5-2025

Quantifying Temperature Effects on Developmental Rate and Plant Quality of Compact Container-grown Tomato (Solanum lycopersicum)

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Citation

Humphrey, M. (2025). Quantifying Temperature Effects on Developmental Rate and Plant Quality of Compact Container-grown Tomato (Solanum lycopersicum). *Horticulture Undergraduate Honors Theses* Retrieved from https://scholarworks.uark.edu/hortuht/11

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Date of Defense: February 24, 2025

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Abstract

Mean daily temperature effects on plant development rates and quality were evaluated for compact container-grown tomato (*Solanum lycopersicum*). Compact tomato varieties ‘Siam’ and ‘Red Velvet’ were grown in greenhouses at 18 to 26 °C (Experiment 1) and 20 to 30 °C (Experiment 2) under supplemental high-pressure sodium lighting and 16-hour photoperiod. The number of days to first open flower, first ripe fruit, and from flower to ripe fruit were measured and development rates calculated by taking the reciprocal (e.g. 1/days). Temperature effects were predicted by fitting a linear (for first open flower) and a nonlinear exponential function (for first ripe fruit and between first open flower and ripe fruit) which included base temperature (T_{min}) and maximum developmental rate (R_{max}) parameters. Plant quality attributes were measured in Experiment 2. As temperature increased, the time to flower and fruit decreased (i.e. developmental rates increased) for both varieties. Estimated T_{min} was 8.7 °C for ‘Siam’ and 11.4 °C for ‘Red Velvet’ whereas R_{max} was similar between varieties (0.030 at fruit, and 0.037 from flower to fruit). ‘Siam’ and ‘Red Velvet’ grown at ≈25 °C had a relatively short crop time, compact canopy, adequate fruit size, and a high number of fruits per plant at finish. Compact tomatoes are new crops being grown by greenhouse floriculture operations for ornamental and edible value, and the information from this study can help growers schedule these crops to meet critical market windows and determine the impacts of changing growing temperature on crop timing and quality.

Introduction and Literature Review

Compact tomato (*Solanum lycopersicum*) is increasing in popularity as a container crop grown by floriculture operations to meet the demand of an expanding container edibles and home gardening market (Cruz and Gomez, 2022; Cruz et al., 2022). Compact tomatoes tend to be short-statured compared to traditional garden varieties and provide consumers with both ornamental and edible value (Cruz and Gomez, 2022; Cruz et al., 2022; Langenfeld and Bugbee, 2023). Compact tomatoes are marketable when plants have at least one ripe and ready-to-harvest fruit plus multiple unripe fruits, open flowers, and emerging flower buds (i.e. future harvests).

Greenhouse operations producing compact tomato in containers need the ability to schedule production so that the crops finish during desired market windows, which requires knowledge of the specific crop time needed to produce a marketable plant. The development of empirical models has been one method used to help growers predict crop time under various environmental conditions for economically important container crops including chrysanthemum [*Chrysanthemum* × *grandiflorum* (Ramat.) Kitam.; Larsen and Persson, 1999], Easter lily (*Lilium longiflorum* Thunb.; Erwin and Heins, 1990), poinsettia (*Euphorbia pulcherrima* Willd. ex Klotz; Liu and Heins, 2002), potted rose (*Rosa* L.; Steininger et al., 2002), and a range of annual bedding plant and herbaceous perennial species (Blanchard and Runkle, 2011).

Crop time is determined by the rate at which plants develop, such as the unfolding of leaves or the production of flowers and fruit, which is largely influenced by the integrated mean daily temperature (MDT) (Roberts and Summerfield, 1987). For example, the rate of development increases as the MDT increases between the base temperature (T_{min}) and the optimal temperature (T_{opt}), where T_{min} is the low temperature at which the rate is zero and T_{opt} is the temperature corresponding to the maximum rate. Additionally, as MDT increases past T_{opt} the development rate then decreases until it reaches the maximum temperature (T_{max}), where the rate is zero from heat stress. The development rate to a particular stage (i.e. flowering, fruiting) can be calculated as the reciprocal of the time required to complete the stage of development (e.g. 1/days), and therefore relating crop time with development rate. The temperature parameters T_{min}, T_{opt}, and T_{max} are species-specific (Blanchard et al., 2011), and sometimes variety-specific, and their estimation requires quantifying plant development rates across a wide range of MDT values.

Different functions including linear, quadratic, cubic, and exponential have been used in empirical modeling to describe the relationship between MDT and plant development rates (Blanchard and Runkle, 2011; Landsberg, 1977; Larsen, 1990). Depending on species and variety, the shape around T_{opt} has been described as either symmetrical (Pearson et al., 1993; Volk and Bugbee, 1991) or asymmetrical (Brøndum and Heins, 1993; Faust and Heins, 1993, 1994) regarding how plant development rate responds to MDT. The temperature range resulting in the highest crop quality often falls between T_{min} and T_{opt}, and therefore a practical outcome of characterizing these relationships is the estimation of these parameters (Blanchard and Runkle, 2011). In addition, T_{min} can be used as a reference when reducing greenhouse temperatures to slow growth and achieve greater energy efficiency (i.e. reduced heating).

The first objective of this study was to investigate the effects of MDT on crop time and flowering and fruiting rates for two compact tomato varieties. The second objective was to evaluate temperature effects on potential yield (the total number of fruits and flowers), fruit weight, and canopy size. We hypothesized that increasing temperature would reduce fruit weight and yield and that plant development rates would differ between the stages of flowering and fruiting for compact container-grown tomatoes.

Materials and Methods

Experiment 1: Compact tomato varieties evaluated from 18 to 26 °C

Tomato varieties ‘Siam’ and ‘Red Velvet’ (Pan American Seed, West Chicago, IL, USA) were chosen due to their market popularity and compact growth habit in containers. Seed of compact tomato (*Solanum lycopersicum* L.) varieties ‘Siam’ and ‘Red Velvet’ (Pan American Seed, West Chicago, IL) were sown in plug trays [128-cell (12-mL volume)] with ProMix BX substrate (Premier Tech, Quebec, Canada) and were placed in a polycarbonate climate-controlled greenhouse at the University of Arkansas in Fayetteville, AR (36.0627° N, 94.1606° W). The sow dates differed by variety and was 4 Dec 2021 for ‘Siam’ and 23 Dec 2021 for ‘Red Velvet.’ These varieties were selected for their compact growth habit in containers and market popularity. Seedlings were irrigated after germination as needed using a commercial 13N-0.9P-10.8K (J.R. Peters, Allentown, PA) water-soluble fertilizer mixed in tap water at 100 $mg \cdot L^{-1}$ N. The tap water in this experiment had an electrical conductivity (EC) of 0.3 $mS \cdot cm^{-1}$ and bicarbonate alkalinity of <60 $mg \cdot L^{-1}$.

Seedlings were ready for transplant at 38 d after sowing and each variety had 3-4 true leaves per seedling. At this time, 20 seedlings per variety were randomly assigned to each temperature treatment and placed in identical adjacent greenhouse compartments with day and night air temperature set-points of 18, 20, 22, 24, and 26 °C. Each seedling was transplanted into 15.4-cm diameter containers with ProMix BX substrate (Premier Tech, Quebec, Canada) at one seedling per container. Within each greenhouse, the plants and varieties were randomized within 20 blocks set up across two adjacent benches at an initial density of 36 plants per m^2 and were later spaced to 9 plants per m^2. Plants were top-irrigated as needed with a 17N-2.2P-14.1K (J.R. Peters, Allentown, PA) water-soluble fertilizer mixed at 150 mg·L^{-1} N in tap water. Each container was irrigated with fertilizer solution to container capacity once the substrate dried to ≈50% moisture content, determined visually using the method described by Healy (2008). The experiment started with the transplant of seedlings on 11 Jan 2022 for 'Siam' and 30 Jan 2021 for 'Red Velvet.'

Experiment 2: Compact tomato varieties evaluated from 20 to 30 °C

The tomato varieties and cultural practices were the same as in Experiment 1, with the exception that there were only six plants per variety and treatment, the sow dates were the same for both varieties, and the temperature setpoints differed and consisted of 20.0, 22.5, 25.0, 27.5, and 30.0 °C. The experiment began on 6 Mar 2022 (experimental run 1) and was replicated on 3 Apr 2022 (experimental run 2). Plants were sub-irrigated with the same water-soluble fertilizer solution used in Experiment 1 and supplied 150 mg·L^{-1} N and 80 mg·L^{-1} N at each irrigation event for the first and second experimental runs, respectively. The fertilizer N concentration was lowered for the second experimental run to reduce excess vegetative growth (leaves and stems). Applied N concentration did not interact with temperature effects on flower and fruit development rates but appeared to influence plant quality and yield (see Results and Discussion).

Environmental monitoring

The temperature treatments for each greenhouse compartment were achieved using an environmental control system (QCom Greenhouse Controls, Temecula, CA) programmed to target each setpoint and record temperature data at the height of the plant canopy. Tables 1 and 2 show the mean daily temperatures (±1 standard deviation) from transplant to first open flower (anthesis), transplant to first ripe fruit, and between first flower and first fruit for both experiments. High-pressure sodium lamps suspended above the greenhouse benches provided a 16-hour photoperiod and photosynthetic photon flux density (PPFD) of approximately 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$. In two greenhouse compartments (20 and 24 °C setpoints for Experiment 1, 22.5 and 27.5 °C setpoints for Experiment 2), a line quantum sensor (SQ-301X-SS; Apogee Instruments, Logan, UT) was connected to the environmental control computer and placed at canopy height to measure photosynthetically active radiation (every 60 seconds) and estimate the mean daily light integral (MDLI). The estimated MDLI at first flower and ripe fruit for plants in Experiment 1 was (mean ± standard deviation) 7.1 ± 2.3 and 9.0 ± 3.0 $mol \cdot m^{-2} \cdot d^{-1}$, respectively. In Experiment 2 (data from both experimental runs were pooled), the estimated MDLI was 12.6 ± 0.22 and 14.4 ± 1 $mol \cdot m^{-2} \cdot d^{-1}$, respectively.

Data collection and analysis

The date of the first open flower and first ripe fruit was recorded for each plant. Open flower was defined as anthesis, and first ripe fruit as the point where one fruit per plant had completely transitioned from green to red. The number of days (i.e. time) from transplant to flowering and fruiting stages and the days between flower and fruiting were determined. These data were then converted to flowering and fruiting rates by calculating the reciprocal (e.g. 1/d to flower or fruit).

The relationship between MDT and the time to first open flower was evaluated using the following linear equation described by Blanchard et al. (2011):

$$1/\text{d to flower} = B \times (\text{MDT} - T_{\min})) \qquad (1)$$

The regression slopes for ‘Siam’ were nonsignificant ($P \geq 0.05$) between Experiments 1 and 2 and both replications of Experiment 2, and therefore the data were pooled for statistical analysis (Figure 1A). In contrast, regression slopes differed between experiments and replications for ‘Red Velvet’ and therefore each data set was analyzed separately (Figure 1B).

The exponential function described by Larson (1990) was used to characterize the relationship between MDT and the rate to first ripe fruit as well as the rate between first open flower and first ripe fruit:

$$1/\text{d to fruit} = R_{\max} \times (1 - \exp(-C \times (\text{MDT} - T_{\min}))) \qquad (2)$$

Both equations (1) and (2) have been used to model the rates of leaf unfolding and flowering for a range of containerized and flowering crops (Blanchard and Runkle 2011; Larsen 1988, 1989; Hidén and Larson 1994; Larsen and Hidén 1995; Larsen and Persson 1999). These equations are appropriate when the relationship between MDT and temperature follows a linear [Eq. (1)] or exponential curve [Eq. (2)] where $T_{\min} < \text{MDT} < T_{\text{opt}}$. For Eq. (1), B defines the slope. For Eq. (2), $R_{\max}$ has biological meaning and refers to the maximum rate of plant development at T_{opt}. $T_{\min}$ and MDT are measured in °C and C defines the skew in Eq. (2). The regression slopes describing the MDT effect on the rate to fruiting and rate from flowering to fruiting were non-significant ($P \geq 0.05$) between experiments and replications for both varieties, and therefore data from Experiments 1 and 2 were pooled and analyzed by variety.

$T_{\min}$, $R_{\max}$, B, and C for equations (1) and (2) were estimated using PROC NLIN in SAS (SAS 9.4; SAS Institute, Cary, N.C.). Initial parameter estimates were obtained visually by inspecting the graphs of the observed data. Psuedo-r^2 values were determined by performing linear regression analysis between the observed data and the data predicted by the parameter-fit functions, as recommended by Maceina and Pereira (2007).

After collecting the crop timing data in Experiment 2, all plants remained in the greenhouse to allow for at least three fruits to ripen per plant, which occurred within 20 d from the time of the first ripe fruit per variety. After an individual plant developed three ripe fruits, additional data were collected consisting of plant canopy width, canopy height from the substrate surface, individual ripe fruit weight, and the total numbers of fruit (ripe and unripe), opened flowers, and unopened flowers. Canopy width was determined as the average of two perpendicular measurements per plant. Each ripe fruit weight measurement consisted of the average weight of the three ripened fruits per plant. The total number of fruit (ripe and unripe) and opened and unopened flowers were evaluated also as a percentage of the total reproductive plant organs per plant. Data were analyzed using PROC GLIMMIX in SAS, and because temperature treatment interacted significantly ($P < 0.05$) with replication in effects on several response variables, data were evaluated separately by replication in Experiment 2. For each replication, pairwise comparisons between treatments were performed using Tukey's honestly significant difference (HSD) test at $\alpha=0.05$.

Results and Discussion

In general, the MDT at first flower, first ripe fruit, and between first flower and fruit for 'Siam' and 'Red Velvet' were near the target greenhouse temperature set-points for Experiments 1 and 2 (Tables 1 and 2). MDT at first flower was lower for 'Siam' than the 24 and 26 °C set-points in Experiment 1 (Table 1), because the greenhouse had difficulty maintaining heat during early spring in 2022. This trend did not occur for 'Red Velvet' which had a later transplant date (by 19 d) than 'Siam' (see Materials and Methods). Experiment 2 started later in spring 2023 compared to Experiment 1, and MDT was greater than the 20 °C set-point because of the warmer outdoor temperatures (*data not shown*) and limitations in greenhouse cooling (Table 2).

Increasing greenhouse temperature resulted in fewer days to flowering, fruiting, and between flowering and fruiting for both tomato varieties (Figure 1). The time to flower ranged from 12 to 28 d for both 'Siam' and 'Red Velvet', and time to first fruit ranged from 49 to 92 d and from 50 to 93 d, respectively. The time between flower and fruit ranged from 34 to 64 d for 'Siam' and from 36 to 68 d for 'Red Velvet'. Flowering and fruiting rates increased as temperature increased from approximately 18 to 30 °C (Figure 1). The flowering rate ranged from 0.037 to 0.084 for 'Siam' and 0.036 to 0.082 for 'Red Velvet' (Figure 1A, 1B), whereas fruiting rate ranged from 0.011 to 0.021 for both varieties (Figure 1C, 1D). The flowering to fruiting rate ranged from 0.016 to 0.030 for 'Siam' and from 0.015 to 0.030 for 'Red Velvet' (Figure 1E, 1F).

The estimated T_{min} and regression slope (B) parameters predicting the flowering rate for 'Red Velvet' differed significantly between Experiments 1 and 2 and experimental replications within Experiment 2 (Table 3). The negative T_{min} values (-5.2±8.4 °C and -1.5±12.8 °C, respectively) and lower slope coefficients (0.0021±0.0007 and 0.0027±0.0012, respectively) for Experiment 1 and for Experiment 2 Replication 2 suggested that MDT had less influence on the rate of flowering compared to Experiment 2 Replication 1 (T_{min} = 12.6±2.4 °C, B = 0.0041±0.0008; Table 3). In addition, the lower coefficients of determination (r^2) for flowering rate equations in Experiment 1 and Experiment 2 Replication 2 (0.31 and 0.41, respectively) indicated a greater degree of variability and less accuracy compared to the higher r^2 value for Experiment 2 Replication 1 (0.82; Table 3). In contrast, the T_{min} and B values for the 'Red Velvet' flowering rate equation in Experiment 2 Replication 1 were statistically similar to T_{min} and B for the 'Siam' flowering rate equation, for which data were pooled across experiments, in Table 3. Therefore, for

‘Red Velvet’, the authors have the greatest confidence in the flowering rate $T_{\min}$ and B parameters from Experiment 2 Replication 1 (Table 3). However, further investigation is needed into the observed differences in flowering responses for ‘Red Velvet’ between experiments and replications.

For ‘Siam’, similar $T_{\min}$ values were estimated between the flowering rate (10.1±1.7 °C), fruiting rate (8.2±3.2 °C) and flowering to fruiting rate (7.8±4.4 °C) equations where $T_{\min}$ averaged 8.7 °C overall (Tables 3 and 4). For ‘Red Velvet’, the estimated $T_{\min}$ values were also statistically similar for the flowering rate (12.6±2.4 °C) equation from Experiment 2 Replication 1 (Table 3), and the fruiting rate (10.1±2.9 °C) and flowering to fruiting rate (11.5±2.7 °C) equations from Table 4 for an average $T_{\min}$ of 11.4 °C. The estimated maximum rates ($R_{\max}$) for fruiting and from flowering to fruiting were statistically similar between tomato varieties (Table 4).

The coefficients of determination generated for the linear (r^2) and nonlinear equations (R^2) ranged from 0.31 to 0.82 for ‘Siam’ and ‘Red Velvet’ and reflect the accuracy of equations (1) and (2) and the parameters in Tables 3 and 4 at predicting temperature effects on flowering/fruiting times. The variability in the time to first ripe fruit increased at higher temperatures (Figure 1), especially for the second experimental run in Experiment 2. Overall, the r^2 and R^2 values in Tables 3 and 4 were comparable to the linear and nonlinear model coefficients of determination generated for 36 annual bedding plant species evaluated by Vaid and Runkle (2013) and Blanchard and Runkle (2011), which ranged from 0.33 to 0.94 between studies.

In Experiment 2, the temperature effects on canopy height and width differed between experimental replications for each variety (Tables 5 and 6). Increasing the temperature set-point from 20 °C tended to increase individual fruit weight until ≈25.0 to 27.5 °C and increase total fruit per plant until ≈22.5 to 25.0 °C across varieties (Tables 5 and 6), whereas further increases in temperature set-point resulted in decreased fruit weight and number. Increasing temperature from 20 to 30 °C increased the total number of flowers (unopened and opened) for ‘Siam’ and ‘Red Velvet’ (Tables 5 and 6). Figures 2 and 3 show how the proportions of reproductive organs per finished plant shifted from mostly fruits to mostly opened and unopened flowers for both varieties as temperature increased.

The average individual fruit weight across temperature treatments was 8.2 g/fruit for ‘Siam’ and 4.3 g/fruit for ‘Red Velvet’ in Replication 1, which was lower compared to individual fruit weights of 11.2 and 5.8 g/fruit in Replication 2, respectively (Tables 5 and 6). The opposite trend was observed for fruit number per plant, where ‘Siam’ and Red Velvet’ averaged 86 and 55 fruit/plant in Replication 1, respectively, and 73 and 37 in Replication 2. Similarly, average canopy height, canopy width, and flowers (opened and unopened) per plant were greater in Replication 1 compared to Replication 2 for both varieties (Tables 5 and 6). It is possible the higher fertilization rate in Replication 1 (see Materials and Methods) promoted the growth of vegetative and reproductive tissues compared to Replication 2, which had a reduced fertilization rate and may have restricted canopy size and flower/fruit numbers per plant. Similar effects from reduced fertilization have been observed with floriculture container crops, and the mild restriction of nitrogen and phosphorus is used as a strategy in floriculture to control plant growth and height (Heins and Yelanich, 2013).

An exponential function adequately described the effect of temperature on tomato fruiting rates because the temperature range in this study (18–30 °C) was between $T_{\min}$ and T_{opt} for these varieties and the responses were curvilinear. However, it is likely the 30 °C temperature set-point was near the optimum temperature (T_{opt}), and temperatures above the optimum often cause a rapid decrease in plant development rates (Cave et al., 2013; Blanchard et al., 2011; Brøndum and Heins, 1993). The predictive equations in Table 4 may therefore be inaccurate at temperatures >30 °C. Development rates for container crops can also be influenced by other environmental conditions such as daily light integral (DLI) and photoperiod also (Erwin and Warner, 2002; Faust et al., 2005). The predictive equations developed for tomato 'Siam' and 'Red Velvet' therefore assume a DLI of ≥7 $\mathrm{mol{\cdot}m^{-2}{\cdot}d^{-1}}$ and 16-hour photoperiod and may not be valid under lower DLI conditions, which can limit development rate (Faust and Heins, 1994), or if varieties with a facultative long-day flowering response are grown under a shorter photoperiod (Vaid and Runkle, 2013).

Vaid and Runkle (2013) reported that containerized plant species can be subjectively categorized in terms of cold tolerance according to the estimated T_{min}, where cold-sensitive floriculture container species can be associated with $T_{\mathrm{min}} \geq 8$ °C as shown for both tomato varieties (Tables 3 and 4). Cold-sensitive floriculture container species typically show a larger flowering delay (i.e. longer crop time) when grown at cooler temperatures compared to cold-tolerant species [$T_{\mathrm{min}} \leq 4$ °C, (Blanchard and Runkle, 2011; Vaid and Runkle 2013)], meaning they are often less suitable for energy efficient production at lower temperatures and therefore cost savings from reduced greenhouse heating (Blanchard, 2009). Results from this study suggest compact containerized tomato should be grown relatively warm at ≈25 °C for a near optimal combination of production attributes, including a relatively short crop time, low canopy height, a high fruit weight, and a high number of fruits per plant (Figures 1 through 2, Tables 5 and 6).

Conclusions

This study quantified the effects of mean daily temperature on the growth and development of compact container-grown tomato varieties ‘Siam’ and ‘Red Velvet’ in controlled greenhouse environments. As temperature increased from 18 to 30 °C, the developmental rates for flowering increased linearly and fruiting increased exponentially. Results suggest ‘Siam’ and ‘Red Velvet’ grown at ≈25 °C would result in a near optimum combination of a relatively short crop time, compact canopy, large fruit size, and a high number of fruits per plant at finishing. The equations characterizing the relationship between temperature and crop timing from this study are, to our knowledge, the first developed for compact container-grown tomatoes. These equations also incorporate T_{min} and R_{max}, which have biological meaning and can be used to draw inferences regarding tomato cold-tolerance and optimal growing temperatures. Compact container-grown tomatoes are relatively new crops being grown by greenhouse floriculture operations for both ornamental and edible value. Information from this study can be used to help growers schedule compact tomatoes alongside other containerized ornamental crops to meet critical market windows as well as determine the impacts of changing growing temperature on crop timing and quality.

Acknowledgements

I would like to acknowledge funding by the Arkansas Division of Agriculture, Arkansas Agricultural Experiment Station, the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture projects #1022864 and #1019001, and Pan American Seed. I also would like to thank Leala Machesney, Josh Tebow, Felicia Vandervelde, and Josh Kirschenbaum for their technical assistance and greenhouse support in conducting this research. I would also like to thank Dr. Ryan Dickson for all his help with research and the final document.

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Table 1. Mean daily temperature (MDT) at first flower and first ripe fruit from transplant and from first flower to first ripe fruit for tomato varieties grown at temperature setpoints of 18, 20, 22, 24, and 26 °C during Experiment 1. Data represent the least square means of at least 19 plants (observational units) per variety and temperature setpoint treatment ±1 standard deviation.

	Temperature set-point (°C)				
	18	20	22	24	26
Tomato 'Siam'					
MDT at flower (°C)	19.3 ± 0.19	21.1 ± 0.15	22.3 ± 0.05	22.3 ± 0.15	22.4 ± 0.56
MDT at ripe fruit (°C)	17.6 ± 0.03	20.1 ± 0.04	22.2 ± 0.01	23.9 ± 0.06	25.4 ± 0.20
MDT from flower to fruit (°C)	16.9 ± 0.10	19.6 ± 0.04	22.1 ± 0.02	24.9 ± 0.11	27.1 ± 0.28
Tomato 'Red Velvet'					
MDT at flower (°C)	17.5 ± 0.30	20.2 ± 0.11	22.5 ± 0.10	24.6 ± 0.18	26.3 ± 0.17
MDT at ripe fruit (°C)	17.4 ± 0.09	19.7 ± 0.03	22.1 ± 0.01	24.9 ± 0.02	27.4 ± 0.11
MDT from flower to fruit (°C)	17.4 ± 0.24	19.5 ± 0.06	22.0 ± 0.04	25.0 ± 0.05	27.9 ± 0.12

Table 2. Mean daily temperature (MDT) at first flower and first ripe fruit from transplant and from first flower to first ripe fruit for tomato varieties grown at temperature setpoints of 20, 22.5, 25.0, 27.5, and 30.0 °C during Experiment 2. Data represent the least square means of at least 5 plants (observational units) per variety and temperature setpoint treatment ±1 standard deviation.

	Repl.[a]	Temperature set-point (°C)				
		20.0	22.5	25.0	27.5	30.0
Tomato 'Siam'						
MDT at flower (°C)	1	20.4 ± 0.11	22.2 ± 0.05	24.0 ± 0.05	26.6 ± 0.04	28.9 ± 0.11
	2	22.0 ± 0.16	23.0 ± 0.03	24.7 ± 0.01	27.9 ± 0.02	30.2 ± 0.03
MDT at ripe fruit (°C)	1	21.9 ± 0.02	22.8 ± 0.05	24.4 ± 0.03	27.4 ± 0.18	29.6 ± 0.00
	2	22.7 ± 0.01	23.5 ± 0.12	24.9 ± 0.00	28.2 ± 0.03	30.2 ± 0.04
MDT from flower to fruit (°C)	1	22.6 ± 0.05	23.2 ± 0.07	24.6 ± 0.05	27.8 ± 0.26	30.0 ± 0.04
	2	23.0 ± 0.17	23.7 ± 0.14	25.0 ± 0.02	28.3 ± 0.05	30.2 ± 0.05
Tomato 'Red Velvet'						
MDT at flower (°C)	1	20.5 ± 0.33	22.2 ± 0.10	24.1 ± 0.01	26.6 ± 0.04	28.9 ± 0.03
	2	22.0 ± 0.18	23.0 ± 0.01	24.7 ± 0.00	27.9 ± 0.02	30.2 ± 0.02
MDT at ripe fruit (°C)	1	21.9 ± 0.04	22.8 ± 0.06	24.4 ± 0.03	27.4 ± 0.18	29.6 ± 0.09
	2	22.7 ± 0.00	23.3 ± 0.04	24.8 ± 0.01	28.2 ± 0.08	30.2 ± 0.02
MDT from flower to fruit (°C)	1	22.8 ± 0.21	23.1 ± 0.08	24.6 ± 0.04	27.8 ± 0.17	29.9 ± 0.05
	2	23.0 ± 0.16	23.4 ± 0.05	24.9 ± 0.01	28.3 ± 0.10	30.2 ± 0.03

[a] Experiment replication.

Table 3. Parameter estimates for the linear equation [Eq. (1)] relating flowering rates to mean daily air temperature in two compact container tomato varieties using data from Experiments 1 and 2. Parameter estimates were used to generate Figure 2. Base ($T_{\min}$) temperature refers to the temperature at which the flowering rate is zero. B defines the slope for Eq. (1). $T_{\min}$ and B are followed by columns containing their 95% confidence interval (ACI).

	Expt.[a]	Replication[a]	$T_{\min}$ (°C)	ACI (±)	B	ACI (±)	No.[b]	r^{2c}
Tomato 'Siam'								
Flowering rate			10.1	1.7	0.0039	0.0005	159	0.59
Tomato 'Red Velvet'								
Flowering rate	1		-5.2	8.4	0.0021	0.0007	99	0.31
Flowering rate	2	1	12.6	2.4	0.0041	0.0008	28	0.82
Flowering rate	2	2	-1.5	12.8	0.0027	0.0012	30	0.41

[a] Data were pooled for ‘Siam’ across Experiment 1 and 2 datasets because regression slopes were nonsignificant. Regression slopes for ‘Red Velvet’ were significant between Experiment 1 and both replications of Experiment 2.

[b] Number of observations in data set.

[c] Generated by performing linear regression analysis on the predicted versus observed data.

Table 4. Parameter estimates for the nonlinear equation [Eq. (2)] relating fruiting rates and flower to fruit rates to mean daily air temperature in two compact container tomato varieties using data from Experiments 1 and 2. Parameter estimates were used to generate Figure 2. Base (T_{min}) temperature refers to the temperature at which the flowering and/or fruiting rate is zero and R_{max} refers to the maximum rate of development. C defines the skew for the function in Eq. (2). T_{min}, R_{max}, and C_1 are followed by columns containing their asymptotic 95% confidence interval (ACI).

	T_{min} (°C)	ACI (±)	R_{max}	ACI (±)	C	ACI (±)	No.[b]	R^{2c}
Tomato 'Siam'								
Fruiting rate	8.2[a]	3.2	0.0330	0.0155	0.0414	0.0361	159	0.82
Flower to fruit rate	7.8	4.4	0.0394	0.0168	0.0548	0.0530	159	0.69
Tomato 'Red Velvet'								
Fruiting rate	10.1	2.9	0.0274	0.0085	0.0676	0.0495	155	0.75
Flower to fruit rate	11.5	2.7	0.0348	0.0092	0.0898	0.0644	155	0.66

[a] Regression slopes were nonsignificant between Experiment 1 and 2 datasets for both varieties and therefore data were pooled for analysis.

[b] Number of observations in data set.

[c] Generated by performing linear regression analysis on the predicted versus observed data.

Table 5. The effect of temperature on canopy width, height, individual fruit mass, total number of fruit (ripe and unripe), number of open flowers, and number of unopened flowers per plant for compact tomato ‘Siam’ during Experiment 2. Data were analyzed separately by experimental replication.

Tomato ‘Siam’	Temperature set-point (°C)										
	20.0		22.5		25.0		27.5		30.0		Significance
Replication 1											
Canopy width (cm)	41.5	b	46.1	ab	48.6	a	50.5	a	39.8	b	***
Canopy height (cm)	25.1	b	33.9	a	28.9	ab	31.7	a	29.5	ab	***
Individual fruit mass (g)	6.3	b	7.7	ab	9.1	ab	9.9	a	8.1	ab	*
No. of fruit	109	a	118	a	106	ab	65	bc	30	c	***
No. of open flowers	5	bc	1	c	3	bc	13	b	23	a	***
No. of unopened flowers	0	b	5	b	11	b	14	b	31	a	***
Replication 2											
Canopy width (cm)	37.6	a	41.0	a	43.3	a	39.3	a	41.5	a	NS
Canopy height (cm)	26.3	ab	22.8	b	24.5	ab	28.5	ab	33.5	a	*
Individual fruit mass (g)	8.5	c	11.0	abc	14.4	a	12.5	ab	9.6	bc	***
No. of fruit	79	ab	82	a	93	a	63	ab	50	b	***
No. of open flowers	2	b	0	b	0	b	3	b	11	a	***
No. of unopened flowers	8	a	0	a	0	a	11	a	7	a	NS

NS, *, **, and *** indicate non-significance and significance at $P<0.05$, $P<0.01$, and $P<0.001$, respectively.

Means within rows followed by the same letter are not significantly different by Tukey’s honestly significant difference test at $\alpha=0.05$.

Table 6. The effect of temperature on canopy width, height, individual fruit weight, total number of fruit (ripe and unripe), number of open flowers, and number of unopened flowers per plant for compact tomato ‘Red Velvet’ during Experiment 2. Data were analyzed separately by experimental replication.

Tomato ‘Red Velvet’	Temperature set-point (°C)										
	20.0		22.5		25.0		27.5		30.0		Significance
Replication 1											
Canopy width (cm)	30.8	b	37.5	a	33.6	ab	32.9	ab	28.4	b	**
Canopy height (cm)	19.3	a	19.8	a	20.7	a	20.2	a	20.0	a	NS
Individual fruit weight (g)	3.5	b	4.2	ab	5.8	a	3.9	ab	4.0	ab	**
No. of fruit	84	ab	96	a	59	b	29	c	8	c	***
No. of open flowers	1	b	1	b	1	b	10	a	12	a	***
No. of unopened flowers	3	b	4	b	4	b	24	a	42	a	***
Replication 2											
Canopy width (cm)	36.5	a	34.4	ab	32.0	ab	30.4	b	23.8	c	***
Canopy height (cm)	21.5	b	25.0	ab	21.6	b	23.4	ab	25.6	a	*
Individual fruit weight (g)	6.1	a	7.3	a	5.6	a	5.1	a	4.7	a	NS
No. of fruit	47	a	56	a	52	a	20	b	11	b	***
No. of open flowers	2	ab	1	b	0	b	6	a	6	a	**
No. of unopened flowers	6	b	5	b	5	b	28	a	10	b	***

NS, *, **, and *** indicate non-significance and significance at $P<0.05$, $P<0.01$, and $P<0.001$, respectively.
Means within rows followed by the same letter are not significantly different by Tukey’s honestly significant difference test at $\alpha=0.05$.

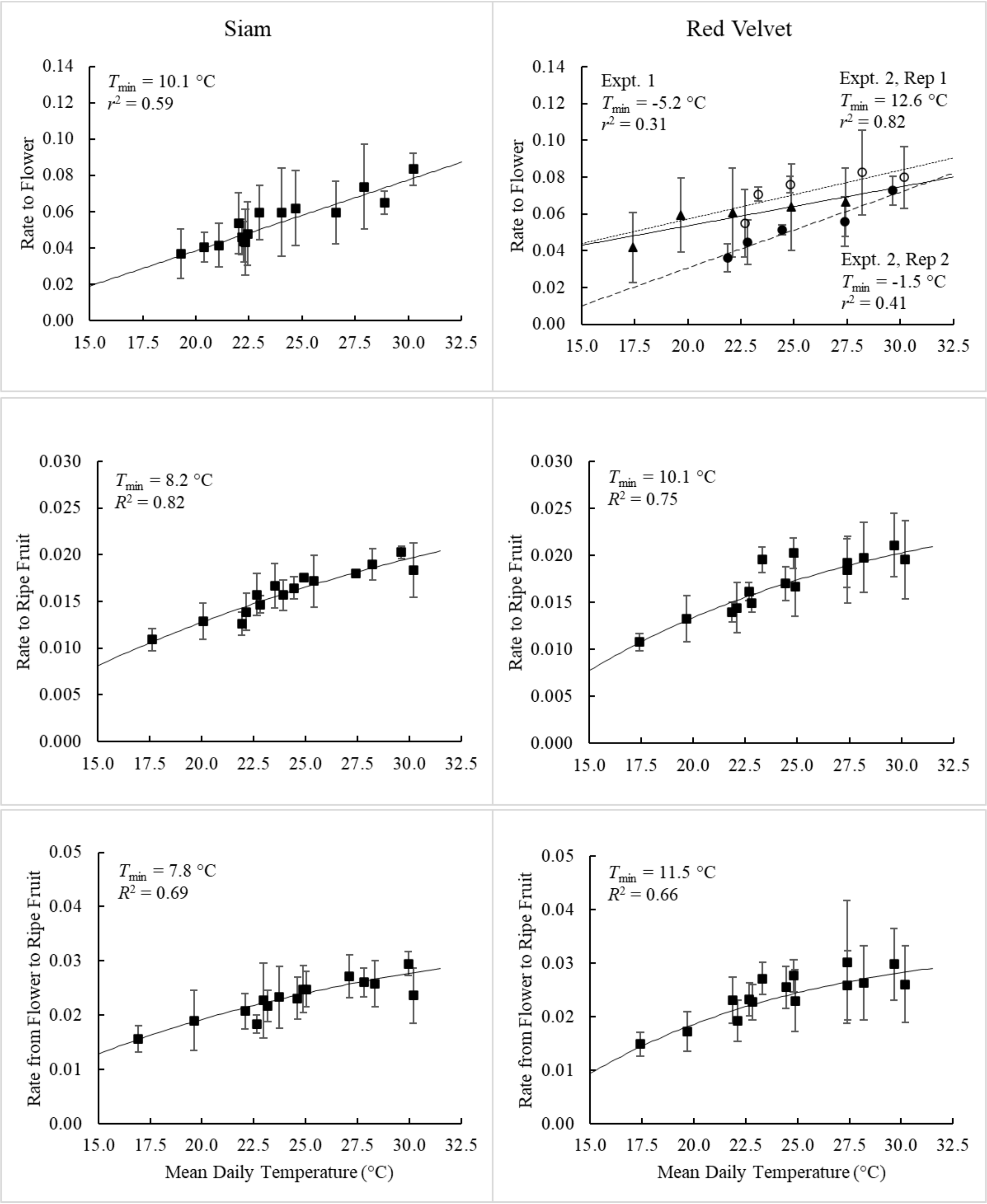

Figure 1. Details on next page.

The effect of mean daily temperature (°C) on the flowering and fruiting rates in compact tomato 'Siam' and 'Red Velvet' using Eq. (1) (panels A and B) and Eq. (2) (panels C, D, E, F) and parameter estimates from Table 3 (panels A and B) and Table 4 (panels C, D, E, F). When regression slopes were nonsignificant ($P \geq 0.05$) between Experiments 1 and 2 and replications (Experiment 2), data were pooled (■) for statistical analysis. Flowering/fruiting rates were calculated by taking a reciprocal of the number of days to first open flower, first ripe fruit, and between flower and fruit. Each symbol represents the treatment means, and error bars represent 95% confidence intervals. T_{min} (base temperature) is the estimated minimum temperature at or below which the rate of development towards flowering or fruiting is zero. r^2 and R^2 are the coefficients of determination generated for linear and nonlinear equations, respectively. Trendlines are the predicted rates as a function of temperature. In panel B, regression slopes differed between Experiment 1 (▲, solid trendline), Experiment 2 Replication 1 (●, dashed trendline), and Experiment 2 Replication 2 (○, dotted trendline).

α=0.05.

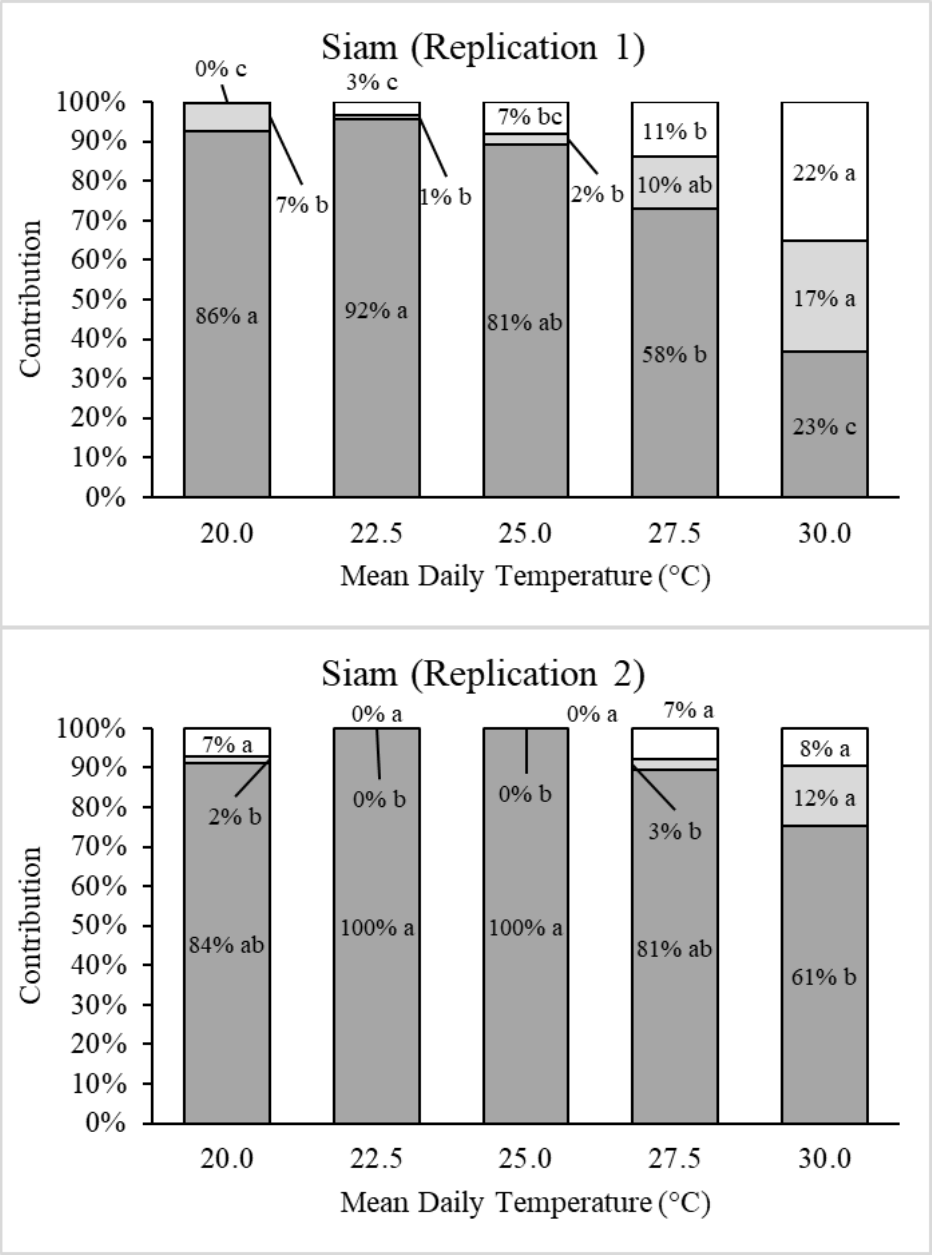

Figure 2. Temperature setpoint effects the percentage of fruit (lower, dark grey bars), open flowers (middle, light grey bars), and unopened flowers (upper, white bars) per plant for tomato 'Siam' during Experiment 2 for replications 1 and 2. There were 3-4 ripe fruit per plant at data collection, with the remainder as unripe and green in color. Means within a category with the same letter are not significantly different by Tukey's honestly significant difference test at α=0.05.

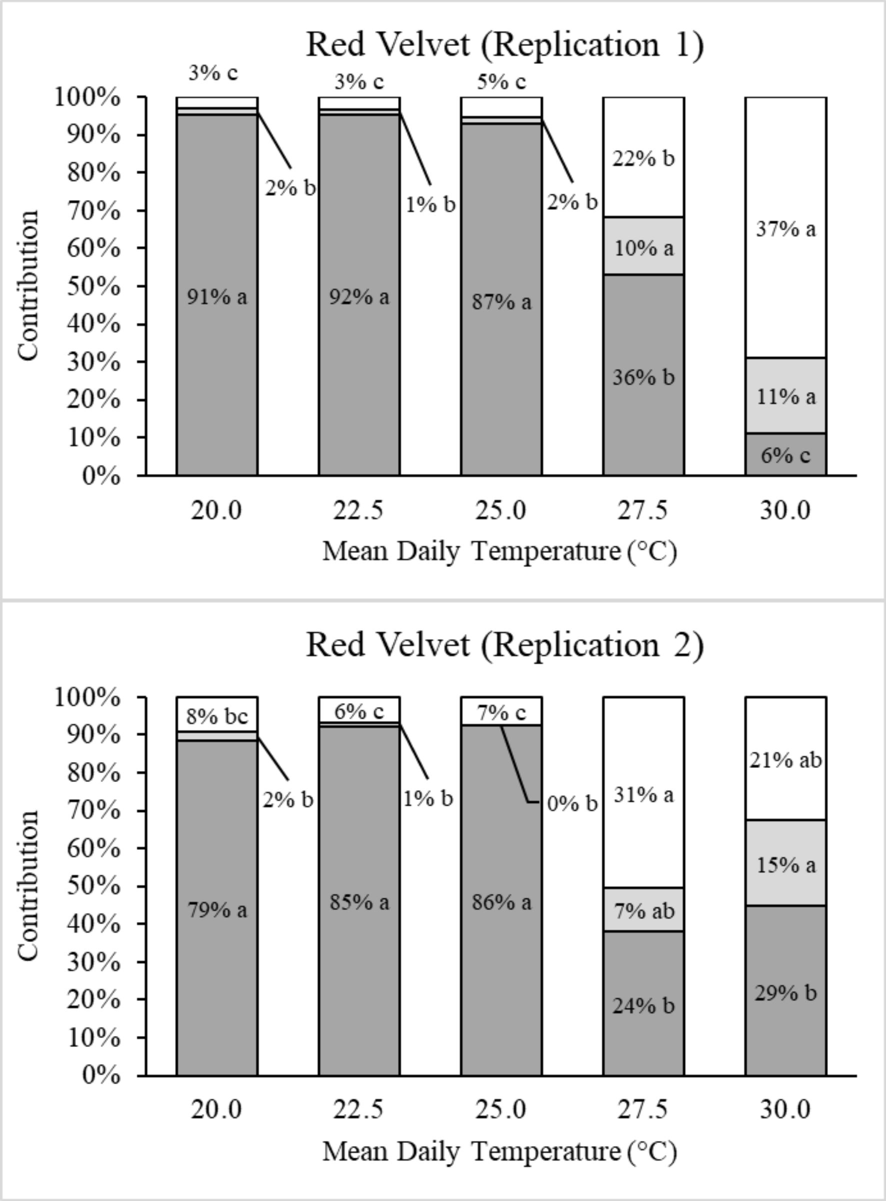

Figure 3. Temperature setpoint effects the percentage of fruit (lower, dark grey bars), open flowers (middle, light grey bars), and unopened flowers (upper, white bars) per plant for tomato ‘Red Velvet’ during Experiment 2 for replications 1 and 2. There were 3-4 ripe fruit per plant at data collection, with the remainder as unripe and green in color. Means within a category with the same letter are not significantly different by Tukey’s honestly significant difference test at α=0.05.