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Maximizing Tomato Seed Germination: Quantifying Cardinal Temperatures and Thermal Time Requirements

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ABSTRACT

Seed germination is a crucial stage in the life cycle of plants. It determines their growth and reproduction success. Temperature is one of the most important environmental factors that affect seed germination. This research aimed to estimate the cardinal temperatures and the thermal time requirement for seed germination. The effects of different temperature levels were evaluated on the germination characteristics of tomatoes (*Lycopersicon esculentum* cv. 'Early CH'). An experiment was conducted using a completely randomized design with four replications and seven temperature levels, i.e. 5, 10, 15, 20, 25, 30, and 35 ° C. The relationship between germination rate and temperature was described and the cardinal temperatures for the seed germination of tomato (cv. 'Early CH') were calculated. Four regression models were used: segmented, dent-like, original beta, and modified beta. The highest germination percentage (81-86%) and vigor index (4.04-5.47 cm) were similarly obtained in the 20-30 °C range. The highest germination rate (5/7 seeds per day) was observed at 25 °C. The lowest mean germination time (4.5-4.84 days) occurred in the 20-25 °C range. Germination characteristics were significantly different when the temperature increased above 30 °C. While measuring the regression models, the segmented model was best for estimating the cardinal temperature of this cultivar. In general, cardinal temperatures for seed germination were estimated using a superior regression model for minimum (0.5-3 °C), optimal (25-26 °C), and maximum (35.4-40 °C) temperatures. Additionally, the thermal time model accurately predicted the seed germination process (R2 = 0.90). The amount of thermal time to achieve 50% germination in this cultivar was estimated at 1848.29 degree-hours.

Introduction

Tomato (*Lycopersicon esculentum* Mill.) belongs to the Solanaceae family and is native to South and Central America. It is cultivated worldwide in a wide range of climates. Rich in vitamin C and lycopene, tomato is the second most important vegetable after potato (*Solanum tuberosum* L.). Its germination is a complex physiological process and an essential stage in plant phenology, influencing seedling growth, viability, and plant population dynamics. Desirable germination is also crucial for determining plant density per unit area. Proper germination and seedling establishment are considered determinant factors in yield and performance (Ashraf and Waheed, 1990). Studying the basic requirements for seed germination can increase its chances of successful deployment under various conditions. Among the many factors that affect seed germination, temperature and humidity are crucially important (Parmoon et al., 2015). After moisture, temperature is the most crucial factor determining the success or failure of plant

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establishment (Al-Ahmadi and Kafi, 2007). This is mostly because germination involves various catabolic and anabolic enzymatic processes that react to temperature. Plants encounter three cardinal temperatures in their leaves: minimum temperature (Tb), optimum temperature (To), and maximum temperature (Tc) (Parmoon et al., 2015). Germination does not occur below the minimum and above the maximum temperatures, whereas the optimum temperature is needed for increasing the rate of germination (Eberle et al., 2014). At an optimal temperature, germination occurs in the shortest possible time, indicating a maximal germination rate (Alvarado and Bradford, 2002). Different mathematical models have been introduced to describe the relationship between germination rate and temperature (Shafii and Price, 2001). Thus, some researchers have utilized these models to determine the cardinal temperatures of germination (Hardegree, 2006; Hardegree and Winstral, 2006). The main issue with using these models is their variation. The most suitable specific model should be applied for each species. Karami et al. (2021) conducted a study on estimating cardinal temperatures on barley seed germination using the hydro time model, which is based on the concept of hydro time and represents the duration required for a seed to accumulate a certain amount of water and initiate germination. This model estimates the time needed for seed germination under varying temperatures and moisture conditions by integrating the hydro time concept with the thermal time concept. Accordingly, the researchers collected seeds from four barley cultivars and tested their germination under different temperatures and moisture levels. They employed the hydro time model to estimate the cardinal temperatures for each cultivar, including the base temperature (the temperature below which germination does not occur), the optimum temperature (the temperature at which germination occurs fastest), and the ceiling temperature (the temperature above which germination does not occur). The results revealed that the estimated cardinal temperatures varied among the cultivars, with the base temperature ranging from 1.8 °C to 3.3 °C, the optimum temperature ranging from 29.2 °C to 31.2 °C, and the ceiling temperature ranging from 40.3 °C to 41.9 °C. Also, it was discovered that the hydro time model provided a good fit for the observed germination data across all four cultivars. Overall, the study offers insights into the germination requirements of barley seeds and emphasizes the potential of the hydro time model for predicting seed germination under various temperatures and moisture levels. Kafi et al. (2012) employed three regression models to evaluate how four Iranian black cumin cultivars (*Bunium persicum*) respond to temperature for germination. It was reported that the investigated models yielded different estimates for predicting the cardinal temperatures among the cultivars.

Some other researchers have utilized the thermal time model to estimate the effect of temperature on germination. The thermal time model was initially developed for studying plant development and was later employed to predict the development of small insects, spiders, worms, and springtails (Trudgill et al., 2005). Currently, this model is applied in germination studies. At temperatures below the optimum threshold (ranging from Tb to To), the germination time can be explained by the thermal time constant or thermal unit (Bierhuizen and Wagenvoort, 1974). Several reports discussed the relationship between germination rate and temperature while emphasizing that cardinal temperatures for germination depend on the plant species. Furthermore, variations have been observed among genotypes of a species (Jalilian et al., 2004).

Studying cardinal temperatures is important in tomato cultivation. It assists in determining the optimal temperature range for the growth and development of plants. Cardinal temperatures are the minimum, optimum, and maximum temperatures required for plant growth and development (Cabrera-Santos et al., 2022). In the case of tomatoes, understanding cardinal temperatures can help determine the optimal temperature range for germination, flowering, fruit set, and ripening. For example, the minimum temperature required for tomato seed germination is around 10 °C, whereas the maximum temperature for successful germination is around 35 °C (Maleki et al., 2022). If the temperature falls below or rises above the optimal range, it can lead to stunted growth, delayed flowering, poor fruit set, and lower yield. Therefore, understanding cardinal temperatures can guide growers to select the right time and temperature for sowing, transplanting, and managing tomato crops (Angmo et al., 2021). In addition, knowing cardinal temperatures allows growers to optimize resource consumption, i.e. irrigation and heating, as they can adjust the crop's optimal growth conditions. Overall, studying cardinal temperatures can assist in maximizing the yield and quality of tomato crops (Saqib et al., 2022).

Cardinal temperatures are important for the 'Early CH' tomato cultivar, just like any other tomato variety, as it helps determine the optimal temperature range for the growth and development of the plant. The 'Early CH' cultivar is popular among home gardeners and commercial growers alike. It is disease-resistant and grows easily. It thrives in warm, sunny climates and requires regular watering and fertilization to produce high-quality fruits. In considering the 'Early CH' tomato cultivar, understanding cardinal temperatures can help determine the optimal temperature range for germination, vegetative growth, flowering, fruit set, and ripening. It may facilitate the identification of temperature stress points where the growth and development of the plant may be negatively affected. For example, the 'Early CH' tomato cultivar is known for its early maturity and high-yield potential. Studying its cardinal temperatures can help growers select the best time and temperature for sowing and transplanting seedlings. Also, it contributes to managing the crop during different growth stages. Additionally, knowing the cardinal temperatures can help growers optimize the use of resources such as water and energy by adjusting the timing and temperature of irrigation and heating to match the crop's optimal growth conditions. This can enhance yield, quality, and profitability of the 'Early CH' tomato cultivar. Therefore, the current research was conducted to evaluate regression models for describing the germination rate of tomato plants ('Early CH' cv.) at different temperatures. The research involved estimating the cardinal temperatures for germination while evaluating the responses of its germination characteristics to various temperatures.

Material and Methods

This experiment was conducted using a completely randomized design. Seven temperatures were applied (5, 10, 15, 20, 25, 30, and 35 °C) during the 2021-2022 harvest year. Each temperature level consisted of four replications, each containing 25 seeds. The seeds of tomato (*L. esculentum Mill.* cv. 'Early CH') were purchased from the DELTA GREEN SOUTH company. The 'Early CH' is a determinate, bush-type variety known for its early maturation and high yield. It is a red, round tomato about 2-3 inches in diameter, with smooth skin and sweet, juicy flesh. This variety is often recommended for home gardeners who want to grow tomatoes in containers or small garden spaces. It does not require much room to grow and produces fruits relatively quickly. In terms of flavor and culinary use, the 'Early CH' tomato is generally considered a good all-purpose tomato. While it is usable in salads, sandwiches, and sauces, it can be considered appropriate for canning and preserving. The area coverage of the 'Early CH' tomato cultivar can vary depending on several factors, such as the spacing between plants, the size of the plants, and growing conditions. As a determinate variety, however, 'Early CH' tomatoes typically grow to a height of about 2-3 feet and have a compact, bushy growth habit. This means they can be planted closer together than indeterminate varieties which require more space to grow. To achieve the best results, it is generally recommended to plant 'Early CH' tomatoes about 18-24 inches apart in rows that are spaced 3-4 feet apart. This will allow the plants to have enough space to grow and produce fruit while enabling easier access to the plants for watering, fertilizing, and harvesting. In terms of area coverage, planting 2-3 'Early CH' tomato plants per square meter is recommended. This can vary depending on the specific growing conditions, so it is always a good idea to consult with a gardening expert or reference guide for more specific recommendations based on your particular situation.

The seeds germinated in 9 cm-wide Petri dishes on two layers of Whatman No. 1 filter papers containing 5 mm of sterilized distilled water. Petri dishes were then sealed with parafilm to prevent moisture loss and incubated in a growth chamber under constant light conditions (16 hours of light, 8 hours of darkness) until germination occurred. Seed evaluations were performed daily at the determined time and the seeds were considered to have germinated upon radicle emergence (≥2 mm). During the experiment, distilled water was added to the Petri dishes when needed. At the end of the experiment (14 days), germination characteristics were calculated as follows:

The germination percentage was calculated using equation 1 (Scott et al., 1984):

Eq. 1 $$Gt = (n / N \times 100)$$

Where Gt is the total germination percentage, n is the number of germinated seeds at the end of the experiment, and N is the total number of seeds.

Equation 2 determined the germination rate (Ellis and Roberts, 1981):

Eq. 2 $$Rs = \sum_{i=1}^{n} \frac{Si}{Di}$$

Where Rs is the germination rate (number of germinated seeds per day), Si is the number of germinated seeds per count, and Di is the number of days to the nth count.

The average germination time, which is an indicator of the rate and acceleration of germination, was calculated by Eq. 3 (Ellis and

Roberts, 1981).

Eq. 3 $$MGT = \frac{\sum (nd)}{\sum n}$$

Where n is the number of germinated seeds during d days, d is the number of days since the beginning of the germination and $:\sum n$ is the total number of germinated seeds.

The vigor index was calculated using equation 4 (Rahnama-Ghahfarokhi and Tavakkol-Afshari, 2007).

Eq. 4 $$VI = \frac{\mathrm{Ls} \times \mathrm{Pg}}{100}$$

Where VI is the vigor index, Ls is the mean of seedling length, and Pg is the germination percentage.

Equation 5 quantified the germination response to the temperature and determined the cardinal temperatures for the seed germination (Soltani et al., 2002).

Eq. 5 $$R50 = f(t) R_{\max}$$

Where f (t) is the temperature function and varies from zero (at minimum and maximum temperatures) to 1 (at optimum temperature), and $R_{\max}$ is the maximum intrinsic germination rate at an optimal temperature.

The following equation estimated the cardinal temperatures using a segmented model (Mwale et al., 1994).

Eq. 6
$$f(t) = \frac{(T - T_b)}{(T_o - T_b)} \quad \text{if} \quad T_b < T < T_o$$
$$f(t) = \left[1 - \left(\frac{T - T_b}{T_c - T_o} \right) \right] \quad \text{if} \quad T_o < T < T_c$$
$$f(t) = 0 \quad \text{if} \quad T < T_b \text{ or } T > T_c$$

The following equation estimated the cardinal temperatures using the beta model (O'Meara et al., 2006).

Eq. 7 $$f(T) = \left(\frac{(\mathrm{T} - \mathrm{T_b})}{(\mathrm{T_o} - \mathrm{T_b})} \right) \left(\frac{(\mathrm{T_c} - \mathrm{T}_o)}{(\mathrm{T}_o - \mathrm{T_b})} \right)^{\left(\frac{(\mathrm{T_c} - \mathrm{T_o})}{(\mathrm{T_o} - \mathrm{T_b})} \right)^{c}}$$

The following equation estimated the cardinal temperatures using the modified beta model (Fry, 1983).

Eq. 8 $$f(T) = \left(\frac{(\mathrm{T} - \mathrm{T_b})}{(\mathrm{T_o} - \mathrm{T_b})} \right) \left(\frac{(\mathrm{T_c} - \mathrm{T}_o)}{(\mathrm{T}_o - \mathrm{T_b})} \right)^{\left(\frac{(\mathrm{T_c} - \mathrm{T_o})}{(\mathrm{T_o} - \mathrm{T_b})} \right)}$$

To estimate the cardinal temperatures using a dent-like model, the following equation was used (Ellis et al., 1986).

Eq. 9
$$f(t) = \left(\frac{T - T_b}{T_{o1} - T_b} \right) \quad \text{if} \quad T_b < T \le T_{o1}$$
$$f(t) = \left(\frac{T_c - T}{T_c - T_{o2}} \right) \quad \text{if} \quad T_{o2} < T \le T_c$$
$$f(T) = 1 \quad \text{if} \quad T_{o1} < T \le T_{o2}$$
$$f(t) = 0 \quad \text{if} \quad T \le T_b \, or T \ge T_c$$

In the above equations, T is the average daily temperature (tested temperature), Tb is the minimum temperature, Tc is the maximum temperature, To1 is the lower optimum temperature, To2 is the upper optimum temperature, To is the optimum temperature and C is the constant coefficient of regression.

To evaluate the fitting of regression models for the cardinal temperatures, calculations considered the root mean square of error (RMSE) (Eq. 10), coefficient of determination (R2), and coefficient of correlation (r).

$$\mathrm{RMSE} = \sqrt{\left(\frac{1}{n} \right) \sum (Y_{obs} - Y_{pred})^2}$$

Eq. 10

Where Yobs and Ypred are the observed and predicted values, respectively, and n is the number of points. The closer R2 and r are to 1 and the smaller the RMSE is, the model is more expected to have a better fit to the data.

To quantify the response of germination rate to the temperature, the thermal time model was used for a specific percentage (g) as follows (Bradford, 2017):

$$\theta T_{(g)} = (T - T_b) t_{(g)}$$

Eq. 11

Where T is the tested temperature, Tb is the base temperature for germination, and tg is the time required to germinate in a certain percentage of the seeds.

Since the germination rate (GR) is the inverse of tg, equation 12 can be expressed as follows (Wang et al., 2005):

Eq. 12 $$GR_{(g)} = 1/t_{(g)} = (T - T_b)/\theta_{t(g)}$$

Larsen et al. (2004) used Probit analysis of the equation (13) with the change of Tb to obtain the best fit, in such a way that all germination percentages in the Probit scale were taken in regression versus the logarithm of the thermal time:

Eq. 13 $$Probit_{(g)} = \{Log[(T - T_b)t_{(g)}] - Log[\theta T_{(50)}]\} / \sigma\theta T$$

Where probit (g) is the probit transformation of the cumulative germination percentage g, θT(50) is the median thermal time to germination, and σθT is the standard deviation in logθT among individual seeds in the population. Once Tb is estimated, all thermal times to germination tg can be normalized on a thermal time scale via multiplying by the factor (T – Tb).

Results

Based on the analysis of variance, there was a significant difference ($p < 0.01$) between the vigor index, root length, shoot length, percentage germination, germination rate, and time to 50% germination of tomato seeds at different temperatures (Table 1).

Table 1. Analysis of variance of germination traits of tomato seeds at different temperatures.

		Mean of squares			
S.O.V	**df**	**Germination (%)**	**Germination rate (seed. day^{-1})**	**Vigor index**	**Mean germination time (day)**
Temp	5	2446.17**	23.18**	3.72**	45.93**
Error	18	76.94	0.19	0.02	0.25
C.V	-	14.6	18.2	13.64	6.12

** Significant at the 1% probability levels.

The results of the mean comparison showed that increasing the temperature from 5 °C caused the germination percentage to increase. However, at a temperature range of 20-30 °C, the germination percentage became stable, with the highest germination percentage (81 to 86%) observed in this range. Nonetheless, with a further increase in temperature, the germination percentage decreased significantly (Table 2).

Another aspect of germination in tomatoes that may be affected by temperature is the germination rate. Similar to the germination percentage, the germination rate increased with an increase in temperature from 5 °C, peaking at 25 °C (5.7 seeds a day). However, a further increase in temperature caused a significant decrease in this trait (Table 2). The highest vigor index of tomato seedlings (4.40-5.47 centimeters) was observed at a temperature range of 20-30 °C, whereas a further increase in temperature caused a significant decline in the rate (Table 2). With an increase in temperature from 5 °C, the mean germination time decreased, so the lowest mean germination time was observed in the range of 20-25 °C (Table 2). However, increasing the temperature to more than 25 °C significantly increased the mean germination time (Table 2).

Table 2. Mean comparison of tomato seed germination at different temperature levels.

Temp (°C)	Germination rate (seed. day^{-1})	Germination (%)	Vigor index	Mean germination time (day)
5	0.142^{d}	7^{d}	0.036^{c}	12.59^{a}
10	0.5^{cd}	25^{cd}	0.16^{c}	12.41^{a}
15	1.3^{c}	52^{bc}	0.68^{b}	7.1^{c}
20	4.45^{b}	81^{ab}	4.58^{a}	4.83^{d}
25	5.7^{a}	86^{a}	5.47^{a}	4.5^{d}
30	4.53^{b}	83^{ab}	4.04^{a}	6.34^{c}
35	139^{d}	4^{d}	0.063^{c}	9.67^{b}

** Significant at the 1% probability level.

Quantification of tomato seed germination response

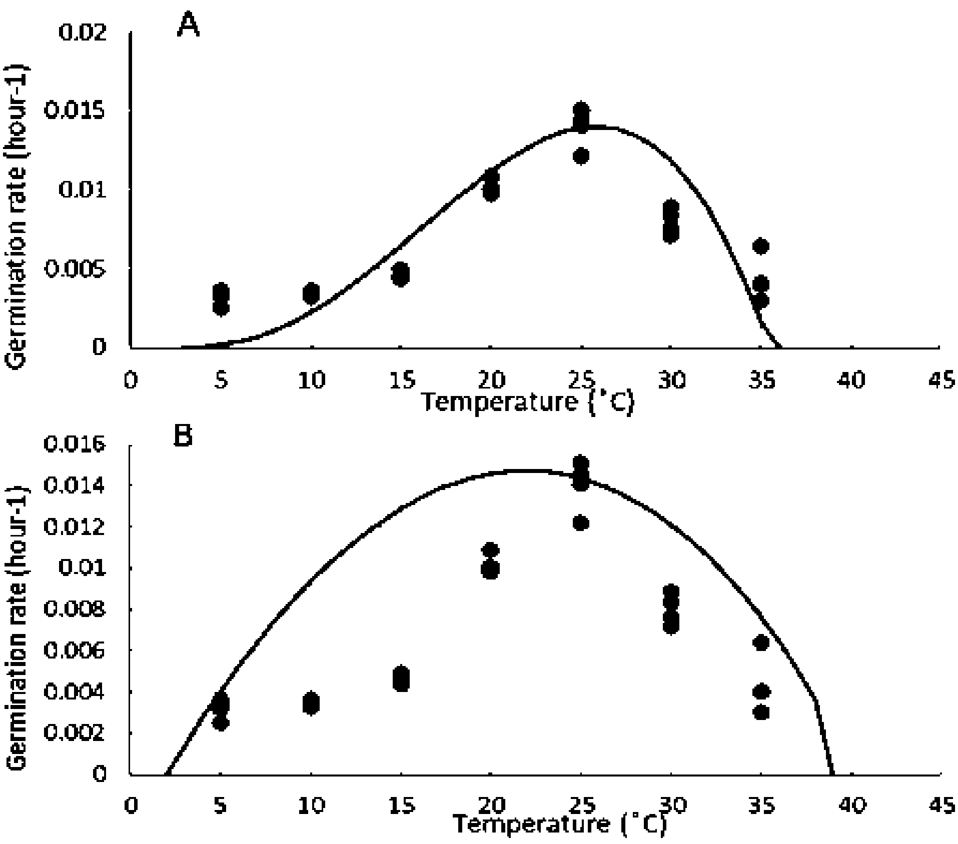
In general, fitting the models showed that in almost all models, segmented, dent-like, original beta, and modified beta, with increasing the temperature from 5 to 25 °C, the germination rate increased due to a better germination temperature. As the temperature increased further, the germination rate decreased (Table 3 and Fig. 1).

By quantifying the germination rate in response to temperature using different regression models, cardinal temperatures and fitness assessment parameters of the regression models were calculated for tomato seeds and presented in Table 3.

Table 3. Calculated cardinal temperatures of tomato for four fitted models based on germination rate (GR50).

Model	T_b	T_o	T_{o1}	T_{o2}	T_c	R^2	r	RMSe	c
Segmented	0.5	25	-	-	40	0.85	0.92	0.000415	-
Dent-like	0.55	-	23	25	39	0.79	0.89	0.000491	-
Beta	2	26	-	-	40	0.55	0.74	0.00103	1.58
Modified Beta	3	25.8	-	-	35.4	0.80	0.89	0.000538	-

Note. T_b = base temperature; T_o = optimum temperature; T_{o1} = Lower optimum temperature for segmented function; T_{o2} = Upper optimum temperature for segmented function; T_c = ceiling temperatures; R^2 = Coefficients of determination; r = Coefficients of correlation; RMSe = Root mean square of error; and c = a shape parameter for the beta function that determines the curvature.



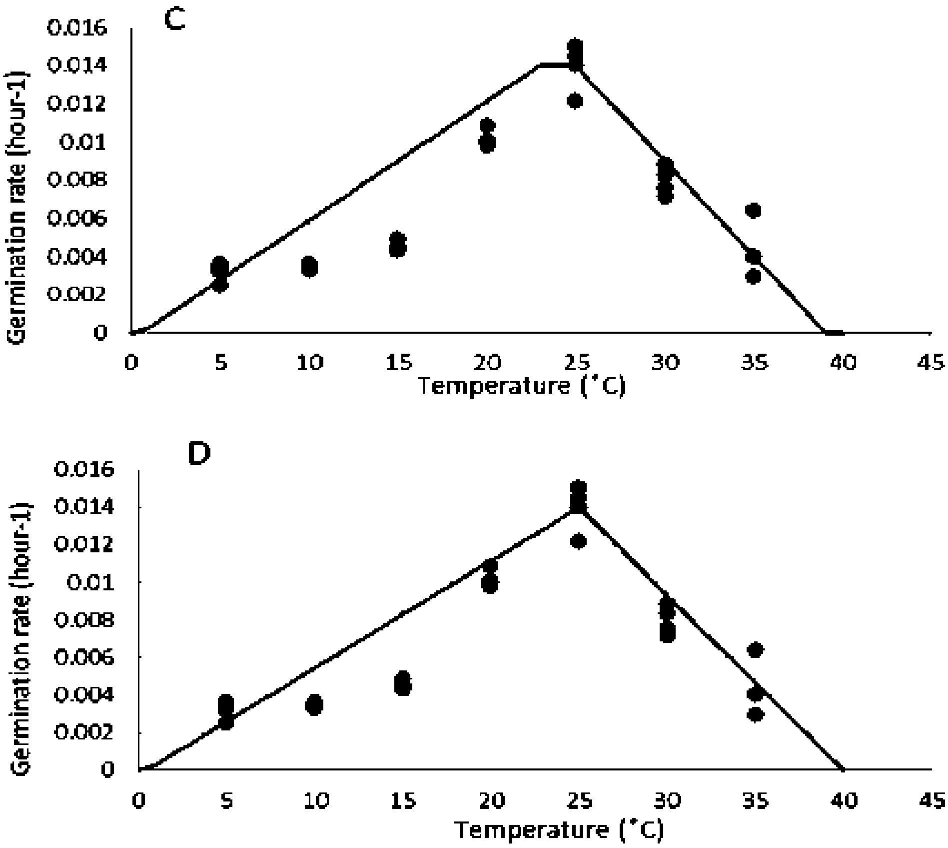


Fig. 1. Effect of different temperatures on the germination rate of tomato based on Modified Beta model (A), Beta model (B), Dent-like model (C), and segmented model (D).

Based on the coefficient of determination, coefficient of correlation (higher values), and root mean square of error (lower values), the segmented model ($R^2 = 0.85$, $r = 0.92$, and RMSe $= 0.000415$) and then dent-like ($R^2 = 0.79$, $r = 0.89$, and RMSe $= 0.000491$) and modified beta ($R^2 = 0.80$, $r = 0.89$, and RMSe $= 0.000538$) models were selected as superior models (Table 4).

The beta model showed the lowest model evaluation indices ($R^2 = 0.55$, $r = 0.74$, and RMSe $= 0.00103$) among the four models used in this study. Therefore, its application to determine the cardinal temperatures of tomatoes is not very useful. Based on the fitting of superior regression models, the values of cardinal temperatures were determined according to the segmented ($T_b = 0.5$, $T_o = 25$, $T_c = 40$), dent-like ($T_c = 39$, $T_b = 0.55$, $T_{o1} = 23$, $T_{o2} = 25$), and modified beta ($Tb = 3$, $T_c = 35.4$, $T_o = 25.8$) models. In Fig. 1, along with the observed values for the germination rate relative to the temperature, the curve for the predicted germination rate values was presented by the best-known models.

To quantify the thermal time model, sub-optimal temperatures were used for predicting the germination time of the tomato seeds. Table 4 presents the parameters of the thermal time model. Accordingly, the coefficient of determination for this model was 0.9 at sub-optimal temperatures, which indicates that this model is highly efficient in predicting the germination time of the tomato seeds. The estimated base temperature (T_b) was 2 °C using the thermal time model. Also, the estimated constant value of thermal time (θ_T) for tomatoes in the range of sub-optimal temperatures was 1848.29 °Ch (degree hours) and the standard deviation from the constant value of thermal time ($\sigma\theta_{T(50)}$) was 703.6 °Ch (Table 4).

Also, in Fig. 2, the fitting of the Thermal-Time Model is shown for the tomato seed germination at a sub-optimal temperature range.

Table 4. Estimation of the parameters of the thermal time model to predict the response of tomato germination to the optimum temperatures.

Sub-optimal (°C)	T_b (°C)	θ_T (°Ch)	$\sigma\theta_T$ (°Ch)	R^2
5-25	2	1848.29	703.68	0.90

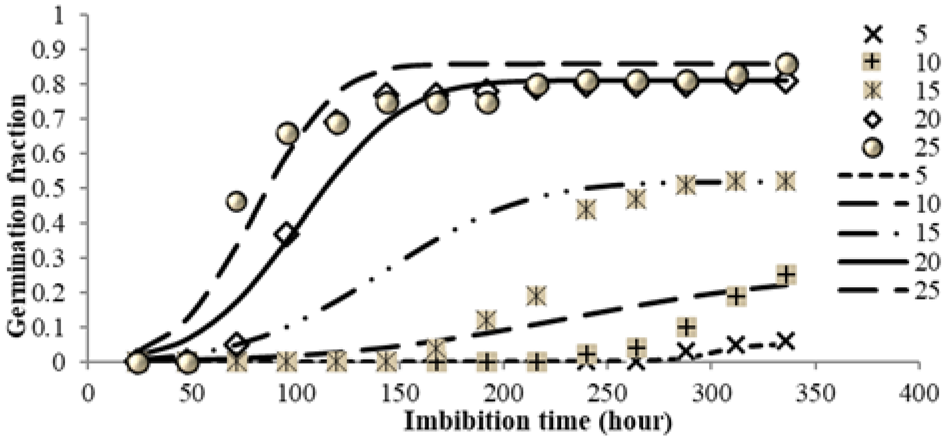


Fig. 2. Cumulative germination process of tomato seeds in the range of sub-optimal temperatures (5-25 °C). The symbols indicate the observed germination percentage and the lines indicate the predicted germination percentage using the thermal time model.

Like the germination, the highest value of the vigor index was observed at 20-30 °C (Table 2). However, by increasing the temperature from 25 °C, the average germination time increased significantly (Table 2). The predictive models of germination rate in response to temperature variations were in good agreement with the observed data (Table 3, Fig. 1). Based on the output of the superior regression models (segmented, dent-like, and beta), the minimum germination temperature of tomato was between 0.5 and 3 °C (with a 2.5 °C difference). Also, the optimum temperature was estimated between 25 and 26 °C (with a 1 °C difference) and the maximum temperature was estimated between 35.4 and 40 °C (with a 4.6 °C difference) (Table 3). Based on the output of the model, the thermal time required for 50% germination in tomatoes was 1848.29 degree-hours with a deviation of 703.6 degree-hours (Table 4).

Discussion

Plant germination is part of an ecology with continuous interactions between changing environmental conditions and the sensitivity of seed populations that respond to these conditions per unit time (Liu et al., 2020). Gaining information about the critical temperatures of the different stages in a plant's life in a particular area is critical for a successful prediction of the ripening, adaptation, and performance of a plant (Yan and Hunt, 1999). Therefore, having awareness of the temperature requirements of a plant through germination studies is one of the effective methods of determining suitable areas for production and, consequently, increasing the plant yield (Tolyat et al., 2014). The results of this experiment suggested that the studied characteristics of tomato germination were temperature-dependent. Thus, the mean values of germination parameters were significantly different ($P \leq 0.05$). The most suitable temperature for the potential germination of tomato seeds was provided at a temperature range of 20-30 °C. Thus, the germination percentage in this range was between 81% and 86%. Dashti et al. (2015) studied *Salvia leriifolia* and reported that the highest average germination percentage can be achieved at 10-25 °C. Khaleghi and Moalemi (2009) reported that the highest germination percentage of cocks comb (*Celosia argentea*) can be achieved at 25 °C. A study on seeds of the MM genotype in *Solanum lycopersicum* (cv. 'Moneymaker') found that 90% of the seeds germinated at 25 °C in both darkness and light but were unable to germinate at 37 °C.
In the presence of light at 25 °C, the seeds that had been imbibed at 37 °C for 4 days (4DI)

germinated more and faster than the seeds that had been imbibed for 6 days at 37 °C (6DI). It may be inferred that at high temperatures, thermo-dormancy was induced concomitantly with the induction of light sensitivity. Light is one of the factors that can predominantly affect thermo-dormancy (Geshnizjani et al., 2015). Boroumand and Kouchaki (2006) studied three herbs, dill (*Anethum graveolens*), ajowan (*Trachyspermum ammi*), and fennel (*Foeniculum vulgare*), showing that temperature had a significant effect on the germination percentage of these three herbs. The highest germination percentage in ajowan, fennel, and dill occurred at 25-10, 20-10, and 10 °C, respectively. One of the main factors that inhibit seed germination in tomatoes is the weakening of the endosperm (Kępczyński et al., 2006). The temperature ranges of these studies were partly in line with the current research. Interestingly, in this study, the sensitivity of tomato seeds to high (35 °C) and low (5-10 °C) temperatures was significant. At low temperatures, the germination decreased; the most logical reason was the delay in germination and seed death (Joly et al., 2013). It has been reported that the long-term effects of high temperatures on germinating seeds may include weak seedling establishment. Probably, the alteration of the proteins necessary for germination is a factor in stopping germination at high temperatures (Copeland and McDonald, 2012). In this regard, Taghvaei et al. (2015) studied two *Calotropis procera* populations collected from the Zahedan dune desert seed source. It was reported that by increasing the temperature to 20-30 °C, the germination rate increased. But a further increase in temperature caused a sudden decline in the germination rate.

The germination rate at different temperatures usually varies due to their different reactions to heat. At very low temperatures, proteins and enzymes are not sufficiently flexible to adapt to the changes required for the reaction. As the temperature rises, however, the activity of the enzymes increases and the germination rate increases. On the other hand, very high temperatures cause some enzymes to become inactive, thereby decreasing the rate of reactions (Bonhomme, 2000). Despite the wide range of temperatures for maximum germination percentage (20-30 °C), compared to the constant 25 °C as the maximum rate of germination, there was a significant reduction in the germination rate at 30 °C. It seems that the germination rate was more sensitive to temperature, compared to the sensitivity of germination percentage. Previous findings by Tabrizi et al. (2005) supported the current results.

The high level of vigor index was due to the high amount of germination percentage and seedling length. The lowest values of the vigor index occurred at 5-10 °C. It seems that at lower temperatures, water absorption by the seed occurs more slowly. Likewise, several processes are slowed down for the commencement of germination, such as the activation of enzymes, breakdown of molecules, and their transfer to the embryonic axis. The radicle excretion will then be delayed and the length of the radicle and plumule decrease (Arun et al., 2022; Szczerba et al., 2021). In a relevant study, the highest vigor index of pear seedlings was induced by 25-40 °C (Rahimi and Kafi, 2010). It seems that by increasing the temperature to 20-25 °C, temperature conditions became apt for the germination of tomato seeds. The germination rate improved as a result of a decrease in the germination time. Some reports suggested that the average germination time was directly related to radicle emergence in corn seeds (Matthews and Khajeh Hosseini, 2006). Generally, the duration and rate of germination correlated significantly with seed quality. Therefore, the longer the germination period, the higher the seed quality (Falleri, 1994).

Based on the output of the superior regression models (segmented, dent-like, and beta), the minimum germination temperature for tomato seeds was 0.5-3 °C (with a 2.5 °C difference). Although tomato seeds are capable of germination (7 to 25%) at lower temperatures (below 10 °C), the germination rate usually becomes very slow and makes it difficult for the seedling to establish itself. In part, this is because the seeds can be attacked by a range of pathogens before they germinate (Zhou et al., 2012).

Moreover, the optimum and maximum temperatures were estimated to be 25-26 °C and 35.4-40 °C, respectively. Regression models were used to estimate the cardinal temperatures of medicinal, crop, and weed species. Heidari et al. (2014) studied fennel (*Foeniculum vulgare* Mill L.) and used three models, segmented, dent-like, and beta. They reported that only the dent-like model provided a good estimation of the cardinal temperatures of the plant. In another study, Fallahi et al. (2015) used three different regression models to predict a model for cardinal temperatures in two species of basil (*Ocimum basilicum* L.). According to the results of the experiment, all three models successfully estimated the cardinal temperatures for germination. In another study, the cardinal temperatures of *Silybum marianum*, including minimum, optimal, and maximum temperatures, were reported to be 19.5, 20.01, and 32.34 °C, respectively (Parmoon et al., 2015). Al-Ahmadi and Kafi (2007) conducted research on *Kochia*

scoparia L. and reported a minimum temperature of 3.5 °C, an optimum temperature of 24 °C, and a maximum temperature of 50 °C. In an experiment on six basil varieties, it was reported that the minimum temperature varied significantly among different cultivars and ranged from 10.1 °C to 13.3 °C. Similarly, regarding optimum and maximum temperatures, there was no significant difference among the studied cultivars in this experiment. The optimum temperature was 35 °C and the maximum temperature was 43.0 °C ± 1.3 °C (Zhou et al., 2012). In an experiment on two basil species, the minimum, optimum, and maximum temperatures for purple basil were obtained in the range of 4.99-7.4 °C, 24.15-28 °C, and 41-41.84 °C, while for green basil, they were obtained at 4.99-7.13 °C, 25.65-28.98 °C, and 43.58-47 °C, respectively (Fallahi et al., 2015).
Parmoon et al. (2015) used a thermal time model to estimate the temperature requirements of *Silybum marianum* at optimal temperatures. The results showed that the amount of thermal time for 50% and 90% of germination was 177.12 and 116.90 degree-hours, respectively. Also, in another research, the effects of thermal time and an increase in soil temperature was measured on the germination time of two cactus species (*Polaskia backeb*) using the thermal time model. It was reported that this model is a very useful tool for determining and predicting the effects of climate change on developmental processes such as germination (Ordoñez-Salanueva et al., 2015).

Conclusion
The results of this study confirmed that in the absence of other limiting factors (e.g. moisture, light, and oxygen), tomato germination was affected by temperature. According to the obtained results and the findings of other researchers, it can be concluded that the response of species, varieties, and landraces to environmental conditions is different. It is necessary to consider this when cultivating a plant. These differences are primarily evident in germination. Cardinal temperatures are affected by moisture conditions. The minimum germination temperature increases in response to a decrease in water potential. Therefore, in areas where drought or salinity stress dominates, it is better to postpone the planting date so that the conditions are thermally favorable for germination. Under salinity and drought stress conditions, planting this variety is more suitable in areas where the average temperature during germination is between 20 and 30 °C. Also, the results of this study indicated that the germination and emergence of the 'Early CH' cultivar are predictable. It is possible to use segmented, dent-like, and modified beta models because these models describe the rate of germination for this variety very well. Therefore, these models and the estimated parameters of these models can be used in the preparation and evaluation of germination prediction models.

Conflict of Interest
The authors indicate no conflict of interest for this work.

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