need for season-specific adjustments (mid-February for summer-spring, late July for kharif). Complementary measures such as adopting high temperature-tolerant cultivars, and improving irrigation management can further alleviate stress, aligning with IPCC (2024) recommendations that prioritize sowing shifts as a low-cost adaptation strategy (Zhang *et al.*, 2019; Pathak *et al.*, 2022). By comparing four cucurbit species, this study shows that resilience is crop- and season-dependent, with cucumber consistently tolerant and ridge gourd consistently vulnerable. Incorporating under-researched cucurbits such as ridge gourd and sponge

gourd extends physiological insights beyond well-studied crops like cucumber. Most importantly, the integration of diverse traits into CCGI and SI establishes a quantitative, decision-support framework that transcends routine agronomy, offering a robust, data-driven approach to climate-resilient cucurbit cultivation.

This study demonstrates that sowing date-induced temperature shifts strongly regulate cucurbit growth, physiology, and yield through the shortening of phenological cycles, altered reproductive allocation, and intensified oxidative stress. Species responses diverged, varied with ridge gourd consistently showing high sensitivity, cucumber maintaining resilience, and bottle gourd and sponge gourd exhibiting intermediate plasticity depending on season. The integration of multivariate traits into the Composite Cucurbit Growth Index (CCGI) and Sensitivity Index (SI) provided a robust framework for quantifying crop resilience. These indices consistently identified mid-season sowing as the most favorable strategy, while very late sowing proved universally detrimental. Seasonal comparisons further confirmed summer-spring as a more stable production window than kharif. By moving beyond routine agronomic evaluation and adopting integrative indices, this study establishes sowing window optimization as a low-cost, data-driven adaptation strategy for cucurbit production under climate variability. The framework presented here offers practical guidance for farmers and policymakers while highlighting the need for future studies incorporating broader genetic diversity and multi-location validation to enhance the generalizability of these findings.

This study, conducted at a single location over one year, limits extrapolation across agro-climatic zones and seasons. Evaluation was restricted to four cucurbit species with fixed genotypes, leaving genotype × environment interactions unaddressed. Additionally, the focus on temperature stress through sowing shifts did not account for interactions with other abiotic and biotic factors. Future research should involve multi-location, multi-year trials with a broader genetic base, complemented by molecular and transcriptomic analyses to elucidate stress tolerance mechanisms. Integrating crop simulation models with weather-based advisories and assessing combined agronomic interventions will further enhance climate-resilient cucurbit production.

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