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OPTIMIZING THE SOWING WINDOW FOR TOMATO PRODUCTION. A GLOBAL REVIEW OF WEATHER INTERACTIONS, VARIETAL RESPONSES, AND AGRONOMIC OUTCOMES

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ABSTRACT
Tomato (Solanum lycopersicum L.) is highly sensitive to temperature, radiation, and humidity, making the sowing window a decisive factor in determining its growth, phenology, yield, and quality. This review systematically synthesizes global evidence from 138 studies published between 2000 and 2024, examining how different sowing dates interact with weather, genotype, and management practices. Early or optimally timed sowing consistently enhances vegetative vigour, pollen viability, fruit set, and marketable yield by aligning critical phenophases with favourable thermal and radiation regimes. In contrast, delayed sowing exposes the crop to heat stress, excessive humidity, and increased pest and disease pressure, leading to reduced fruit number and quality. Varietal differences and genotype × sowing window interactions highlight the need for location-specific recommendations. Physiological and biochemical analyses reveal that sowing time influences hormonal balance, photosynthetic efficiency, assimilate partitioning, and oxidative stress responses. Integrating these insights with crop modelling and agrometeorological indices can refine climate-smart sowing calendars. Overall, optimizing the sowing window offers a low-cost, high-impact strategy for sustaining tomato productivity and quality under increasing climatic variability.

KEYWORDS: Tomato, sowing window, phenology, temperature, yield, genotype × environment, climate-smart agriculture

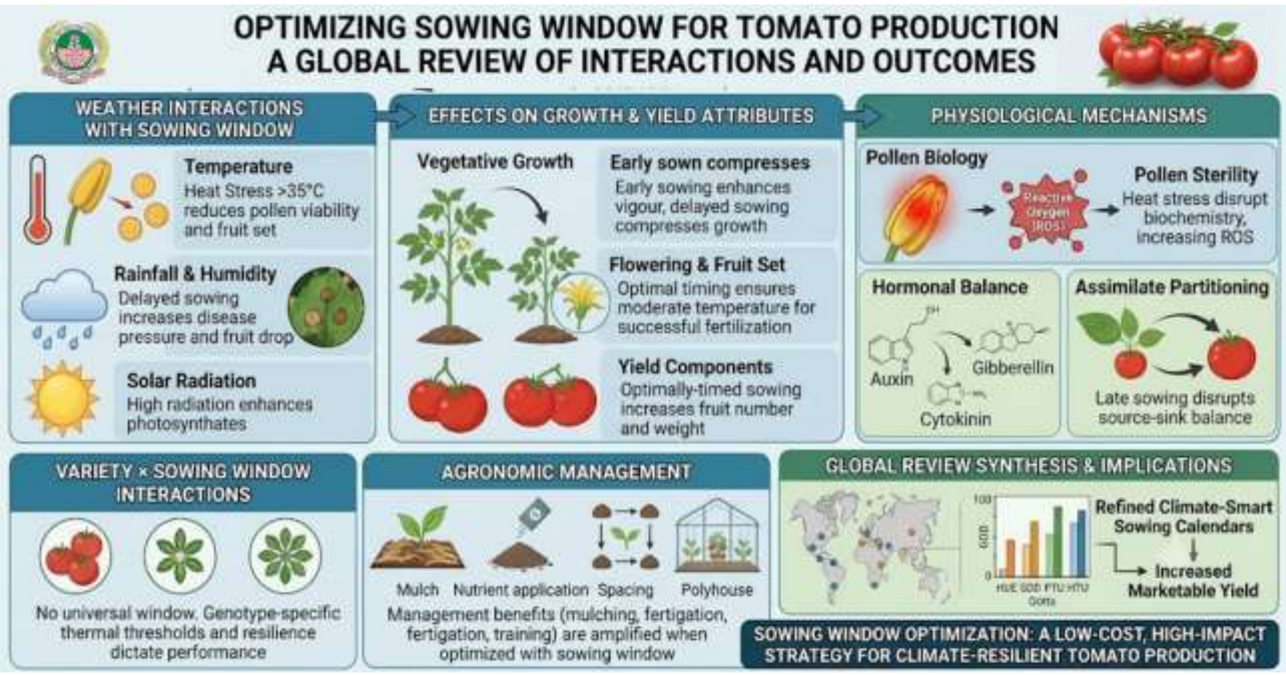

Fig. 1 Graphical Abstract

Abbreviations

BBCH - Biologische Bundesanstalt and CHemical Industry

SOD - Superoxide Dismutase
CAT - Catalase
APX - Ascorbate Peroxidase
SUT - Sucrose Transporter
SUC - Sucrose Carrier

1. INTRODUCTION

Tomato (Solanum lycopersicum L.) is one of the world's most widely cultivated and economically important vegetable crops, ranking second only to potato in global production. It serves as a major component of both fresh-market consumption and the processing industry, contributing to products such as paste, sauce, ketchup, puree, and dehydrated powders. India is the second-largest producer after China, with an annual production of 20.57 million tonnes and a national productivity of 25 t ha^{-1} (Singh et al., 2025 and Tiwari, 2022). Despite its global significance, tomato productivity remains highly sensitive to climatic variability, particularly temperature, rainfall, humidity, and solar radiation, which collectively govern growth, phenology, fruit set, and marketable yield.

Among the various agronomic factors influencing tomato production, the sowing window is consistently identified as one of the most critical determinants of crop performance. Planting time regulates the thermal and moisture environment experienced by the crop at each developmental stage, thereby influencing vegetative growth, flowering behaviour, pollen viability, fruit development, and susceptibility to pests and diseases (Rahman et al., 2020; Subbulakshmi, 2018). Temperature plays a particularly decisive role: while tomatoes grow optimally between 18.3–32.2°C, exposure to temperatures above 35°C during flowering severely impairs pollen development and fruit set (Yadav, 2021). Conversely, low temperatures delay phenological progression, prolonging the time to first flowering and reducing early fruit set (Hassan, 2012).

The phenological development of tomato follows a well-defined sequence from germination (BBCH 00–09) to senescence (BBCH 90–99), with each stage exhibiting distinct climatic sensitivities (Cardoso, 2021). Environmental conditions prevailing at the time of sowing determine the rate at which these stages progress. Early sowing often aligns critical reproductive phases with favourable temperature and radiation regimes, resulting in higher fruit number, improved fruit quality, and greater marketable yield. In contrast, delayed sowing exposes the crop to supra-optimal temperatures, excessive rainfall, or high humidity conditions that reduce pollen viability, increase flower drop, and elevate pest and disease pressure (Mutkule, 2018; Engida, 2017).

The optimal sowing window for tomato varies widely across agro-climatic regions. Studies report July sowing in West Africa (Agoungbome, 2023), October sowing in Bangladesh (Hossain M., 2014), June–July in Bulgaria (Hochmuth, 2012), and July–October in India depending on regional temperature and rainfall patterns. These variations underscore the need for a location-specific understanding of sowing time, weather interactions, and varietal adaptability. Moreover, the increasing use of crop simulation models such as DSSAT and CROPWAT has enabled researchers to quantify thermal accumulation (GDD), photothermal responses (PTU), and heat use efficiency (HUE) across sowing windows, offering predictive insights under current and future climate scenarios (Singh et al., 2025).

Given the strong influence of sowing time on growth, yield, quality, and pest dynamics, a comprehensive synthesis of global research is essential. This review consolidates evidence on how sowing window interacts with weather variables, phenology, varietal responses, agronomic management, and physiological mechanisms to determine tomato productivity. By integrating findings across diverse agro ecologies, this article aims to provide a scientifically grounded framework for optimizing sowing windows under both present and projected climatic conditions.

2. METHODOLOGY OF THE SYSTEMATIC REVIEW (PRISMA-STYLE)

A systematic literature review was conducted to consolidate global evidence on how sowing window influences tomato phenology, physiology, yield, and quality. Relevant studies published between 2000 and 2024 were identified through structured searches in Scopus, Web of Science, Google Scholar, CAB Abstracts, and ScienceDirect, using combinations of keywords such as tomato, sowing date, planting time, phenology, yield, temperature, and fruit set. Studies were included if they evaluated different sowing dates and reported measurable responses in growth, phenology, yield, quality, or physiological traits of Solanum lycopersicum under field or protected conditions. Review papers, non-experimental reports, and studies lacking clear sowing-date treatments were excluded.

The initial search yielded 447 records, which were screened for relevance after removing duplicates. Titles and abstracts of 312 studies were examined, and 200 full texts were assessed in detail. Ultimately, 138 studies met all inclusion criteria and were synthesized (Fig.1). Data extracted from each study included location, climate, variety, sowing dates, weather variables, phenological responses, yield components, quality traits, and pest/disease incidence. These studies were grouped into thematic categories covering phenology, growth and yield, genotype × sowing window interactions, weather–pest relationships, and physiological mechanisms.

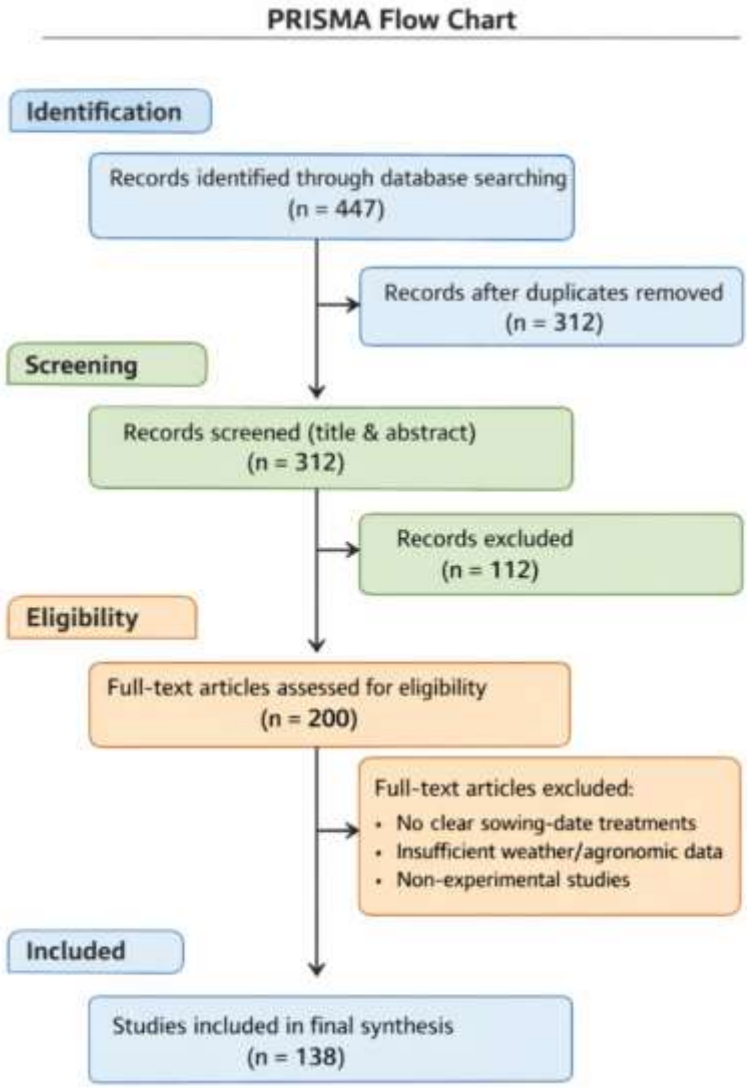

Fig. 2 Systematic Literature Review – PRISMA Flow chart

Overall, the evidence base was strong and consistent, though limited by the scarcity of multi-location trials, inconsistent reporting of microclimate data, and relatively few studies integrating physiology with modelling. Despite these limitations, the reviewed literature provides a robust foundation for understanding how sowing window shapes tomato performance across diverse agro-ecological regions.

3. Phenology of Tomato (BBCH Scale)

Phenology provides a sensitive integrator of how tomato responds to its thermal and moisture environment, as it captures the timing of key life cycle events such as germination, flowering, fruit development, and senescence (Chanal, 2021). The phenological development of tomato (Solanum lycopersicum L.) is well described by the BBCH scale, which divides the crop cycle into distinct, sequential stages from seed germination (BBCH 00–09) to senescence (BBCH 90–99) (Cardoso, 2021). Germination (BBCH 00–09) is characterized by seed sprouting and radicle emergence; the seedling stage (BBCH 10–19) involves cotyledon expansion and the appearance of the first true leaves; and the vegetative growth phase (BBCH 20–29) is marked by rapid stem elongation and side shoot formation, during which the plant builds its photosynthetic canopy.

As the crop transitions to the reproductive phase, flower bud emergence (BBCH 50–59) is observed as visible inflorescences and developing buds, followed by the flowering or anthesis stage (BBCH 60–69), when flowers open, pollination occurs, and fertilization takes place. Successful progression through this stage is highly sensitive to temperature and humidity, as these factors regulate pollen viability, pollen tube growth, and stigma receptivity. The subsequent fruit development stage (BBCH 70–79) is characterized by active green fruit growth, cell division, and dry matter accumulation, while the fruit ripening stage (BBCH 80–89) involves colour change from green to red due to lycopene accumulation and associated biochemical transformations. Finally, the senescence stage (BBCH 90–99) is marked by progressive tissue desiccation and plant death (Cardoso, 2021).

Temperature and radiation regimes prevailing at different sowing dates can substantially accelerate or delay these phenophases. Warmer conditions within the optimal range shorten the duration from transplanting to flowering and fruit set, whereas sub-optimal low temperatures prolong the vegetative period and delay first flowering (Hassan, 2012; Srivastava, 2004). Under climate variability and projected warming, several studies have reported advancement of anthesis and fruiting, with compressed crop duration and altered source–sink balance, ultimately affecting yield and quality. The environmental conditions prevailing during the particular date of sowing in different regions affect the flower initiation time and flowering period.

To quantify these shifts, crop simulation models increasingly link temperature and radiation inputs to phenological outputs, using indices such as growing degree days to predict stage-wise development under different sowing windows (Singh et al., 2025). Thus, phenology serves as a critical bridge between weather conditions at sowing and the final agronomic performance of tomato.

4. Seasonal Cropping Pattern and Market Economics

Tomato cultivation in tropical and subtropical regions, including India, follows three major production seasons such as Kharif (June–September), Rabi (October–February), and Summer (February–May), each characterized by distinct thermal and moisture regimes that strongly influence crop performance (Dhaliwal, 2014). Among these, the Rabi season is widely recognized as the most favourable for open-field tomato production. The cool and dry weather prevailing during October–January aligns closely with the crop's optimal temperature range for flowering and fruit set, resulting in higher fruit number, improved fruit quality, and maximum marketable yield (Mutkule, 2018). In contrast, the Kharif season exposes the crop to elevated temperatures, heavy rainfall, and high relative humidity, conditions that increase vegetative growth at the expense of reproductive development and intensify disease pressure, particularly foliar pathogens and fruit rots (Engida, 2017).

The Summer season presents a contrasting challenge. In the plains, high temperatures during flowering (>35°C) impair pollen viability, reduce fruit set, and limit yield potential, making it a relatively unfavourable period for open-field cultivation. However, in hilly and cooler regions, Summer becomes the principal production window, as moderate temperatures and longer daylengths support vigorous growth and extended harvest periods (Sunil, 2005). These seasonal differences highlight the strong dependence of tomato productivity on the alignment between crop phenology and prevailing weather conditions.

Seasonal production patterns also exert a profound influence on market economics. Tomato prices exhibit a clear inverse relationship with seasonal supply. During the Rabi season, when production peaks across major growing regions, market arrivals increase substantially, leading to depressed farm-gate prices (Rahman et al., 2020). Conversely, tomatoes produced during the Kharif and Summer seasons, despite their higher production risks that command premium prices due to limited supply and greater off-season demand. This price differential incentivizes farmers to adopt off-season cultivation strategies, including protected structures, heat-tolerant varieties, mulching, and optimized sowing dates (Singh et al., 2025).

Thus, the seasonal cropping pattern of tomato is shaped by a complex interplay of weather suitability, production risk, and market opportunity. Understanding these seasonal dynamics is essential for identifying the most profitable and climatically resilient sowing windows, particularly under increasing climate variability.

5. Weather Interactions with Sowing Window

The sowing window determines the specific weather regime under which tomato plants initiate, progress through, and complete their phenological stages. Temperature, rainfall, relative humidity, and solar radiation collectively shape the microclimate experienced by the crop, thereby influencing growth, flowering behaviour, fruit set, and final yield. Numerous studies across agro-ecological regions consistently demonstrate that even slight deviations from the optimal thermal and moisture environment during critical stages can significantly reduce productivity.

a. Temperature Effects Across Sowing Windows

Temperature is the most influential weather variable governing tomato performance. The crop grows optimally between 18.3–32.2°C, while temperatures exceeding 35°C during flowering drastically reduce pollen viability, pollen tube growth, and anther dehiscence, leading to poor fruit set (Sommer, 2012; Singh & Kumar, 2005). Early or appropriately timed sowing ensures that reproductive stages coincide with moderate temperatures, whereas delayed sowing exposes the crop to heat stress during anthesis and fruit set.

For example, in Anand district, sowing dates that aligned fruit set with 30–33°C day temperatures and 13–16°C night temperatures produced significantly higher yields than earlier sowings that encountered sub-optimal temperatures (Vasani, 2024). Conversely, low temperatures at sowing prolong the time to first flowering, while moderate increases in temperature accelerate floral initiation (Hassan, 2012). Sunshine availability further enhances photosynthate accumulation, promoting early flowering (Srivastava, 2004).

b. Rainfall and Humidity Dynamics

Rainfall patterns during the sowing window influence both soil moisture availability and disease pressure. Sowing immediately after the first rains, before adequate soil moisture storage has accumulated, increases the risk of early-season water stress and poor establishment (Agoungbome, 2023; Woli et al., 2012). Excessive rainfall during flowering and fruit development increases fruit drop and reduces fruit number per plant (Mutkule, 2018; Oladitan & Akinseye, 2014).

Relative humidity plays a dual role. Moderate humidity (50–70%) favours pollination and fertilization (Harel, 2014), whereas high humidity (>80%) during late sowings promotes foliar diseases and reduces fruit quality. Late-transplanted crops exposed to high humidity and elevated temperatures during flowering exhibit poor fruit set and reduced yield (Hossain M., 2021).

c. Solar Radiation and Sunshine Hours

Solar radiation regulates photosynthesis, fruit development, and quality attributes such as ascorbic acid and lycopene content. High sunshine hours before harvest enhance vitamin C accumulation, whereas elevated temperatures reduce it

(Dumas, 2003; Ghamande et al., 2018). Early sowing windows that coincide with high radiation levels during vegetative and early reproductive phases generally produce superior canopy development and higher fruit set.

d. Agrometeorological Indices and Sowing Window Optimization

Agrometeorological indices provide integrative measures of weather effects across sowing windows:

- Growing Degree Days (GDD): quantifies thermal accumulation above a base temperature of 10°C.
- Photothermal Units (PTU): combine temperature and daylength, useful for predicting flowering.
- Heliothermal Units (HTU): integrate sunshine hours with GDD, reflecting radiation–temperature interactions.
- Heat Use Efficiency (HUE): measures yield per unit of accumulated heat.

Optimal sowing windows accumulate GDD gradually and avoid rapid heat accumulation during reproductive stages, thereby protecting pollen viability and fruit set. These indices are increasingly incorporated into crop simulation models such as DSSAT and CROPWAT, enabling prediction of sowing-date performance under current and future climate scenarios (Singh et al., 2025).

e. Regional Evidence of Weather–Sowing Interactions

Regional studies further highlight the importance of aligning sowing dates with favourable weather:

- In Bulgaria, June sowing aligns with the optimal 18.3–32.2°C range, producing the highest yields (Hochmuth, 2012).
- In West Africa, delaying sowing to mid-June or July avoids early-season dry spells and improves soil moisture availability (Agoungbome, 2023).
- In India, sowing between July and October varies by region depending on monsoon onset, temperature, and humidity regimes.
- In Ethiopia, tomatoes can be grown year-round, but rainy-season crops require stronger IDM strategies due to high disease pressure (Engida, 2017).

Weather interactions with the sowing window determine whether tomato plants experience favourable thermal and moisture conditions during their most sensitive stages—flowering, fruit set, and early fruit development. Early or optimally timed sowing aligns these stages with moderate temperatures, adequate sunshine, and manageable humidity, whereas delayed sowing exposes the crop to heat stress, excessive rainfall, and disease-favouring conditions. Thus, optimizing the sowing window is fundamentally a process of matching phenology with climate.

6. Effect of Sowing Window on Growth and Yield Attributes

The sowing window exerts a profound influence on tomato growth and yield by determining the thermal, moisture, and radiation environment experienced during the crop's vegetative and reproductive phases. Across global studies, early or optimally timed sowing consistently enhances vegetative vigour, accelerates flowering, improves fruit set, and increases marketable yield, whereas delayed sowing compresses vegetative growth, exposes reproductive stages to heat or humidity stress, and reduces overall productivity.

a. Vegetative Growth Responses

Early sown plants typically exhibit superior vegetative growth, including greater plant height, higher leaf number, increased branching, and larger leaf area index (LAI). These traits collectively enhance photosynthetic capacity and assimilate production. Shreejana (2021) reported that early sown tomatoes produced significantly more leaves, branches, and taller plants compared to late sown crops, which showed progressive reductions in vegetative vigour with each delay in planting. Similar findings were observed by Mutkule (2018), who noted that postponing sowing beyond the optimal window reduced canopy development and dry matter accumulation.

The enhanced vegetative growth in early sowings is attributed to favourable temperature and radiation regimes during the early growth stages, which promote rapid cell division, internode elongation, and canopy expansion. Ahmed et al. (2012) further demonstrated that increased plant height and branching in early sowings translated into higher photosynthetic efficiency and greater biomass production.

b. Flowering Behaviour and Fruit Set

Sowing time strongly influences the timing and success of flowering. Early or optimal sowing aligns anthesis with moderate temperatures, ensuring high pollen viability, efficient pollen tube growth, and successful fertilization. In contrast, delayed sowing often exposes flowers to supra-optimal temperatures (>35°C), which impair anther dehiscence, reduce pollen germination, and increase flower drop (Singh & Kumar, 2005). Multiple studies confirm this pattern. Pardhe (2022) observed that tomatoes transplanted on August 25 under polyhouse conditions flowered earlier and set more fruits due to cooler temperatures during reproductive stages. Similarly, Afreen (2017) reported that tomatoes planted on 2nd week of December exhibited earlier flowering and higher fruit set, particularly when supported with horizontal mechanical training systems.

c. Fruit Number, Fruit Weight, and Yield Components

Yield attributes such as fruit number per plant, fruit weight, and marketable yield are highly sensitive to sowing date. Early sown crops consistently outperform late-sown ones. Shreejana (2021) found that fruit number decreased progressively with delayed sowing, while early and regularly sown plants produced significantly more fruits. Mira (2011) also reported a gradual decline in branch and fruit production with delayed transplanting. In Rajasthan, 4th week August sowing produced the highest fruit number, fruit weight, and marketable yield due to favourable temperatures during flowering and fruit development (Pardhe, 2022). In Bangladesh, 1st October sowing resulted in early flowering, early harvest, and maximum yield, whereas October 30 sowing experienced extreme cold during fruiting, reducing yield (Hossain M., 2014).

d. Mechanistic Basis for Yield Decline in Late Sowing

Delayed sowing compresses the vegetative phase, limiting canopy development and reducing the plant's ability to accumulate assimilates before entering the reproductive stage. Heat stress during late-season flowering accelerates respiration, reduces photosynthate availability, and increases flower and fruit drop. High humidity and rainfall during late sowings further reduce fruit set and increase physiological disorders. Mutkule (2018) demonstrated that late sown tomatoes experienced reduced photosynthetic efficiency due to heat induced stomatal closure and increased photorespiration. These physiological constraints translate directly into lower fruit number, smaller fruit size, and reduced marketable yield. Across diverse agro-climatic regions, the evidence is unequivocal: Early or optimally timed sowing ensures that tomato plants complete their vegetative and reproductive phases under favourable thermal and radiation conditions, maximizing canopy development, photosynthate production, fruit set, and yield. Delayed sowing exposes the crop to heat, humidity, or cold stress, compresses growth duration, and significantly reduces yield potential.

7. Variety × Sowing Window Interactions

The interaction between genotype and sowing window is a critical determinant of tomato productivity, as varieties differ widely in their thermal requirements, phenological plasticity, and tolerance to abiotic and biotic stresses. Numerous studies demonstrate that the same sowing date can produce markedly different outcomes across varieties, and conversely, the same variety may perform optimally only within a specific planting window. This underscores the importance of aligning varietal choice with the prevailing climatic conditions of the sowing period.

a. Genotypic Differences in Response to Sowing Time

Varieties differ in their sensitivity to temperature, photoperiod, and humidity during flowering and fruit development. In Maharashtra, Phule Raja and PKM-1 exhibited significant variation in ascorbic acid content across sowing dates, with the highest values recorded in the second sowing window, indicating strong genotype × environment interaction (Vindya Sabbineni, 2020). Total soluble solids and acidity, however, remained relatively stable across dates, suggesting that some quality traits are less sensitive to sowing time.

In Bangladesh, sowing on 1st October consistently produced early flowering, early fruit harvest, and the highest yield across genotypes, particularly in BARI Tomato-2 and BARI Tomato-9 (Hossain M., 2014). Delayed sowing (30th October) exposed plants to extreme cold during fruiting, reducing fruit set and yield, with genotypes showing differential tolerance to low-temperature stress.

b. Yield Performance Across Varieties and Planting Windows

In Telangana, the cultivars US-440 and TO-3251 (Saaho) were evaluated across eight planting dates from 2nd July to 13th September, where the earliest planting (July 2) produced the highest fruit yield, plant height, branch number, LAI, and fruit number per plant, with US-440 outperforming TO-3251 despite minimal statistical differences (Shravika L., 2020). The superior performance of early sowing was attributed to higher temperatures during early vegetative growth, which enhanced photosynthate accumulation.

In Rajasthan, the Bavandar variety performed best when transplanted between December 30 and January 15, outperforming WS-1299 and Krishna varieties. This window minimized pest and disease incidence and avoided harsh environmental conditions, resulting in higher yield and net returns (Singh U., 2024). Similarly, in Bangladesh, BARI Tomato-14 and BARI Tomato-3 achieved maximum yield when transplanted on 18th December, highlighting the importance of synchronizing genotype with favourable thermal regimes (Hossain S., 2023).

c.Region-Specific Recommendations

Regional studies provide clear evidence that optimal sowing windows vary by genotype:

- Odisha (Western Undulating Zone): Hybrid Arka Rakshak performed best when sown on September 30, benefiting from favourable temperatures during flower initiation in December (Sahoo, 2021).
- Telangana: October planting combined with the variety ‘Heemsona’ produced the highest benefit–cost ratio (4.26), due to longer growing periods and favourable temperatures (Chaitanya, 2024).
- Semi-arid regions: Planting between July 2–12 and again on September 13 produced the highest net returns (B:C ratio 8.75) due to optimal temperature–radiation balance (Shravika, 2021).

These findings highlight that varietal adaptability is strongly linked to the thermal and moisture environment of the sowing window.

d. Mechanistic Basis for Genotype × Sowing Window Interaction

The differential performance of varieties across sowing dates is driven by:

- Thermal tolerance: Varieties differ in their ability to maintain pollen viability and fruit set under heat or cold stress.
- Phenological plasticity: Some genotypes adjust flowering time more flexibly in response to temperature shifts.
- Assimilate partitioning: High-yielding hybrids often require longer vegetative phases, making them more sensitive to delayed sowing.
- Disease susceptibility: Late sowing increases exposure to tomato yellow leaf curl virus, early blight, and leaf miner, with varietal differences in resistance.

Thus, the optimal sowing window for each variety is a function of its physiological thresholds and stress-response mechanisms.

Across global studies, the evidence is clear that no single sowing window is universally optimal for all tomato varieties. Instead, each genotype performs best when its thermal, photoperiodic, and stress-tolerance characteristics align with the climatic conditions of a specific planting window. This makes genotype × sowing window matching a cornerstone of climate-smart tomato production.

8. Influence of Sowing Window on Agronomic Management

The effectiveness of agronomic management practices such as nutrient application, mulching, spacing, training systems, and protected cultivation is strongly modulated by the sowing window. The microclimate created by a particular planting date determines how efficiently these practices enhance growth, fruit set, and yield. Across studies, early or optimally timed sowing consistently amplifies the benefits of improved management, whereas delayed sowing often diminishes their effectiveness due to heat stress, humidity, or shortened crop duration.

a.Nutrient Management × Sowing Window

Nutrient uptake and assimilation are highly sensitive to temperature and soil moisture conditions prevailing at different sowing dates. At Ponnaniyar, Trichy district in Tamil Nadu, India, the early sowing combined with optimal nitrogen levels significantly increased marketable fruit yield, even though quality parameters remained unaffected by sowing date (Bhuvanaswari, 2018). Early sowing ensured that flowering and fruiting coincided with favourable temperature and radiation, enabling efficient nitrogen assimilation and improved canopy development. Higher nitrogen doses have been shown to increase total soluble solids (TSS) and fruit quality (Erdal et al., 2007), but these benefits are maximized only when the crop is sown within a window that supports vigorous vegetative growth and prolonged reproductive duration.

b.Mulching and Microclimate Modification

Mulching interacts strongly with sowing time by modifying soil temperature, conserving moisture, and reducing weed competition. Straw mulch increased branch number and vegetative vigour compared to unmulched crops (Gandhi & Bains, 2006). In Jabalpur, early sowing on September 15, combined with 50% RDF (Recommended Dose of Fertilizer) + Farm yard manure + poultry manure + biofertilizer, produced superior growth, higher fruit number, and improved quality attributes such as TSS and ascorbic acid (Singh, 2015). Early sowing allowed sufficient time for vegetative expansion, while organic amendments enhanced nutrient availability and soil biological activity. Plastic mulches, particularly white mulch, produced higher yields in spring compared to fall due to optimal soil temperature regulation and moisture conservation (Elsayed-Farag, 2018). These benefits were most pronounced when sowing dates aligned with moderate ambient temperatures.

c.Spacing, Training Systems, and Sowing Window

Plant spacing and training systems influence canopy architecture, light interception, and fruiting behaviour, and their effectiveness depends on the sowing window.

Under protected cultivation in the Himalayas, wider spacing (75 × 30 cm) and two-shoot training significantly reduced days to flowering, enhanced fruit set, and increased fruit number when sown on 30th March (Singh, 2019). This date provided optimal temperatures (~25°C), whereas 15th March was too cool and April 15 too warm for ideal reproductive development. Similarly, horizontal mechanical support systems enhanced plant height, leaf number, branch number, and fruit yield when tomatoes were sown on 10th December, outperforming vertical support systems (Afreen, 2017). The favourable microclimate during early sowing amplified the benefits of improved canopy management.

d.Protected Cultivation and Sowing Window

Protected structures buffer temperature extremes and allow manipulation of sowing dates to exploit favourable microclimates. In Rajasthan, transplanting on 25th August under polyhouse conditions produced the highest yield due to cooler temperatures during flowering and fruiting (Pardhe, 2022). Protected cultivation thus extends the viable sowing window, but the magnitude of benefit still depends on aligning reproductive stages with optimal temperature and radiation.

e.High-Density Planting and Early Sowing Synergy

In North Kordofan, Sudan, early sowing on 1st October combined with high-density planting (20 cm intra-row spacing) maximized marketable yield of the Red Star variety (El Naim, 2010). Early sowing ensured favourable temperatures for vegetative growth, while high density increased total plant population per unit area, enhancing overall productivity.

Across studies, the interaction between sowing window and agronomic management follows a consistent pattern:

- Early or optimal sowing enhances the effectiveness of nutrient management, mulching, spacing, and training systems.
- Delayed sowing reduces the benefits of improved management due to heat stress, humidity, shortened vegetative phase, and increased pest/disease pressure.
- Protected cultivation can partially buffer adverse weather, but optimal sowing timing remains critical.

Thus, agronomic interventions achieve their maximum potential only when synchronized with a sowing window that provides favourable thermal and moisture conditions.

9. Pest and Disease Incidence Across Sowing Windows

The sowing window plays a decisive role in determining the pest and disease pressure experienced by tomato crops. Temperature, humidity, and rainfall patterns associated with different planting dates influence pest population dynamics, pathogen sporulation, vector activity, and host susceptibility. Across global studies, early or optimally timed sowing reduces pest and disease incidence, whereas delayed sowing exposes the crop to peak vector populations, favourable pathogen microclimates, and weakened plant physiological status.

a. Insect Pest Incidence Across Sowing Dates

i. Aphids and Leaf Miner

Aphid populations and serpentine leaf miner infestation show strong seasonal patterns linked to sowing time. In Nagaland, tomatoes planted on 19th December recorded the lowest aphid population, while early planting on 19th November minimized leaf miner incidence (Waluniba, 2015). Similarly, Singh (2005) reported that crops sown on 7th December had the lowest leaf miner infestation, whereas those sown on 22nd December experienced the highest. The increased infestation in late sowings is attributed to:

- declining plant antibiosis with age
- higher oviposition rates by adult leaf miners
- favourable temperature–humidity conditions for larval development

ii. Fruit Borer and Defoliators

Fruit borer incidence increases steadily with delayed sowing. In Meghalaya, tomatoes sown on 8th November recorded the highest fruit borer damage (7.58%), while September sowings had lower infestation (Pongen, 2022). Green looper incidence peaked in early sowings (23rd September), indicating that different pests respond differently to seasonal microclimates.

b.Viral Diseases and Vector Dynamics

Tomato Yellow Leaf Curl Virus (TYLCV), transmitted by Bemisia tabaci, is highly sensitive to sowing time. In Iran, sowing on 20th September and 5th October significantly reduced TYLCV incidence, whereas early August–September sowings did not reduce disease severity (Azadvar, 2016). The reduction in late-September sowings is linked to:

- lower whitefly populations
- cooler temperatures reducing vector activity
- reduced virus transmission efficiency

c.Fungal Diseases: Early Blight and Foliar Pathogens

Early blight (Alternaria solani) showed strong seasonal dependence. In the Gangetic plains, the disease begins in November in Kharif sown crops and persists until April–May in Rabi sown crops (Pandey, 2011). Sowing on November 11 resulted in the lowest disease severity index and highest fruit yield (Kumar, 2019). Disease severity was:

- positively correlated with rainfall and relative humidity
- negatively correlated with sunshine hours

This highlights the importance of aligning sowing dates with periods of lower humidity and higher radiation.

d.Mechanistic Basis for Pest and Disease Variation Across Sowing Windows

The differential pest and disease incidence across sowing dates is driven by:

i. Microclimate Effects

- Late sowings coincide with higher humidity, warmer nights, and frequent rainfall, creating ideal conditions for fungal pathogens.
- Early sowings often experience lower vector populations and reduced pathogen pressure.

ii. Plant Physiological Status

- Early-sown plants have stronger vegetative vigour and higher defensive capacity.
- Late-sown plants experience heat or moisture stress, reducing resistance to pests and pathogens.

iii. Vector Ecology

- Whiteflies, aphids, and leaf miners peak during specific temperature–humidity windows.
- Aligning sowing dates to avoid vector peaks reduces disease transmission.

e.Integrated Interpretation

i. Across regions, the pattern is consistent:

- Early or optimally timed sowing reduces pest and disease incidence by avoiding peak vector activity and unfavourable microclimates.
- Delayed sowing increases susceptibility due to heat stress, high humidity, and weakened plant defences.
- Sowing window manipulation is a powerful, low-cost cultural tool

10. Physiological and Biochemical Mechanisms Behind Sowing Date Effects

The physiological and biochemical responses of tomato to different sowing windows are governed by the thermal, photoperiodic, and moisture environments experienced at each developmental stage. These environmental cues regulate germination, photosynthesis, hormonal balance, pollen viability, assimilate partitioning, and fruit ripening. Consequently, the sowing window determines whether the crop progresses through its phenophases under optimal or stress-inducing conditions, ultimately shaping yield and quality.

a. Seed Germination and Seedling Establishment

Tomato seeds germinate optimally at 25–30°C, where gibberellin activated enzymes such as α-amylase and protease efficiently mobilize stored reserves (Yadav et al., 2021; Cantliffe, 2003). Early or optimal sowing ensures that soil temperatures remain within this favourable range. Low temperatures (<15°C) elevate abscisic acid (ABA) levels and suppress gibberellin synthesis, delaying germination and reducing seedling vigour. Conversely, high temperatures (>35°C) denature hydrolytic enzymes and increase ethylene accumulation, inhibiting radicle emergence. Thus, sowing date determines the uniformity and vigour of seedling establishment.

b.Photosynthesis and Carbon Assimilation

Tomato, a C3 species, exhibits maximum RuBisCO carboxylation efficiency at 25–30°C. Early sowing aligns vegetative growth with this optimal thermal window, enhancing net photosynthesis (Pn), stomatal conductance, and chlorophyll stability. Delayed sowing often exposes plants to supra-optimal temperatures, which:

- thermally inactivate Photosystem II
- increase photorespiration
- induce stomatal closure due to high vapour pressure deficit (VPD)
- reduce carbohydrate accumulation (Mutkule, 2018; Hatfield & Prueger, 2015)

Sub-optimal low temperatures in very early sowings similarly impair electron transport and reduce Pn (Srivastava, 2004). These physiological constraints directly influence canopy development and subsequent reproductive success.

c.Hormonal Regulation of Flowering and Fruit Set

Flowering and fruit set are highly sensitive to the hormonal environment, which is strongly modulated by temperature. Under optimal sowing windows, balanced levels of auxin (IAA) and cytokinins support pollen tube growth, stigma receptivity, and ovary development. However, late sowing often exposes flowers to temperatures above 35°C, which:

- accelerate IAA degradation via peroxidase activity
- increase ethylene biosynthesis (via ACC synthase and ACC oxidase)
- promote premature flower abscission

• elevate ABA levels, suppressing cell division in developing ovaries (Peet et al., 1998; Sato et al., 2006)
These hormonal disruptions explain the sharp decline in fruit set observed in late-sown crops.

d.Pollen Viability and Male Reproductive Biochemistry

Pollen development is one of the most temperature sensitive processes in tomato. Heat stress during microsporogenesis (>35°C day / >20°C night) disrupts:

• sporopollenin deposition
• starch and soluble sugar accumulation
• tapetal cell function
• anther dehiscence

High temperatures also trigger excessive production of Reactive Oxygen Species (ROS) such as H_2O_2 and $O_2^{\bullet -}$, which cause lipid peroxidation, protein denaturation, and DNA damage in anthers (Sato et al., 2006; Singh & Kumar, 2005). When ROS (Reactive Oxygen Species) exceed the detoxification capacity of antioxidant enzymes (SOD, CAT, APX), pollen sterility results. This mechanistic pathway explains the poor fruit set in late-sown crops exposed to heat stress.

e.Assimilate Partitioning and Sink–Source Dynamics

Early sowing allows the crop to develop a robust photosynthetic canopy before entering the reproductive phase. This enhances phloem loading of sucrose via sucrose transporter (SUT/SUC) proteins and supports strong sink activity in developing fruits. In fruits, sucrose is hydrolysed by acid invertase and sucrose synthase into hexoses, driving cell expansion and fruit growth. Late sowing disrupts this balance by

• shortening the vegetative phase
• increasing respiration under heat stress
• reducing carbohydrate availability for fruit development (Nangare et al., 2016; Ahmed et al., 2012)

As a result, late-sown plants produce fewer and smaller fruits with lower marketable yield.

f.Fruit Ripening: Lycopene and Ascorbic Acid Biosynthesis

Fruit ripening is strongly temperature dependent. Lycopene biosynthesis via phytoene synthase (PSY1) is optimal at 12–24°C. Temperatures above 30°C suppress PSY1 transcript levels, leading to reduced lycopene accumulation and yellow/orange fruit coloration (Ghamande et al., 2018). High temperatures also accelerate ascorbic acid oxidation via L-ascorbate oxidase, reducing vitamin C content (Dumas et al., 2003). Thus, sowing windows that align ripening with moderate temperatures produce fruits with superior colour and nutritional quality.

g.Oxidative Stress and Antioxidant Defence

Thermal extremes associated with sub-optimal sowing dates induce oxidative stress, characterized by excessive ROS accumulation. While antioxidant enzymes (SOD, CAT, APX) attempt to neutralize ROS, prolonged heat or cold stress overwhelms these systems, leading to membrane damage, impaired photosynthesis, and reduced fruit set. Early sowing minimizes exposure to such stress, preserving physiological integrity throughout the crop cycle.

Across physiological and biochemical pathways, the evidence is consistent: The sowing window determines whether tomato plants experience optimal or stress-inducing environments during critical developmental stages. Early or optimal sowing supports favourable hormonal balance, pollen viability, photosynthesis, assimilate partitioning, and fruit ripening, whereas delayed sowing disrupts these processes through heat stress, oxidative damage, and hormonal imbalance.

11. Synthesis and Knowledge Gaps

The global evidence reviewed across agro-ecological regions demonstrates a consistent and compelling pattern: the sowing window is the single most influential agronomic factor determining tomato growth, phenology, fruit set, yield, and quality. However, despite broad agreement on the importance of planting time, significant regional contradictions and unresolved scientific gaps remain. These gaps limit the development of universally applicable sowing recommendations and highlight the need for more integrated, climate-responsive research.

a. Synthesis of Global Evidence

Across studies, several unifying conclusions emerge:

i. Early or optimal sowing consistently enhances productivity

Favourable temperature, radiation, and humidity during vegetative and reproductive phases promote:

• vigorous canopy development
• high pollen viability
• efficient assimilate partitioning
• improved fruit set and yield

ii. Delayed sowing exposes crops to stress

Late sowing often coincides with:

• heat stress during flowering
• high humidity during fruit development
• increased pest and disease pressure
• shortened vegetative duration

These factors collectively reduce fruit number, fruit weight, and marketable yield.

iii. Variety × sowing window interactions are strong

No single sowing window suits all genotypes. High-yielding hybrids, heat-tolerant lines, and cold-sensitive varieties respond differently to planting dates, emphasizing the need for location- and genotype-specific recommendations.

iv. Agronomic practices amplify sowing window effects

Nutrient management, mulching, spacing, and protected cultivation are most effective when synchronized with optimal sowing dates.

v. Weather indices and crop models improve prediction
GDD, PTU, HTU, and HUE provide quantitative tools to evaluate sowing windows, while DSSAT and CROPWAT help simulate performance under future climates.

c.Contradictions in the Literature

Despite broad agreement, several contradictions persist:

i. Optimal sowing windows vary widely across regions

For example:

- July in West Africa
- June–July in Bulgaria
- September–October in India
- October in Bangladesh

These differences arise from contrasting thermal regimes, monsoon patterns, and varietal preferences.

ii. Conflicting responses to rainfall and humidity

Some studies report that moderate rainfall enhances early growth, while others show negative correlations between rainfall and fruit number due to fruit drop (Mutkule, 2018; Oladitan & Akinseye, 2014).

iii. Varietal inconsistencies

The same variety performs differently across locations and years due to:

- genotype × environment × management interactions
- variable pest/disease pressure
- inconsistent microclimatic conditions

iv. Protected cultivation results vary

While some studies show strong yield advantages under polyhouses, others report marginal benefits when sowing dates are sub-optimal. These contradictions highlight the complexity of sowing window optimization under diverse agro-ecologies.

c. Knowledge Gaps and Research Needs

Despite extensive research, several critical gaps remain:

i. Lack of unified, multi-location trials

Most studies are location-specific, limiting the development of regional or national sowing calendars.

ii. Limited integration of physiology with field agronomy

Few studies link:

- pollen biology
- hormonal regulation
- ROS dynamics
- carbohydrate partitioning with field-level yield responses across sowing windows.

iii. Insufficient modelling under climate change scenarios

Crop models are underutilized for:

- predicting future optimal sowing windows
- assessing heat-tolerant genotypes
- evaluating extreme weather impacts

iv. Poor understanding of pest–climate–sowing interactions

Vector ecology (whitefly, aphid, leaf miner) under shifting climates remains poorly quantified.

v. Limited research on quality traits

Most studies focus on yield; fewer examine:

- lycopene
- ascorbic acid
- TSS
- flavour compounds

across sowing windows.

vi. Need for genotype-specific thermal thresholds

Breeding programs require:

- pollen heat tolerance thresholds
- fruit set temperature limits
- ripening temperature optima

for different cultivars.

d. Future Directions

To address these gaps, future research should prioritize:

- Multi-location, multi-year sowing window trials
- Integration of crop physiology, modelling, and field agronomy
- Development of climate-smart sowing calendars
- Breeding for heat-tolerant and cold-tolerant reproductive traits
- Use of remote sensing and AI for sowing date prediction
- Stronger focus on fruit quality and nutritional traits

Optimizing the sowing window is central to maximizing tomato productivity, but achieving this requires a deeper integration of physiology, climate science, modelling, and genotype-specific research.

12. Summary Table: Regional Optimum Sowing Windows for Tomato Production

Table 1 Summary table

Region / Country	Optimum Sowing / Transplanting Date	Variety / Genotype	Key Reason / Outcome	Source
West Africa (savanna)	Mid-June	-	Avoids water stress; soil moisture builds before dry spells	Agoungbome, 2023
West Africa (semi-arid)	July	-	Delayed sowing after first rains reduces water stress risk	Agoungbome, 2023
Bulgaria	20 June	-	Temperature in optimum range 18.3-32.2 °C; higher yield vs July sowings	-
Bangladesh (general)	1 October	BARI Tomato-2, BARI Tomato-9	Early flowering, early harvest, highest marketable yield; avoids extreme cold during fruiting	Hossain M., 2014
Bangladesh (winter)	18 December	BARI Tomato-14, BARI Tomato-3	Best combination for highest tomato production in winter season	Hossain S., 2023
Bangladesh (cherry tomato)	30 November	Cherry tomato	Harvest Mar 1-20; temp, rainfall, RH and sunshine all favourable for yield and quality	Hossain M., 2021
Telangana, India (kharif)	2 July	US 440	Higher photosynthate accumulation; max plant height, branches, LAI, fruit yield; B:C ratio 8.75	Shravika, 2020 & 2021
Telangana, India (general)	October	Heemsona	Favourable temperatures and longer growing period; B:C ratio 4.26	Chaitanya, 2024
Rajasthan, India (polyhouse)	25 August	-	Cooler conditions during flowering and fruiting; highest LAI and marketable yield	Pardhe, 2022
Rajasthan, India (semi-arid)	30 Dec - 15 Jan	Bavandar	Reduced pest/disease attack; higher productivity; better net returns	Singh U., 2024
Odisha, India (western undulating zone)	30 September	Arka Rakshak	Transplanting in last week of October; optimum temp during flower initiation in December	Sahoo, 2021
Jabalpur, India (polyhouse)	15 September	-	Full vegetative phase; combined organic + inorganic manure gives highest yield and quality	Singh, 2015
Nagaland, India	19 November	-	Least serpentine leaf miner incidence; pest management benefit	Waluniba, 2015

Region / Country	Optimum Sowing / Transplanting Date	Variety / Genotype	Key Reason / Outcome	Source
Himalayas, India (protected)	30 March	-	Warmer temp ~25 °C; fewer days to flowering, fruit set and first picking; 75×30 cm + 2-shoot training	Singh K., 2019
Sudan (North Kordofan)	1 October	Red Star	High-density planting (20 cm intra-row); favourable early-sowing conditions; max marketable yield	El Naim, 2010
Iran	20 Sep - 5 Oct	-	Greatly reduced TYLCV (Tomato Yellow Leaf Curl Virus) percentage and intensity	Azadvar, 2016
Nigeria (rainforest zone)	March - June (Season 1)	-	More favourable climate vs Season 2 (Aug-Dec); better crop quantity and quality	Oyelaran, 2018
South Texas, USA	Spring season	Common varieties + white plastic mulch	Temp 20.9-31.1 °C (optimum); white mulch maintains soil moisture; higher yield vs fall season	Elsayed-Farag, 2018

13. CONCLUSION

This review establishes that the sowing window is a decisive factor shaping tomato growth, phenology, fruit set, yield, and quality. Aligning planting time with favourable temperature, radiation, and humidity ensures vigorous vegetative growth, high pollen viability, efficient assimilate partitioning, and superior fruit development. In contrast, delayed sowing exposes the crop to heat stress, excessive humidity, and elevated pest and disease pressure, resulting in reduced fruit number, smaller fruits, and lower marketable yield.

Varietal differences further highlight the need for genotype-specific sowing recommendations, as hybrids and open-pollinated varieties respond differently to thermal regimes. Agronomic practices such as nutrient management, mulching, spacing, and protected cultivation enhance productivity only when synchronized with optimal sowing dates. Physiological evidence, including hormonal balance, pollen biology, and oxidative stress responses explains why sowing time exerts such a dominant influence on yield outcomes.

In the context of increasing climate variability, optimizing the sowing window remains a low-cost, high-impact strategy for sustaining tomato productivity. Future work should integrate multi-location trials, crop modelling, and physiological insights to refine climate-smart sowing calendars tailored to specific varieties and production environments.

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