# Cardinal temperatures and thermal time required foremergence of lenti (Lens culinaris Medik)

**Article** *in* Legume Research · February 2017
DOI: 10.18805/lr.v0i0.7301



Behnam Kamkar
Ferdowsi University Of Mashhad

Legume Research, 40 (2) 2017 : 291-298
Print ISSN:0250-5371 / Online ISSN:0976-0571

AGRICULTURAL RESEARCH COMMUNICATION CENTRE
www.arccjournals.com/www.legumeresearch.in

# Cardinal temperatures and thermal time required for emergence of lenti (*Lens culinaris* Medik)

**Ali reza Safahani[1]*, Behnam Kamakar[2] and Amir Nabizadeh[2]**

Department of Agronomy,
Payame Noor University, Tehran, I. R. of Iran.

Received: 31-02-2016 Accepted: 15-11-2016 DOI:10.18805/lr.v0i0.7301

## ABSTRACT

The present study was performed to compare four nonlinear regression models (segmented, beta, beta modified, and dent-like) to describe the emergence rate–temperature relationships of six lentil (*Lens culinaris* Medik) cultivars at field experiment with a range of sowing dates, with the aim of identifying the cardinal temperatures and physiological days (i.e., number of days under optimum temperatures) required for seedling emergence. Models and statistical indices were calibrated using an iterative optimization method and their performance was compared by root mean square error (RMSD), coefficient of determination ($R^2$) and corrected Akaike information criterion correction (AIC). The beta model was found to be the best model for predicting the response of lentil emergence to temperature, ($R^2$= 0.99; RMSD= 0.005; AICc= -232.97). Based on the model outputs, the base, optimum, and maximum temperatures of seedling emergence were 4.5, 22.9, and 40 °C, respectively. The Six physiological days (equivalent to a thermal time of 94 °C days) were required from sowing to emergence.

**Key words:** Emergence, Regression models, Sowing date, Temperature response.

## INTRODUCTION

Studying basic seed emergence requirements will increase the chance of successful plant establishment under different climatic conditions (Soltani *et al*., 2001). Rapid, uniform and complete emergence of vigorous seedlings, leads to high grain yield potential by shortening the time from sowing to complete ground cover, allows the establishment of optimum canopy structure to minimize interplant competition, maximize crop yield and provide plants with time and spatial advantages to compete with weeds (Soltani *et al*., 2001).

Modeling of seed emergence is considered an effective approach to determining cardinal temperatures for most plant species, although these methods have some limitations due to unpredictable biological changes. Two main concepts widely used by researchers to model seed emergence include empirical and mechanical models (Wang, 2005). Empirical models perform well for fitting individual emergence data over time, but may need empirical variables (Brown and Mayer, 1988). It is difficult to ascribe biological significance to model parameters estimated by empirical methods (Wang, 2005). Mechanical models are developed based on the experimental quantification of environmental effects on seed emergence and seedling emergence. In the long term, this approach is likely to be most successful (Forcella *et al*., 2000). The application of mechanical threshold models of seed emergence and seedling emergence has shown some success (Forcella *et al*., 2000; Roman *et al*., 2000). The results of fitting mechanical models are useful for evaluating seed quality, emergence rate, emergence percentage, emergence uniformity (Wang *et al*., 2005) and seed performance under different environmental stresses such as salinity, drought, and freezing (Bradford, 2002). Regression models incorporating more parameters can produce more precise estimates. Nonlinear curves are used to model the time course of emergence at different temperatures (Shafii and Price, 2001). Such regression models have been used to explain development rate in many crops (Kamkar *et al*., 2012). Seedling emergence of wheat as a function of soil temperature and water potential has been studied using logistic models (Kamkar *et al*., 2008) Cardinal temperature was determined using segmented and logistic models in millet varieties and seedling emergence of wheat (Stapper and Lilley, 2001). In the dent-like model at lower-than-optimum temperature, a linear relationship holds between temperature and emergence rate. This relationship remains linear at higher-than-optimum temperatures, but with a reducing trend. With increasing temperature, emergence rate increases linearly up to an optimum temperature. Beta and beta modified models fit curvilinear relationships between emergence rate and temperature. These models are thus more flexible than other models.

*Corresponding author’s e-mail: safahani_ali@yahoo.com
[1]Department of Agronomy, Payame Noor University, Tehran, I. R. of Iran.
[2]Department of Agronomy, Gorgan University of Agricultural Science and Natural Resources (GUASNR), Faculty of Plant Production, Basij Square, Pardis No. 2, 49189-43464 Gorgan, Iran.

The literature describing temperature effects on seedling emergence in lentil is scarce, but there are some studies on germination in laboratory. Rahban *et al*. (2014) reported a base temperature of 0.89–1 °C, an optimum temperature of 23.41–26.94 °C and a ceiling temperature of 35.15–45 °C for germination in three lentil cultivars. Given the lack of quantitative data on lentil emergence, the main goal in this research was carried out to formulate and validate non-linear regression models that can be used to quantify cardinal temperatures and the effect of temperature on the time from sowing to emergence of lenti.

## MATERIALS AND METHODS

A field experiment with a series of sowing dates was conducted at the Gorgan University of Agricultural Sciences Research Farm, Gorgan (36°51′ N, 54°16′ E and 100 m asl), Iran. The experiment started in December 2011 and continued until January 2013. Six lentil cultivars (Arman, Azad, Hashem, Byvnj, Adas and IlC) were sown at 11 different sowing dates. Sowing dates were 12 December 2011 and 15 January, 15 February, 17 March, 16 April, 18 May, 17 June, 16 August, 15 September, 14 October and 12 November 2012. The cultivars were selected from different geographical areas across Iran. These sowing dates do not necessarily reflect common practices, but were selected to create different temperature regimes and to trigger seedling emergence responses to a wide range of temperatures. The soil physical properties in the 0–0.3 m top layer were: clay 26%, silt 64%, sand 10%, bulk density 1.4 g $cm^{-3}$ and pH 7.9. The experiment was irrigated optimally so that there was no flooding or water deficit. The experimental design was a single split plot with sowing dates in the main plot and cultivars in the sub plot, replicated four times. Plot size was 1.5 m by 4 m. Seeds were hand-sown at a rate of 50 plants $m^{-2}$ and a depth of 4 cm with row spacing of 25 cm. The number of emerged seedlings was recorded daily in early spring, autumn and winter sowings and twice daily in late spring and summer sowings from two 1 m row lengths located in the center of each plot. Emergence percentage was obtained by dividing number of emerged seedlings at any time by total number of seeds sown, multiplied by 100. Estimates of the time taken for cumulative emergence to reach 50% ($D_{50}$) of maximum in each replicate of each treatment were interpolated from the progress of emergence (%) versus time (days) curve. Emergence rate ($R_{50}$, $day^{-1}$) was then calculated as (Soltani *et al*., 2001, 2002)

$$R_{50} = \frac{1}{D_{50}} \quad (1)$$

Daily maximum and minimum temperatures were measured at a standard weather station a few meters from the experimental plots. Data from the field experiment was first subjected to analysis of variance and means of treatments were compared using least significant difference (LSD) at 5% level of probability.

To quantify the response of the emergence rate to temperature and cardinal temperatures for emergence, the following equation was used (Soltani *et al*., 2006):

$$R_{50} = \frac{f(T)}{e_o} \quad (2)$$

Where $R_{50}$ is the emergence rate ($day^{-1}$), f (*T*) is a temperature function that ranges between 0 and 1, and $e_o$ is the physiological day requirement for emergence. $e_o$ indicates the minimum number of days for emergence at optimal temperature and $1/e_o$ is, thus, the maximum emergence rate. Sigma Plot, Ver 12 software was used to calibrate the models (beta, beta modified, segmented, and dent-like) using an iterative optimization method (Table 1). Because of the low frequency of temperature higher than 35 °C (Figure. 1), $T_c$, the ceiling temperature was fixed at 40 °C when fitting the functions to emergence data, but determine the best estimates of other parameters (lower deviations of the intercept from 0 and of the slope from 1 correspond to increased reliability (RMSD; Eq. (3)), the coefficient of determination ($R^2$; Eq. (4)), and the intercept and slope of the regression of predicted vs. observed emergence rate were used.

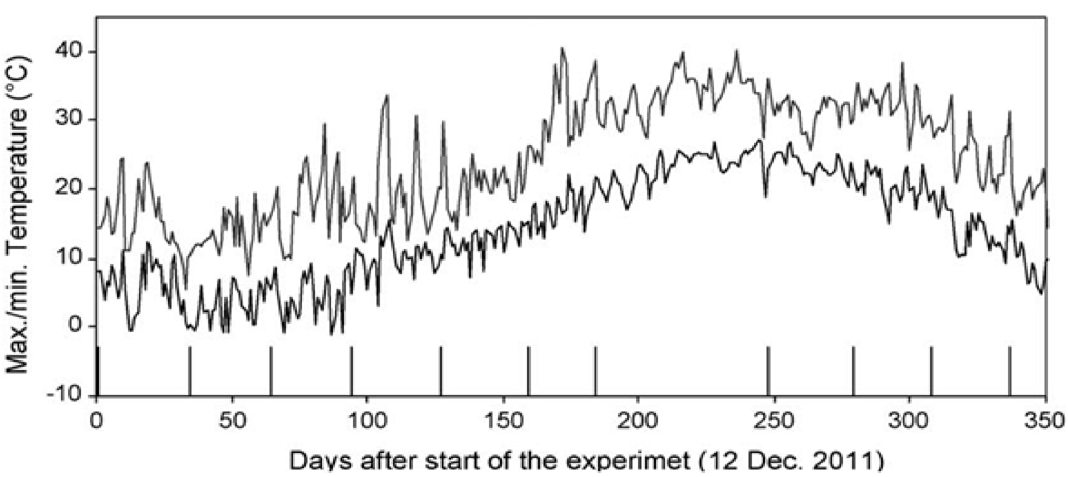


**Fig 1:** Minimum and maximum temperatures during the field experiment at Gorgan, Iran. Short vertical lines indicate sowing dates.

**Table 1:** Beta, Beta modified, segmented, and dent-like models that were fitted to model emergence rate at different temperatures.

| Function | Formula | References |
|---|---|---|
| Beta, five parameter | $f(T) = (\frac{(T-T_b)}{(T_0-T_b)})(\frac{(T_c-T)}{(T_C-T_0)})^{(\frac{(Tc-T0)}{(T0-Tb)})^c}$ | (ÕMeara *et al*., 2006) |
| Beta, four-parameter | $f(T) = \{(\frac{(T-T_b)}{(T_0-T_b)}\frac{(T_c-T)}{(T_C-T_0)})^{\frac{(T_c-T)}{(T_C-T_0)}}\}^c$ | (Fry, 1983) |
| Dent-like | $F(T) = \frac{(T-T_b)}{(T_{01}-T_b)} \ldots\ldots if\ T_b \le T \le T_{01}$<br>$F(T) = \frac{(T_c-T)}{(T_c-T_{02})} \ldots\ldots if\ T_{02} \le T \le T_c$<br>F($T$) = 1 … … if $T_{01} \le T \le T_{02}$<br>F($T$) = 0 … … if $T \le T_b\ or\ T_c \le T$ | (Ellis *et al*., 1986) |
| Segmented | $F(T) = \frac{(T-T_b)}{(T_0-T_b)} \ldots\ldots if\ T_b \le T \le T_0$<br>$f(T) = 1 - \left(\frac{T-T_0}{T_c-T_0}\right)\ if\ T_0 \le T \le T_c$<br>F($T$) = 0 … … if $T \le T_b\ or\ T_c \le T$ | (Bare *et al*., 1978) |

T, the average temperature from sowing to emergence; $T_b$, the base temperature; $T_0$, the optimum temperature; $T_{01}$, the lower optimum temperature for a 3-piece segmented function; $T_{02}$, the upper optimum temperature for a 3-piece segmented function; $T_c$, the maximum temperature; c, a shape parameter for the beta function that determines the curvature of the function.

$$RMSE = \sqrt{\frac{1}{n}\sum(Y_{obs} - Y_{pred})^2} \quad (3)$$

Where $Y_{obs}$ denotes observed value, $Y_{pred}$ predicted value, and n the number of samples (Timmermans *et al*., 2007), and

$$R^2 = \frac{SSR}{SST} \quad (4)$$

Where SSR denotes the sum of squares (SS) for regression $(\sum_{i=1}^{n}(\hat{L} - \bar{L}))$ and SST the total SS$(\sum_{i=1}^{n}(L_i - \bar{L}))$. $L_i$ is the observed value and $\hat{L}$ is the corresponding estimated value. The parameters estimated by nonlinear models were subjected to descriptive statistical analysis of the pooled datasets, after which the best estimated values were also used to calculate the thermal time needed for each emergence percentile.

Low RMSE and $R^2$ near 1 correspond to better model estimation. To identify the best model for estimating cardinal temperature, the Akaike Information Criterion (AIC) was used. This statistic incorporates the amount of reduction of RSS and the model complexity (Burnham and Anderson, 2002).

$$AIC = n\ ln\left(\frac{RSS}{n}\right) + 2k \quad (5)$$

Where RSS denotes the residual sum of squares, n the number of observations, and k is the number of model parameters. It is possible to use a corrected AIC (AICc) instead of AIC. This statistic is used to identify the most accurate model (ÕMeara *et al*., 2006)

$$AIC = n\ ln\left(\frac{RSS}{n}\right) + 2k + \left(\frac{2k\ (k+1)}{n-k-1}\right) \quad (6)$$

The model that yields the most accurate estimate is the one with the lowest AICc value. Although the best model is the one that yields the lowest AICc, there is a method that permits description, ranking, and fitting different models. This method requires the calculation of $\Delta_i$:

$$\Delta_i = \text{AICc} - AICc_{min} \quad (7)$$

Where min AICc is the minimum calculated AICc among all models, and corresponds to the best-fitting model. If $\Delta_i$ < 10, there is no significant difference between models, and a model with higher AICc also could be well-fitting. If $\Delta_i$ > 10, a model with higher AICc is not suitable and not well-fitting. The daily thermal time (DTT) was calculated as DTT = ($T_{01}$ - $T_b$). f($T$) where: f($T$) is the $T$ function, $T_{01}$ is the lower optimum $T$, and $T_b$ is the base $T$. The first components of daily thermal time are the constant and non-optimal temperatures that affect the daily thermal time through f ($T$).

## RESULTS AND DISCUSSION

Temperature conditions during the field experiment are shown in Figure 1. Maximum temperatures ranged from 7 to 36 °C and minimum temperature from -1 to 24 °C. Analysis of variance showed no significant effect of cultivar or cultivar × sowing date interaction for time to emergence, but the effect of sowing date was significant ($P < 0.01$) (Table 2). By contrast, effects of sowing date, cultivar and their

**Table 2:** Results of analysis of variance for days to 50% emergence and final emergence percentage.

| Source of variation | Mean square from analysis of variance | |
|---|---|---|
| | Days to emergence | Final emergence percentage |
| Block (B) | ns | ns |
| Planting date (P) | *** | *** |
| Error (A) | 2.2 | 63.4 |
| Cultivar (C) | ns | *** |
| C × P | ns | *** |
| Error B | 0.6 | 42.7 |

*** Significant at 0.01% level of probability.

interaction were all significant for emergence percentage (Table 2). Days to emergence varied between 6 days for the 18 May 2012 sowing and 21 days for the 15 January 2012 sowing. Final emergence percentage was lowest for the sowing date of 17 March 2012 (57%) and highest for the sowing date of 18 May 2012 (91%) (Table 3). Differences in final emergence percentage were related to variation in temperature; significant but small correlations were found between emergence percentage and temperature ($r=0.36$; $P < 0.01$) and between emergence percentage and time to emergence ($r=0.52$; $P < 0.01$). As duration from sowing to emergence increases at low temperatures, there will be more opportunity for seed and seedling diseases to occur and hence the likelihood of lower emergence percentages (Vigil *et al.*, 1997).

**Table 3:** Means of days to 50% emergence and final emergence percentage for different sowing dates.

| Date | Days to emergence | Final emergence percentage |
|---|---|---|
| 12 December 2011 | 18.1 b | 70.4 e |
| 12 January 2012 | 21.1 a | 74.7 de |
| 15 February 2012 | 14.2 c | 79.3 cd |
| 17 March 2012 | 11.2 d | 57.2 f |
| 16 April 2012 | 8.1 ef | 88 ab |
| 18 May 2012 | 5.6 h | 90.9 a |
| 17 June 2012 | 7.5 f | 85.8 ab |
| 16 August 2012 | 5.8 h | 83.4 bc |
| 15 September 2012 | 6.9 g | 88.1 ab |
| 14 October 2012 | 6.5 g | 86.8 ab |
| 12 November 2012 | 8.5 e | 88.9 ab |

In each column, means followed by the same letter do not differ significantly.

Statistics from model fitting to emergence data of the field experiment are shown in Table 4. Predicted days to emergence versus observed days to emergence in the field experiment are shown in Figure. 2. Root mean square of deviations (RMSD) was similar and ranged between 2 and 3 days for all the temperature functions (Table 4).

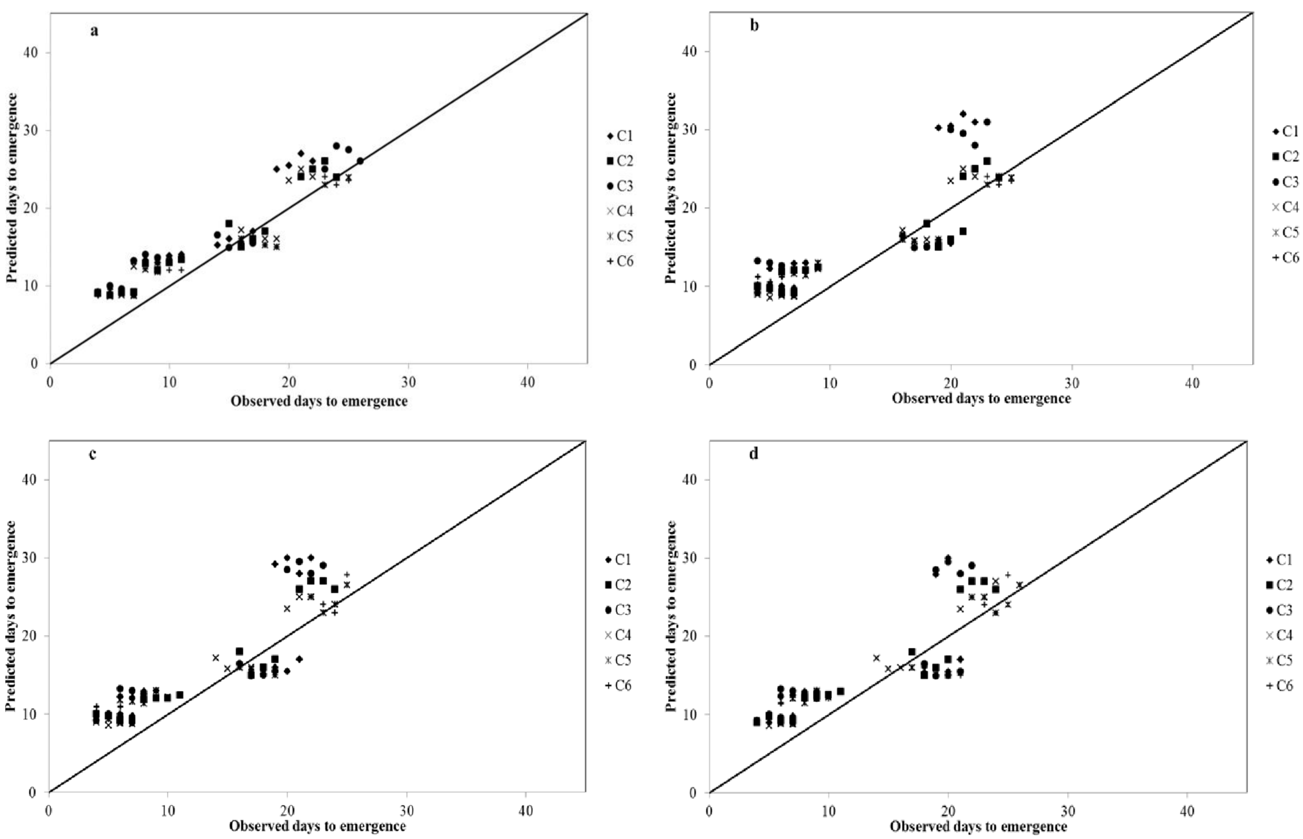


**Fig 2:** Predicted vs. observed days to emergence in four lentil cultivars using (a) beta, (b) segment, (c) beta modified and (d) dent-like functions to describe response of emergence rate to temperature. The solid line is a 1:1 line.

However, beta function had significantly higher $R^2$ values compared to the other functions. There was no significant difference between functions with respect to the correlation coefficient between predicted and observed days to emergence. Predictions based on the segmented function had significant bias as indicated by significant a and b coefficients in the linear regression between predicted and observed days to emergence. However, there was no bias with beta, beta modified and dent-like functions (Table 4). Due to lower $R^2$ values and significant bias for the segmented function, the results of this study indicate that this function is not a suitable function to be used in modeling seedling emergence. This is in contrast with findings of other researchers where the segmented function adequately described the response of germination, leaf appearance and development rate to temperature in different crops (Mwale *et al*., 1994; Robertson *et al*., 2002). Various temperature response curves have been used to describe the effect of temperature on crop development and growth process. For instance, Jame and Cutforth (2004) used the beta function and Ritchie (1991) and Piper *et al*. (1996) used the dent-like function in their studies. The shape of the beta function in the present study is similar to the curvilinear function used by Soltani *et al*. (2006).

Estimates of cardinal temperatures and physiological day requirement for emergence are given in Table 5. Estimates from the segmented function are also included for comparison. There was no significant difference between cultivars for cardinal temperatures or physiological day requirement for emergence based on all the functions used. Using beta function, a base temperature of 4.2 °C, optimal temperature of 22.6 °C and $e_0$ of 5.6 days were obtained. Dent-like function estimates were 2.5 °C for base temperature, 20.2–29.3 °C for optimum temperature, and 6.1 days for $e_0$. There was no significant difference between estimates of the functions. Optimum temperature from the beta function fell within the range of optimum temperature estimated by the dent-like function. The optimum temperature for all models was very close to 23 °C. The beta model was the most reliable, because it had lower standard errors and AICc values for cardinal temperatures and gave more precise estimates (Table 5).

**Table 4:** Root mean square of deviations (RMSD) and coefficient of determination ($R^2$) for the relationship between emergence rate (R50; Eqs. (1) and (2)) and temperature in six lentil cultivars described by various functions. Regression coefficients (a and b) and correlation coefficient (r) for the relationship between observed and predicted days to emergence are also indicated.

| Function-cultivar | RMSD | $R^2$ | a ± S.E. | b ± S.E. | r |
|---|---|---|---|---|---|
| **Segmented** | | | | | |
| Arm | 3.06 | 0.57 | -0.7±0.77 | 1.6±0.28 | 0.92 |
| Azad | 3.02 | 0.72 | -1.8±230.32 | 1.4±0.27 | 0.91 |
| Hashaem | 2.21 | 0.66 | -0.9±0.25 | 1.5±0.31 | 0.93 |
| Byvnj | 3.23 | 0.69 | -0.7±0.45 | 1.3±0.31 | 0.88 |
| Adas | 2.23 | 0.82 | -2.4±0.87 | 1.4±0.34 | 0.87 |
| ILC | 2.76 | 0.65 | -0.25±0.22 | 1.5±.3 | 0.88 |
| **Beta** | | | | | |
| Arm | 2.4 | 0.70 | -1.1 ±0.86 | 2.9±0.6 | 0.95 |
| Azad | 2.33 | 0.83 | 1.2±0.33 | 2.4±0.55 | 0.93 |
| Hashaem | 2.14 | 0.82 | 1.4±0.79 | 0.5±0.52 | 0.94 |
| Byvnj | 2.07 | 0.74 | 0.1±0.23 | 1.7±0.32 | 0.93 |
| Adas | 2.58 | 0.87 | 0.86±0.55 | 1.3±0.37 | 0.89 |
| ILC | 2.67 | 0.79 | 0.68±0.97 | 1.2±0.31 | 0.93 |
| **Beta modified** | | | | | |
| Arm | 2.85 | 0.65 | 1.6±0.32 | 2.2±0.41 | 0.92 |
| Azad | 2.33 | 0.78 | 0.98±0.29 | 2.3±0.5 | 0.89 |
| Hashaem | 2.41 | 0.77 | -1.2±0.13 | 2.8±0.63 | 0.89 |
| Byvnj | 2.77 | 0.74 | -1.9±0.54 | 2.8±0.66 | 0.82 |
| Adas | 2.4 | 0.81 | -1.7±0.93 | 2.7±0.95 | 0.82 |
| ILC | 2.89 | 0.78 | 0.6±0.39 | 2.5±.55 | 0.88 |
| **Dent-like** | | | | | |
| Arm | 2.98 | 0.73 | -0.4 ±1.80 | 1.4±0.19 | 0.90 |
| Azad | 2.4 | 0.80 | -1.0±0.94 | 1.3±0.23 | 0.89 |
| Hashaem | 2.22 | 0.75 | -1.9±0.42 | 1.3±0.21 | 0.88 |
| Byvnj | 2.67 | 0.71 | -0.7±1.36 | 1.1±0.18 | 0.87 |
| Adas | 2.12 | 0.79 | -1.2±0.8 | 1.3±0.32 | 0.87 |
| ILC | 2.56 | 0.77 | 1.2±0.9 | 1.2±0.20 | 0.88 |

**Table 5:** Estimates of base temperature ($T_b$, °C), optimum temperature ($T_0$, °C), lower optimum temperature ($T_{01}$, °C), upper optimum temperature ($T_{02}$, °C), shape parameter (α) and minimum physiological day requirement ($e_0$), for emergence of six Lentil cultivars using segmented, beta and dentlike functions. Ceiling temperature was fixed at 40 °C.

| Parameter | Segmented | | | | | | Beta | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C5 | C6 | C1 | C2 | C3 | C4 | C5 | C6 |
| $T_b$ | 3.32±0.47 | 1.49±0.32 | 2.98±0.66 | 2.96.0±0.37 | 3.8±0.75 | 2.7±0.84 | 4.3 | 3.9 | 3.9 | 4.8 | 4.4 | 4.1 |
| $T_0$ | 27.97±0.5 | 23.78±1.1 | 25.17±1.2 | 25.54±1.8 | 23.1±0.4 | 22.6±0.8 | 21.97±0.51 | 21.78±1.1 | 23.17±1.2 | 23.54±1.89 | 23.25±0.30 | 21.24±1.1 |
| $T_c$ | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| $e_0$ | 5.0±0.26 | 4.7±0.14 | 5.1±0.25 | 5.1±0.26 | 5.0±0.13 | 4.8±0.14 | 5.9±0.31 | 5.1±0.03 | 5.5±0.63 | 5.9±0.3 | 4.9±0.17 | 6.01±0.8 |
| α | | | | | | | 1.2±0.06 | 1.46±0.24 | 1.38±0.22 | 1.31±0.19 | 1.32±0.20 | 1.40±0.11 |
| $R^2$ | 0.95 | 0.98 | 0.94 | 0.91 | 0.90 | 0.92 | 0.99 | 0.99 | 0.98 | 0.99 | 0.99 | 0.98 |
| RMSE | 0.028 | 0.008 | 0.011 | 0.015 | 0.0016 | 0.0021 | 0.008 | 0.004 | 0.007 | 0.005 | 0.005 | 0.005 |
| AIC | -206.78 | -265.53 | -245.07 | -251.11 | -240.11 | -268.25 | -262.95 | -225.17 | -270.02 | -.260.28 | -280.97 | -250.12 |
| AICc | -198.78 | -248.53 | -237.07 | -240.01 | -222.23 | -245.5 | -247.11 | -206.97 | -258.95 | -217.17 | -262.20 | -202.12 |
| Δi | 48.33 | 28.44 | 21.88 | 35.71 | 24.32 | 32.23 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Parameter** | **Beta modified** | | | | | | **Dent-like** | | | | | |
| | **C1** | **C2** | **C3** | **C4** | **C5** | **C6** | **C1** | **C2** | **C3** | **C4** | **C5** | **C6** |
| $T_b$ | 2.8±0.03 | 2.02±0.23 | 2.72±0.20 | 2.96±0.04 | 2.1±0.54 | 3.23±0.021 | 2.14±0.35 | 2.13±0.56 | 2.23±0.65 | 2.96±0.62 | 2.11±0.53 | 2.84±0.39 |
| $T_0$ | 24.66±0.25 | 24.16±0.18 | 24.45±0.32 | 26.9±0.15 | 22.85±1.12 | 24.17±1.98 | | | | | | |
| $T_c$ | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| $T_{01}$ | | | | | | | 22.29±0.48 | 20.4±0.65 | 21.75±0.80 | 20.08±0.75 | 23.03±0.6 | 21.2±0.55 |
| $T_{02}$ | | | | | | | 29.89±0.02 | 25.14±0.56 | 29.55±0.07 | 27.86±0.32 | 26.59±0.04 | 28.45±0.3 |
| $e_0$ | 5.16±0.08 | 4.9±0.06 | 7.19±0.19 | 5.5±0.03 | 5.6±0.26 | 5.4±0.13 | 6.1±0.27 | 5.7±0.18 | 5.9±0.30 | 6.2±0.21 | 6.1±0.12 | 5.8±0.11 |
| α | | | | | | | | | | | | |
| $R^2$ | 0.98 | 0.99 | 0.95 | 0.96 | 0.94 | 0.96 | 0.96 | 0.99 | 0.97 | 0.95 | 0.97 | 0.96 |
| RMSE | 0.018 | 0.006 | 0.008 | 0.015 | 0.003 | 0.004 | 0.025 | 0.006 | 0.007 | 0.005 | 0.0058 | 0.003 |
| AIC | -225.17 | -270.02 | -260.28 | -245.13 | -244.21 | -265.13 | -209.63 | -268.94 | -216.72 | -250.12 | -270.98 | -266.25 |
| AICc | -217.17 | -262.02 | -252.12 | -234.20 | -221.44 | -245.30 | -205.23 | -264.23 | -205.11 | -235.49 | -240.52 | -254.32 |
| Δi | 29.94 | 14.95 | 6.67 | 15.07 | 12.14 | -22.17 | 41.48 | 12.03 | 1.23 | 10.12 | 24.12 | 20.22 |

$T_b$, $T_0$, $T_c$, $T_{01}$, $T_{02}$, $e_0$, and α denote base temperature, optimum temperature, maximum temperature, lower limit of optimum temperature, upper limit of optimum temperature, minimum physiological day requirement for emergence and parameter of beta function, respectively. (Arm, Azad, Hashem, Byvnj, Adas, ILC; C1-C6). Ceiling temperature was fixed at 40 °C.

The calculated f (*T*) used in this study, based on the beta model, is illustrated in Figure 3. It shows an increasing trend up to 22 °C, after which it starts to decrease. This observation suggests that the optimum temperature is around 23 °C. The calculated thermal times for each emergence percentile based on the pooled data are shown in Figure 3.

Base temperature (4.5 °C) obtained in this study for emergence was significantly higher than that found by Rahban *et al*. (2014) and Ellis and Barrett (1994) for germination of lentil (0.89-1.5 °C). Lack of genotypic variation for base temperature in the present study is in agreement with findings of Ellis *et al*. (1986) who found no significant difference between five chickpea genotypes. Base temperature has been reported as a stable trait within crop cultivars (Bradford, 1995). However, Wade *et al*. (1993) in sorghum and Mwale *et al*. (1994) in sunflower reported genetic variation for base temperature.

The optimal temperature of 23 °C reported by Rahban *et al*. (2014) for germination of lentil, in agreement with the optimal temperature range for emergence found in this study (20–29 °C). Based on our study, lentil needs six physiological days for emergence, which is equivalent to a thermal time of 94 °C days (°C day) [= $(T_{01}–T_b)\ e_0$] (Table 5).

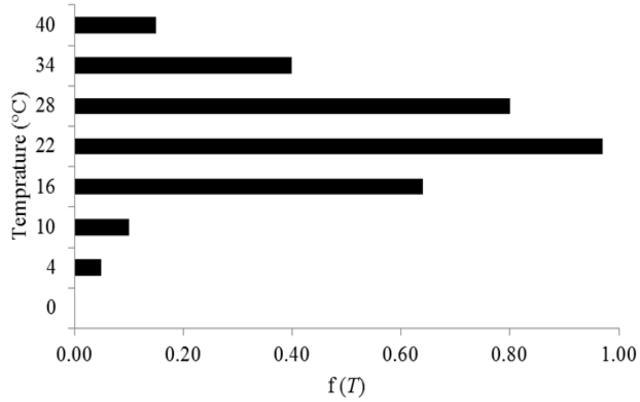


**Fig 3:** f (*T*) values for different temperatures base on the Beta model.

## CONCLUSION

The results of this study showed that the response of lentil emergence to temperature was best explained by a beta function. Cardinal temperatures for emergence were estimated as 4.5 °C for base, 22.9 °C for optimum and 40 °C for ceiling temperature. There was no significant difference between cultivars for cardinal temperatures. Physiological day's requirement for lentil emergence was 6 days. Increased time to emergence resulted in decreased emergence percentage probably due to increased opportunity for seed and seedling disease attack. These kinds of information may be used by producers, researchers, and extension personnel to make informed sowing date decisions with respect to long time climatic and edaphic information.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of Gorgan University of Agricultural Science and Natural Resources, Pardis No 2, Gorgan, Golestan, Iran.

## REFERENCES

Bare, C.E., Tooke, V.K. and Gentner, W.A. (1978). Temperature and light effects on germination of Papaver bracteatum, P. orientale and P. somniferum L. *Planta Med*. **34:** 135–143.

Bradford, K.J. (2002). Applications of hydrothermal time to quantifying and modeling seed germination and dormancy, *Weed Sci*. **50:** 248–260.

Bradford, K.J. (1995). Water relations in seed germination. In Seed Development and Germination, [J. Kigel and G. Galili, eds] Marcel Dekker, New York: pp. 351-396.

Brown, R.F. and Mayer, D.G. (1988). Representing cumulative germination: 2. The use of the Weibull function and other empirically derived curves, *Ann. Bot*. **61:** 127–138.

Burnham, K.P. and Anderson D.R. (2002). Model selection and multimodel inference: a practical information–theoretic approach, Springer-Verlag, New York.

Ellis, R.H. and Barrett, S. (1994). Alternating temperatures and rate of seed germination in lentil. *Ann. Bot.* **74:** 519–524.

Ellis, R.H., Covell, S., Roberts, E.H. and Summerfield, R.J. (1986). The influence of temperature on seed germination rate in grain legumes: II. Intraspecific variation in chickpea (*Cicer arietinum* L.) at constant temperatures, *J. Exp. Bot*. **37:** 1503–1515.

Forcella, F., Benech Arnold, R.L., Sanchez, R. and Ghersa, C.M. (2000). Modeling seedling emergence, *Field Crops Res*. **67:** 123–139.

Fry, K.E. (1983). Heat-unit calculations in cotton crop and insect models, United States Department of Agriculture, Oakland, California.

Jame, Y.W.and Cutforth, H.W. (2004). Simulating the effect of temperature and sowing depth on germination and emergence of spring wheat. *Agric. For. Meteorol*. **124:** 207–218.

Kamkar, B., Jami Al-Alahmadi, M., Mahdavi-Damghani, A. and Villalobos, F.J. (2012). Quantification of the cardinal temperatures and thermal time requirement of opium poppy (*Papaver somniferum* L.) seeds to germinate using non-linear regression models, *Ind. Crops Prod*. **35:** 192–198.

Kamkar, B., Ahmadi, M., Soltani, A. and Zeinali, E. (2008). Evaluating non-linear regression models to describe response of wheat emergence rate to temperature, *Seed Sci. Biotechnol*. **2:** 53–57.

Mwale, S.S., Azam-Ali, S.N., Clark, J.A., Bradley, R.G. and Chatha, M.R. (1994). Effect of temperature on germination of sunflower. *Seed Sci. Technol.* **22:** 565–571.

O'Meara, J.M., Burles, S., Prochaska, J.X. Prochter, G.E. Bernstein, R.A. and Burgess, K.M. (2006). The deuterium-to-hydrogen abundance ratio toward the QSO SDSS J155810. 16-003120.0, *Astrophys. J*. **649:** 61–65.

Piper, E.L., Boote, K.J., Jones, J.W. and Grimm, S.S. (1996). Comparison of two phenology models for predicting flowering and maturity date of soybean. *Crop Sci*. **36:** 1606–1614.

Rahban, S., Resam, G., Torabi, B. and Yazdi, A.K. (2014). Evaluation of regression models for quantifies germination response to temperature in lenti *(Lens culinaris* Medik). *Crop Eco physiology*, **2:** 229-242. (In Persian)

Ritchie, J.T. (1991). Wheat phasic development. In: Hanks, R.J., Ritchie, J.T., (Eds.,) Modeling Plant, Soil, Systems, Agronomy Monograph, No., 31, pp. 31–54.

Robertson, M.J., Carberry, P.S., Huth, N.I., Turpin, J.E., Probert, M.E., Poulton, P.L., Bell, M., Wright, G.C., Yeates, S.J. and Brinsmead, R.B. (2002). Simulation of growth and development of diverse legume species in APSIM. *Aust. J. Agric. Res.* **53:** 429–446.

Roman, E.S., Murphy, S.D. and Swanton, C.J. (2000). Simulation of *Chenopodium album* seedling emergence, *Weed Sci*. **48:** 217–224.

Shafii, B. and Price, W.J. (2001). Estimation of cardinal temperatures in germination data analysis, *J. Agric. Biol. Environ. Stat*. **6:** 356–366.

Soltani, A., Robertson, M.J., Torabi, B., Yousefi-Daz, M. and Sarparast, R. (2006). Modelling seedling emergence in chickpea as influenced by temperature and sowing depth. *Agric. For. Meteorol*. **138:** 156–167.

Soltani, A., Galeshi, S., Zeinali, E. and Latifi, N. (2002). Germination, seed reserve utilization and seedling growth of chickpea as affected by salinity and seed size. *Seed Sci. Technol*. **30:** 51–60.

Soltani, A., Zeinali, E., Galeshi, S. and Latifi, N. (2001). Genetic variation for and interrelationships among seed vigor traits in wheat from the Caspian Sea coast of Iran. *Seed Sci. Technol*. **29:** 653–662.

Stapper, M. and Lilley, J.M., Evaluation of simtag and wheat in simulating wheat phenology in Southeastern Australia, Proceedings of the 10th Australian Agronomy Conference, Hobart, 2001 Available at http://www.regional.org.au/au/asa/ 2001/1/d/stapper.htm (accessed August 2012).

Timmermans, B.G.H. , Vos, J., Van Nieuwburg, J., Stomph, T.J. and Van der Putten, P.E.L. (2007). Germination rates of *Solanum sisymbriifolium*: temperature response models, effects of temperature fluctuations and soil water potential, *Seed Sci. Res*. **17:** 221.

Vigil, M.F., Anderson, R.L. and Beard, W.E. (1997). Base temperature and growing dergree hour requirements for emergence of canola. *Crop Sci*. **37:** 844–849.

Wade, L.J., Hammer, G.L. and Davey, M.A. (1993). Response of germination to temperature amongst diverse sorghum hybrids. *Field Crops Res*. **31:** 295–308.

Wang, R. (2005). Modeling seed germination and seedling emergence in Winterfat (Krascheninnikovia lanata (Pursh) A.D.J. Meeuse and Smit): physiological mechanisms and ecological relevance, University of Saskatchewan.