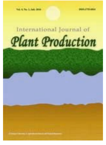

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Seedling emergence response to temperature in safflower: measurements and modeling

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Abstract

Quantitative information about the response of seedling emergence to temperature for safflower (*Carthamus tinctorius* L.) is rare. The main objective of the present study was to develop a model for predicting days to emergence for safflower as influenced by the temperature. In this regard, a field experiment with a range of sowing dates and four safflower cultivars were conducted to describe the response of seedling emergence to temperature and determine cardinal temperatures and biological days required for emergence (number of days to emergence under optimum temperatures). The segmented, dent-like and beta functions were used to describe the response of seedling emergence to temperature. Results showed that the segmented function described well the seedling emergence response to temperature with the cardinal temperatures of 3.4, 22 and 35 °C for base, optimum and ceiling temperatures, respectively. The biological days required for seedling emergence was estimated 8.6 days. Based on the findings, a seedling emergence model was conducted which can estimate time to 50% of emergence under variable temperature conditions. Model evaluation by using the some independent data showed that the model predicted time to 50% of emergence accurately (RMSD=1.3 days and R^2=0.92).

Keywords: Emergence; Model; Safflower; Simulation; Temperature.

Introduction

Safflower (*Carthamus tinctorius* L.) is an oilseed crop and from the Asteraceae (Compositae) family. It is cultivated for its dye, extracted from flowers and high quality oil. Recently, its cultivation has received interest in many countries of the world (Dajue and Mündel, 1996; Ekin, 2005; Dordas and Sioulas, 2008), however, there is a little information for safflower to compared with other common crops. Further research on different aspects of safflower production is needed to support decision making and efficient cultivation of safflower in a variety of production areas. Timely seedling establishment is one of the ways for achieving the high production.

Seedling emergence is one of the important stages of crop's life cycle (Soltani et al., 2006). Timing of emergence is critical for crop-weed competition and also for more efficient pest and fertilizer management. Moreover, time of seedling emergence influences the occurrence of later crop growth and developmental stages (Forcella et al., 2000).

In complex production systems such as crops, prediction of developmental stages, such as seedling emergence, over time by simulation models are important for maximizing cropping system efficiency (Soltani and Sinclair, 2012). There are many environmental factors, affecting the time of seedling emergence under field conditions, such as temperature and soil moisture (Soltani et al., 2006; Torabi et al., 2013; Archontoulis et al., 2014). In cultivation safflower, temperature is usually a dominant factor since the soil moisture is mostly not limiting due to adequate autumn, winter and early spring rainfall or pre-sowing irrigation. Therefore, a seedling emergence model in which the temperature function is included can be predicted seedling emergence time (Soltani et al., 2006).

The response of seedling emergence to temperature is usually described by the linear or nonlinear functions (Soltani et al., 2006; Torabi et al., 2013; Kamkar et al., 2012; Jame and Cutforth, 2004; Adam et al., 2007; Wang et al., 2009; Hardegree, 2006a; Hardegree, 2006b). The most important parameters in these functions are usually base temperature (T_b), optimum temperature (T_o) and ceiling temperature (T_c), so called cardinal temperatures. It is also reported, the point optimum temperature (T_o) would be the range of optimum temperature limited between lower optimum temperature (T_{o1}) and upper optimum temperature (T_{o2}) (Soltani et al., 2006). At the both base and ceiling temperatures, the rate of progress towards emergence is zero (i.e., the time of emergence is infinite), whereas at the optimum temperature or the range of the optimum temperatures the rate of progress towards the emergence is maximal. In these functions, there is an increasing trend between the emergence rate and temperature (T) up to T_o and a decreasing trend above T_o (Covell et al., 1986; Ellis et al., 1986; Hardegree, 2006a; Hardegree, 2006b; Hardegree and Winstral, 2006; Soltani et al., 2006). Knowledge of cardinal temperatures for seedling emergence is useful to screen the tolerance of crops and cultivars to either low or high temperatures, identify the geographical areas where a species or genotype can emergence and establish successfully and develop predictive models of crop growth and yield (Mwale et al., 1994; Soltani et al., 2006).

The objective of the present study is to: a) estimate cardinal temperatures for safflower seedling emergence using three different temperature functions, b) select the superior temperature function for use in the seedling emergence model and c) evaluate the predictive ability of seedling emergence model against the independent datasets.

Materials and Methods

Field experiment

A field experiment with a series of sowing dates was conducted at the Vali-e-Asr University of Rafsanjan, Rafsanjan (latitude 30.23 °N, longitude 56 °E and 1469 m asl), Iran. Four safflower cultivars (Goldasht, Sofeh, Esfahan and Padideh) were sown at 12 different sowing dates included 21 December 2012 and 20 January, 16 February, 18 March, 17 April, 18 May, 18 June, 20 July, 21 August, 24 September, 23 October and 22 November 2013. The seeds did not emerge in 18 June and 20 July 2013. Emergence percentage was less than 50% for Goldasht and Esfahan cultivars in 18 May and 24 September sowing dates as well as Sofeh cultivar in 24 September sowing date. Therefore, data of these sowing dates did not used to describe response of emergence rate versus temperature. The sowing dates were selected to create a wide range of temperatures to seedling emergence.

The seeds were obtained from the Agricultural Research Center of Fars Province (29° 36′ N, 52° 32′ E and 1486 m asl; Goldasht and Padideh cultivars) and Esfahan Province (32° 38′ N, 51° 39′ E and 1570 m asl; Esfahan and Sofeh cultivars). The results of soil analysis in the depth of 0-0.3 m were: loam soil texture, electrical conductivity 4.0 dS m^{-1}, pH 7.3, organic carbon 0.22%, total nitrogen 0.03%, available P 2.61 mg kg^{-1} and available K 292.6 mg kg^{-1}.

The experiment was conducted as single split plot with sowing dates in the main plot and cultivars in the sub plot. Seeds were sown with density of 40 plants m^{-2} and a depth of 5 cm with row spacing of 50 cm. The plots were irrigated after 70 mm cumulative evaporation from standard evaporation pan class A and irrigation amount was based on soil moisture depletion. There was no effect of flooding or water deficit stress. The number of emerged seedlings was recorded daily from a 1 m row length located in the centre of each plot.

Emergence percentage was obtained by dividing number of emerged seedlings at any time by the total sown seeds, multiplied 100. Estimates of the time taken to 50% cumulative emergence (D_{50}) in each replicate of each treatment were obtained by interpolation from the curve of emergence progress (%) versus time (days) (Figure 1). Relative emergence rate was then calculated by dividing emergence rate (inverse of time taken to reach 50% emergence) to maximum emergence rate (emergence rate obtained at the optimum temperature). The average of temperature for time to 50% emergence was calculated by using daily maximum and minimum temperatures measured at a standard weather station near the experimental farm. Emergence rate (R_{50}, d^{-1}) was then calculated as follows (Soltani et al., 2013):

$$R_{50} = 1/D_{50} \tag{1}$$

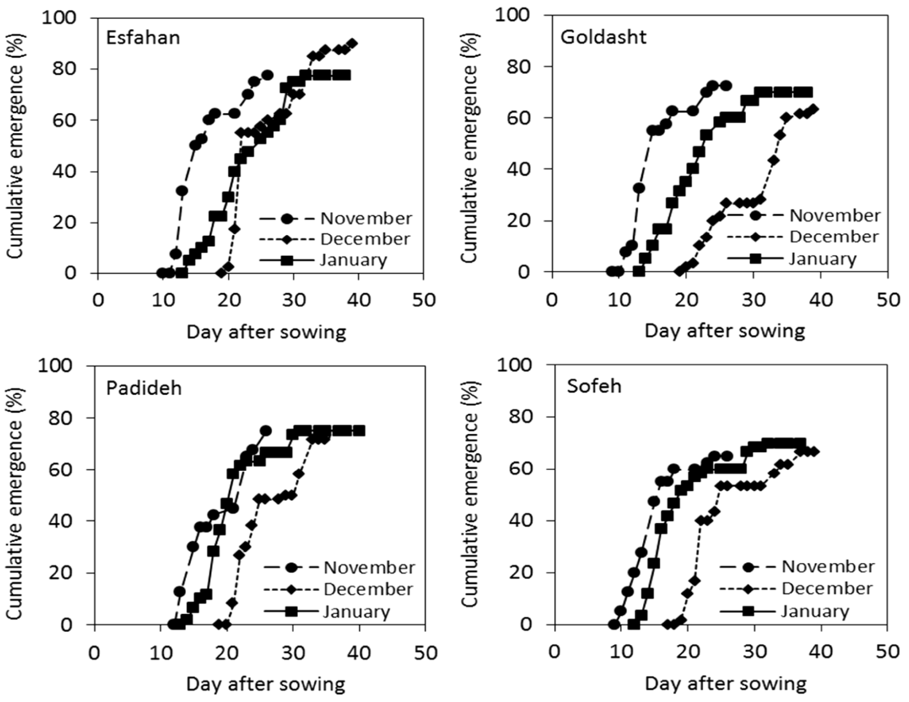

Figure 1. Example of cumulative emergence versus time (days) for two safflower cultivars in three sowing dates.

Analysis

Data from the field experiments were first subjected to analysis of variance and means of treatments were compared using least significant difference (LSD) at 5% level of probability. The seedling emergence model that includes only temperature effect on emergence rate is given by the following model (Soltani et al., 2006; Torabi et al., 2013):

$$R_{50} = f(T) / e_o \qquad (2)$$

where R_{50} is the emergence rate (1/d) for 50% emergence, $f(T)$ is a temperature function which is between 0 and 1 and e_o is the biological days requirement for achieving 50% emergence. The e_o indicates minimum number of days for 50% emergence at optimal temperature and $1/e_o$ is, thus, the maximum emergence rate (R_{max}). The used three temperature functions are described below (Figure 2; Soltani et al., 2006; Torabi et al., 2013):
Segmented function:

$$f(T) = \frac{(T - T_b)}{(T_o - T_b)} \qquad if \qquad T_b < T <= T_o \qquad (3)$$

$$f(T) = \frac{(T_c - T)}{(T_c - T_o)} \qquad if \qquad T_o < T < T_c$$

$$f(T) = 0 \qquad if \qquad T <= T_b \ or \ T => T_c$$

Beta function:

$$f(T) = \left[\left(\frac{T - T_b}{T_o - T_b} \times \frac{T_c - T}{T_c - T_b} \right)^{\left(\frac{T_c - T_o}{T_o - T_b} \right)} \right] \qquad if \qquad T > T_b \ and \ T < T_c \qquad (4)$$

$$f(T) = 0 \qquad if \qquad T <= T_b \ or \ T => T_c$$

Dent-like function:

$$f(T) = \frac{(T - T_b)}{(T_{o1} - T_b)} \qquad if \qquad T_b < T < T_{o1} \tag{5}$$

$$f(T) = \frac{(T_c - T)}{(T_c - T_{o2})} \qquad if \qquad T_{o2} < T < T_c$$

$$f(T) = 1 \qquad if \qquad T_{o1} < T < T_{o2}$$

$$f(T) = 0 \qquad if \qquad T <= T_b \;\; or \; T => T_c$$

where T is the average temperature from sowing to emergence, T_b is the base temperature, T_o is the optimum temperature, T_{o1} is the lower optimum temperature (for dent-like function), T_{o2} is the upper optimum temperature (for dent-like function) and T_c is the ceiling temperature. The parameters were estimated by the least squares method using the non-linear (NLIN) regression (R_{50} as y and T as x) procedure in the Statistical Analysis System (SAS Institute, 2011). T_c was fixed at 35 °C in all functions because of the low frequency of temperature higher than 25 °C. A ceiling temperature of 35 °C represents a biological upper limit for developmental processes in most temperate plants (Eberle et al., 2014). Quadratic, cubic and curvilinear (Hammer et al., 1989) functions were also used to fit the data, but the results are not shown as the beta function encompasses these curve forms. We used some statistics indices to compare the functions performance and then the superior function(s) was chosen. The statistics indices are as following (Archontoulis and Miguez, 2013):

$$\mathrm{R}^2 - \mathrm{adj} = \left(\mathrm{R}^2 - \frac{\mathrm{p}}{\mathrm{n}-1}\right)\left(\frac{\mathrm{n}-1}{\mathrm{n}-\mathrm{p}-1}\right) \tag{6}$$

$$\mathrm{RMSD} = \sqrt{\frac{\sum(\mathrm{y_i} - \hat{\mathrm{y}}_\mathrm{i})^2}{\mathrm{n}}} \tag{7}$$

$$\mathrm{ME} = 1 - \frac{\sum(\mathrm{y_i} - \hat{\mathrm{y}}_\mathrm{i})^2}{\sum(\mathrm{y_i} - \overline{\mathrm{y}})^2} \tag{8}$$

where R^2-adj, RMSD and ME are adjusted determination coefficient, root mean square of deviations and model (function) efficiency, respectively. R^2 is the determination coefficient, p is the number of function parameter, n is total observation, y_i and $\hat{y}$ are the observed and predicted emergence rates, respectively; and $\bar{y}$ is the mean observed value. Additionally, we used the linear regression coefficients (*a* and *b*) and correlation coefficient (r) between observed and predicted days to emergence (Soltani et al., 2006).

To insure the accuracy of estimated cardinal temperatures by the superior function, the thermal time (*TT*) required for emergence of each cultivar, at each sowing date, was calculated as follows:

$$TT = \sum \{(T_o - T_b).f(T)\} \tag{9}$$

The stability of calculated thermal time over the different sowing dates shows reliable cardinal temperatures estimation.

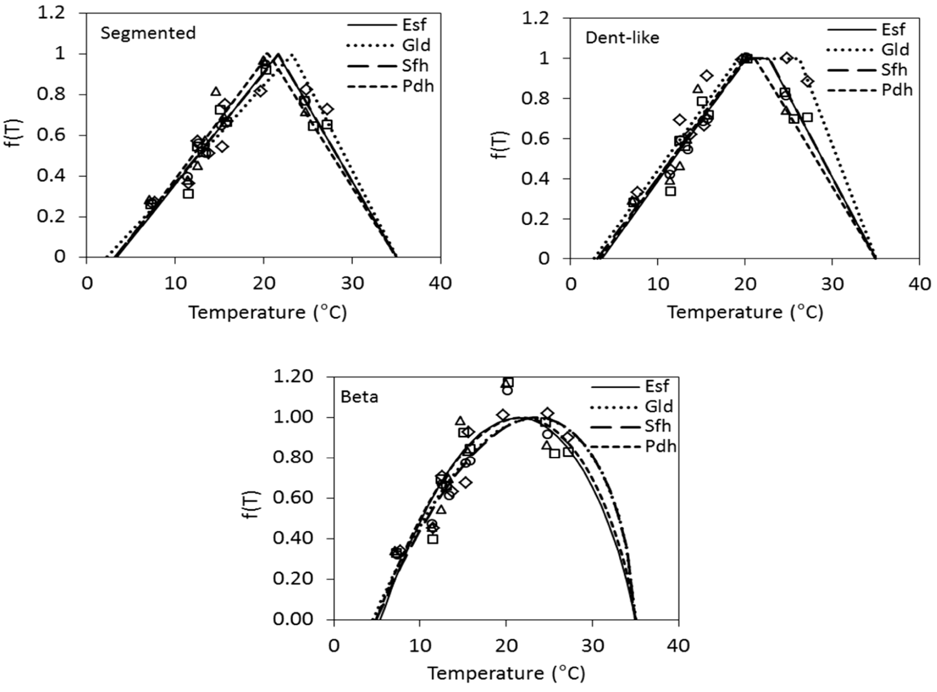

Figure 2. Functions used to describe the response of emergence rate to temperature for different safflower cultivars: Signs are Esfahan (Esf), Goldasht (Gld), Sofeh (Sfh) and Padideh (Pdh).

Results and Discussion

Temperature variation during the experiment

Temperature status during the field experiment is indicated in Figure 3. In during the field experiment, temperatures varied between 2.4 and 42.2 °C for maximum temperature and between -8.2 and 30.4 °C for minimum temperature.

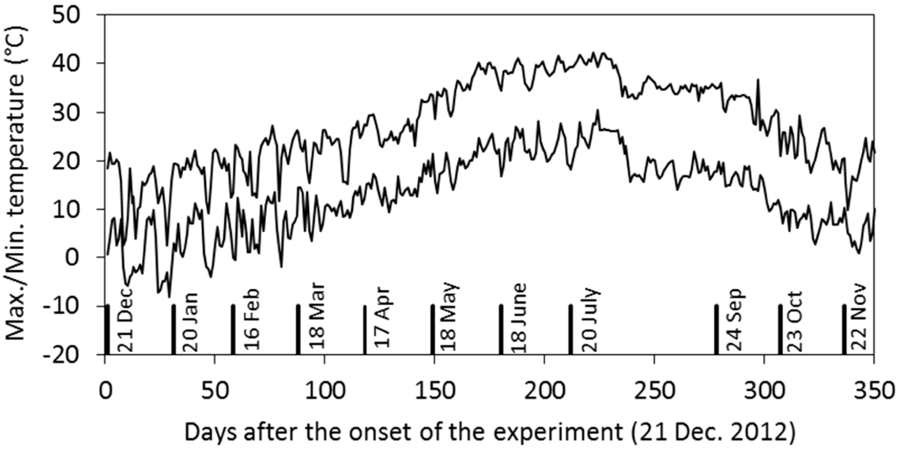

Figure 3. Minimum and maximum temperatures during the field experiment at Rafsanjan, Iran. Short vertical lines indicate the sowing dates.

Emergence percentage variation

Analysis of variance showed a significant effect of sowing date, cultivar and their interaction for emergence percentage (Pr<0.001). Emergence percentage ranged from 49.4 to 92.5% for Esfahan, 34.6 to 70.6% for Goldasht, 38.7 to 84.6% for Padideh and 23.3 to 70.6% for Sofeh (Table 1). For all cultivars, differences in final emergence percentage among the sowing dates were related to variation in temperatures, a small correlation but significant (r= -0.24; P=0.01), so that the emergence percentage was low in the high temperatures (20-27 °C; Table 1). In addition, change in seeds viability and vigor under sub and supra-optimal temperatures would probably decrease the emergence percentage (Tekrony, 2003; Berti and Johnson, 2008). However, in addition to the above-mentioned, the birds attack to planted seeds in late spring and over the summer decreased largely the final emergence percentage.

Table 1. Mean temperature during emergence (Tmean) and final emergence percentage (FEP) of different safflower cultivars for different sowing dates in the field experiment.

Sowing date	T_{mean}	FEP (Esfahan)	FEP (Goldasht)	FEP (Padideh)	FEP (Sofeh)
21 Dec 2012	7.4	91.2^{a}	50.8^{cde}	70.4^{ab}	63.3^{ab}
20 Jan 2013	11.4	73.7^{bc}	60.4^{abcd}	68.3^{ab}	57.1^{b}
16 Feb 2013	13.4	92.5^{a}	61.7^{abc}	84.6^{a}	62.1^{ab}
18 Mar 2013	15.2	90.0^{a}	64.2^{ab}	79.6^{a}	70.4^{a}
17 Apr 2013	20.0	86.9^{ab}	47.5^{def}	67.9^{ab}	52.5^{bc}
18 May 2013	25.6	49.4^{d}	34.6^{f}	44.2^{c}	23.3^{d}
21 Aug 2013	27.2	69.2^{c}	51.7^{bcde}	38.7^{c}	34.2^{de}
24 Sep 2013	24.7	73.1^{c}	46.9^{ef}	51.2^{c}	41.9^{cd}
23 Oct 2013	15.6	71.9^{c}	50.0^{cde}	68.1^{ab}	70.6^{a}
22 Nov 2013	12.6	73.7^{bc}	70.6^{a}	65.0^{b}	57.5^{ab}

In each column, means followed at least by a similar letter do not significantly differ.

Emergence duration variation

Results showed a significant and negative correlation between days to emergence and temperature (r= -0.72; P<0.01). For Padideh, the minimum time required for 50% emergence was 12 days obtained in temperatures of 19 and 24 °C. The minimum time required for 50% emergence obtained 3 days earlier for other cultivars and it occurred in temperature of 20 °C. Results showed that the time required for 50% emergence increased in the low temperatures so that it lasted 33-35 days in temperatures of 7 °C (Figure 4). Increase in time required for emergence at the non-optimal temperatures is probably due to slowing down of biological processes (Kamaha and Maguire, 1992). Soltani et al. (2006) showed that duration from sowing to emergence increased as temperatures were away from optimal condition. Results of other crops such as pea (Olivier and Annandale, 1998), *Vigna subterranea* (Kocabas et al., 1999) and opium poppy (Kamkar et al., 2012) confirm this general trend of time required for emergence versus different temperatures. The response to temperature of time taken to D_{50} followed by the ‘U’ shaped curve that is typical of temperature response of many developmental responses (Olivier and Annandale, 1998).

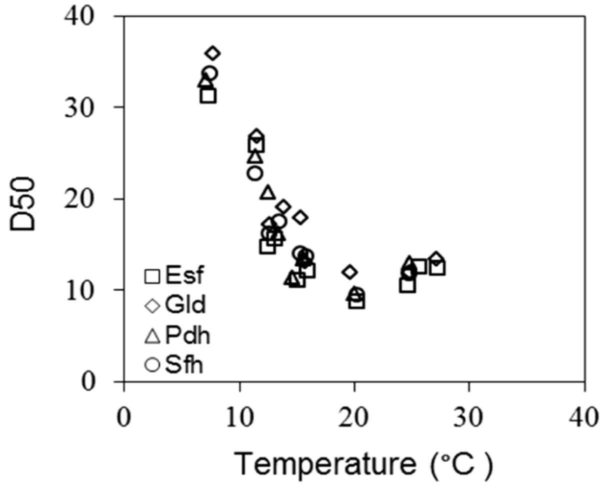

Figure 4. Response of time required for 50% emergence (D_{50}) in different temperatures for safflower cultivars included Esfahan (Esf), Goldasht (Gld), Padideh (Pdh) and Sofeh (Sfh).

Modeling emergence rate

Fit of segmented, dent-like and beta functions on the emergence rate data versus temperature is presented in Figure 2. The Adj-R^2 values for the relationship between emergence rate and temperature in the all cultivars were high in the segmented and dent-like functions (adj-R^2>0.81) compared with the beta function (Table 2). Predicted and observed days to emergence for the all cultivars are showing in the Figure 5. Predictions based on the functions had no significant bias with the *a* and *b* coefficients of 1:1 line (*a*=0 and *b*=1) based on the 95% confidence interval (Table 2). The beta function performance was not appropriate in the long emergence time courses (Figure 5). The correlation coefficient between predicted and observed days to emergence was high for the all cultivars in the segmented and dent-like functions (r>0.90), except for Esfahan and Padideh cultivars in the beta function ($r<0.85$). Root mean squares of deviations (RMSD) ranged from 2 to 4 days for the segmented and dent-like functions and from 3 to 6 days for the beta function (Table 2). The value of RMSD for Esfahan and Padideh cultivar in the beta function was higher than two other cultivars. The value of function efficiency (FE) for the segmented and dent-like function was higher compared to the beta function (Table 2). In general, due to lower RMSD and higher adj-R^2, r and FE for the segmented and dent-like function, these functions were appropriate to describe the emergence rate response to temperature. However, the dent-like function was not appropriated to fit our data due to the narrow range of the optimum temperatures (T_{o1}-T_{o2}), except for Goldasht cultivar and it was not suitable to fit easily on the data of Sofeh cultivar and the overall data. Finally, the segmented function was chosen to describe the emergence rate response to the temperature.

Table 2. Adjusted R^2 for the relationship between emergence rate (R_{50}; Eqs. (1)) and temperature in four safflower cultivars described by various functions. Regression coefficients (a and b), correlation coefficient (r), root mean square of deviations (RMSD), and model efficiency (ME) for the relationship between observed and predicted days to emergence are also indicated.

Function-Cultivar	R^2-Adj	a	b	r	RMSD	ME
Segmented						
Esfahan	0.85	-0.38 ± 2.844	1.03 ± 0.168	0.90	3.3	0.77
Goldasht	0.81	0.63 ± 2.283	0.96 ± 0.113	0.95	2.3	0.91
Padideh	0.79	-3.09 ± 3.984	1.19 ± 0.207	0.92	4.1	0.70
Sofeh	0.95	-2.56 ± 1.891	1.16 ± 0.100	0.97	2.2	0.91
Dent-like						
Esfahan	0.85	-0.63 ± 2.931	1.05 ± 0.173	0.90	3.4	0.76
Goldasht	0.83	-0.18 ± 2.411	1.00 ± 0.119	0.95	2.5	0.90
Padideh	0.79	-3.18 ± 4.021	1.20 ± 0.209	0.92	4.2	0.68
Sofeh	0.95	-2.55 ± 1.895	1.17 ± 0.100	0.97	2.2	0.91
Beta						
Esfahan	0.72	-4.06 ± 4.650	1.30 ± 0.274	0.85	5.8	0.29
Goldasht	0.79	-2.16 ± 3.280	1.12 ± 0.163	0.93	3.4	0.80
Padideh	0.58	-5.68 ± 5.808	1.36 ± 0.302	0.87	6.2	0.30
Sofeh	0.79	-4.06 ± 2.842	1.26 ± 0.151	0.95	3.3	0.79

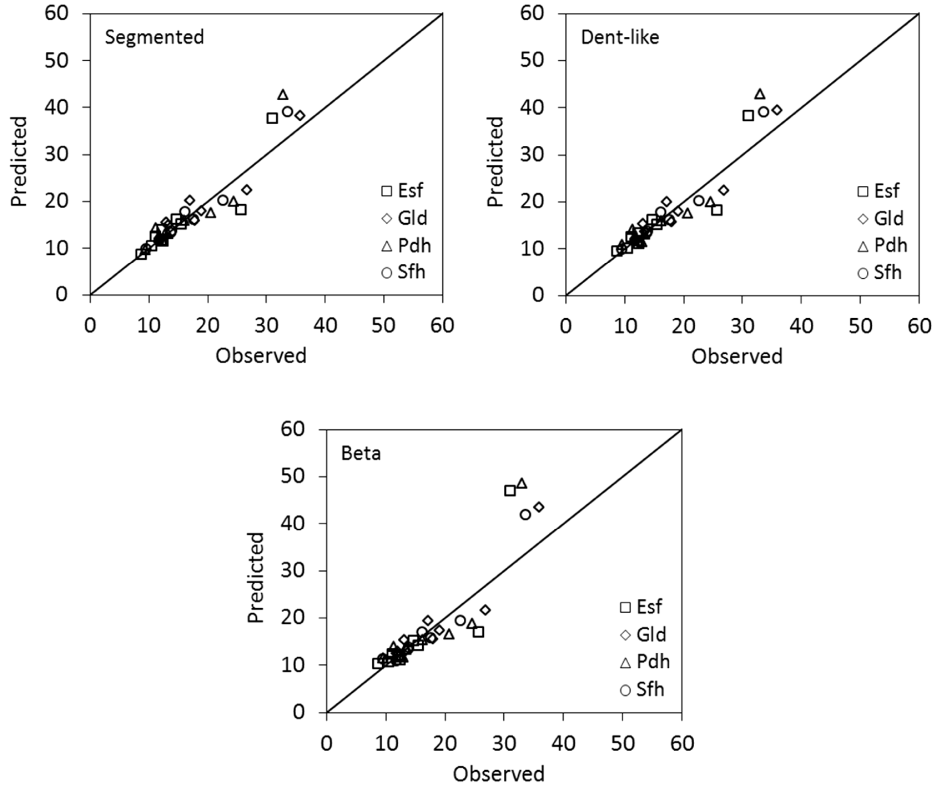

Figure 5. Predicted vs. observed days to emergence in for safflower cultivars included Esfahan (Esf), Goldasht (Gld), Padideh (Pdh) and Sofeh (Sfh) using the segmented, dent-like and beta functions. The solid line is a 1:1 line.

This is in consistent with findings of other researches in which the segmented function adequately described the response of developmental stages in different crops (Olsen et al., 1993; Mwale et al., 1994; Robertson et al., 2002; Covell et al., 1986; Ellis et al., 1986; Ghaderi-Far et al., 2012; Kamkar et al., 2012). Torabi et al. (2013) showed that compared to the dent-like and beta functions, the segmented function described well germination rate response to temperature in different safflower cultivars. However, the other functions such as dent-like and beta have been used to describe the development rate response to temperature (Soltani et al., 2006; Hardegree and Winstral, 2006; Wang et al., 2009).

Estimates of cardinal temperatures and biological day requirements for emergence are given in Table 3. Estimates of the cardinal temperatures based on the segmented function were 2.3-3.4 °C for base temperature and 20.6-23.3 °C for optimal temperature across the all cultivars. The ceiling temperature was fixed in 35 °C for all cultivars. Estimates of biological days (e_o) required to emergence were 8.0-9.8 days across the all cultivars. The dent-like function estimated the base temperature of 2.6-3.6 °C, the lower optimum temperature of 19.2-20.2 °C and the upper optimum temperature of 21.6-26.2 °C. The value of e_0 ranged from 8.7-11.9 days. The estimates of base temperatures for the segmented and dent-like functions were nearly similar. The optimum temperatures in the segmented function were located in the range of the optimum temperatures estimated by the dent-like function. In the beta function, the base temperature ranged from 4.6 to 5.4 °C for the cultivars which was partly higher than that in the segmented function. The optimum temperature estimated by the beta function for Padideh and Sofeh cultivars were partly higher in compared to those in the segmented function.

In the superior function (segmented function), there was no significant difference between cardinal temperatures and biological day required for emergence of different cultivars based on their 95% confidence interval. Based on all data, therefore, the model parameters were estimated 3.4 °C for the base temperature, 22.0 °C for the optimum temperature, 35.0 °C for ceiling temperature and 8.6 days for the biological day requirement (Table 3).

The base temperature (3.4 °C) obtained in this study was similar to the base temperature reported for most crops (Mwale et al., 1994; Marshall and Squire, 1996; Trudgill et al., 2000; Soltani et al., 2006; Kamkar et al., 2012). Torabi et al. (2013) reported base temperature of 4.5 and 6.9 °C for germination of three safflower cultivars. They found no significant difference among the base temperatures of the three safflower cultivars. Oliver and Annandale (1998) reported a base temperature of 3 °C for seedling emergence of pea which was in agreement with our findings. They did not report the variation in the base temperature among the different cultivars. Conversely, Mwale et al. (1994) reported variations in base temperature among different species of sunflower (*Helianthus annuus* L.).

The optimum temperature estimated for seedling emergence of safflower in here was 22 °C, which disagrees with the findings reported by Torabi et al. (2013) on germination of different safflower cultivars. Soltani et al. (2006) reported a range of optimum temperature of 20-30.5 °C for chickpea cultivars. However, the optimum temperatures obtained in the present study were in agreement with the optimum temperature of two cultivars of *Allium ampeloprasum* L. (Ramin, 1997). In respect to the estimated cardinal temperatures, it seems that safflower is a winter-spring annual oilseed crop that may be cultivated under a wide range of environments.

Using the estimated cardinal temperatures by the segmented function, the thermal time required for emergence of each cultivar, at each sowing date, was calculated by the Eq. 9. The mean thermal time for emergence across the sowing dates was 138 °C d^{-1} for Esfahan, 198 °C d^{-1} for Goldasht, 157 °C d^{-1} for Padideh and 168 °C d^{-1} for Sofeh (Table 4). However, the calculated thermal time for seedling emergence of different cultivars in here is similar with that for wheat (173 °C d^{-1}), peanut (150 °C d^{-1}) and chickpea (214 °C d^{-1}) (Soltani and Sinclair, 2012). There was small variation (CV; coefficient of variation) in thermal time across the sowing dates. Values of CV were 5.5% for Esfahan, 6.9% for Goldasht, 6.1% for Padideh and 8.6% for Sofeh (Table 4). In respect to the low variation in the thermal time across the sowing dates, it was concluded that cardinal temperatures estimated by the segmented function are reliable.

Based on the present findings a numerical seedling emergence model for safflower was constructed. To predict of days to emergence of safflower, the model needs a sowing date and weather data (daily data of maximum and minimum temperatures) as input. The model calculated the value of f (T) based on the segmented function Eq. (3) for each day after sowing. The emergence occurs when $\sum f(T) = e_o$. The model uses maximum and minimum air temperature in weather file to calculate daily $f(T)$.

Table 3. Estimates of base temperature (T_b, °C), optimum temperature (T_o, °C), lower optimum temperature (T_{o1}, °C), upper optimum temperature (T_{o2}, °C) and minimum biological day requirement (e_o), for emergence of four safflower cultivars using segmented, dent-like and beta functions. Ceiling temperature was fixed at 35 °C.

Function-Cultivar	T_b	T_o		T_c	e_o
Segmented					
Esfahan	3.4 (1.45)	21.6 (0.68)		35	8.0 (0.36)
Goldasht	2.3 (2.19)	23.3 (0.86)		35	9.8 (0.61)
Padideh	3.4 (1.81)	20.6 (1.21)		35	9.2 (0.68)
Sofeh	3.1(0.93)	21.7 (0.53)		35	9.0 (0.29)
All data	3.4 (1.28)	22.0 (0.58)		35	8.6 (0.34)
Function-Cultivar	T_b	T_{o1}	T_{o2}	T_c	e_o
Dent-like					
Esfahan	3.6 (1.95)	20.1 (2.16)	22.7 (1.32)	35	8.7 (0.74)
Goldasht	2.6 (2.69)	19.2 (2.04)	26.2 (1.14)	35	11.9 (0.82)
Padideh	3.4 (2.50)	19.9 (2.81)	21.1 (2.57)	35	9.6 (1.05)
Sofeh	3.1 (1.34)	20.2 (1.41)	22.8 (1.02)	35	9.9 (0.53)
All data	3.4 (1.28)	20.2 (0.87)	23.2 (0.59)	35	9.6 (0.48)
Function-Cultivar	T_b	T_o		T_c	e_o
Beta					
Esfahan	5.4 (1.38)	21.4 (1.23)		35	10.2 (0.58)
Goldasht	4.6 (1.68)	23.5 (1.66)		35	12.1 (0.65)
Padideh	4.9 (2.10)	21.8 (2.85)		35	11.1 (1.11)
Sofeh	4.6 (1.75)	23.6 (2.54)		35	10.8 (0.85)
All data	4.7 (1.35)	22.3 (0.74)		35	10.5 (0.50)

Table 4. Range of variation, mean, coefficient of variation (CV) and standard error (SE) for thermal time requirement for emergence of safflower cultivars across different sowing dates using the Eq. 9.

Cultivar	Range	Mean	CV	SE
Esfahan	104-202	139	5.5	1.59
Goldasht	152-240	200	6.9	1.78
Padideh	132-202	160	6.1	1.80
Sofeh	142-198	168	8.6	1.56

Table 5. Independent experiments from Iran to evaluation the model performance.

Location	Year	Treatments	Reference
Esfahan	2000	Sowing date, cultivar	Dadashi&Khajehpour (2004)
Esfahan	2003	Sowing date, cultivar	Heidarizadeh&Khajehpour (2008)
Esfahan	2003	Sowing date, cultivar	Heidarizadeh et al. (2008)
Kaboutar-Abad	2009	Sowing date	Khoshhal et al. (2010)
Rafsanjan	2012	Sowing date, plant density	Dastfali-Nejad (2013)

Model evaluation

The model was evaluated using independent dataset of days to emergence in field experiments carried out in Esfahan, Kaboutar-Abad and Rafsanjan, Iran (Table 5). The experiments were mainly carried out in the spring, but there were some winter sowing dates. Simulated days to emergence varied from 8 to 19 and measured days to emergence from 6 to 18 (Figure 6). The model predicted well days to emergence for different sowing dates with RMSD of 1.3 days, which was 12.3% of the measured mean of days to emergence. The model accounted for 92% of the variation in days to emergence without significant bias from slope (*b*=1) and intercept (*a*=0) of 1:1 line. However, there was a small under and over-prediction for some observed days to emergence. This may be due to the fact that a sowing depth of 5 cm was assumed for simulations where sowing depth had not been reported. In general, the model performance is acceptable. Therefore, the model can be useful in identifying geographical areas where safflower can emergence and establish successfully and in developing predictive models of crop growth and yield (Soltani et al., 2006; Torabi et al., 2013).

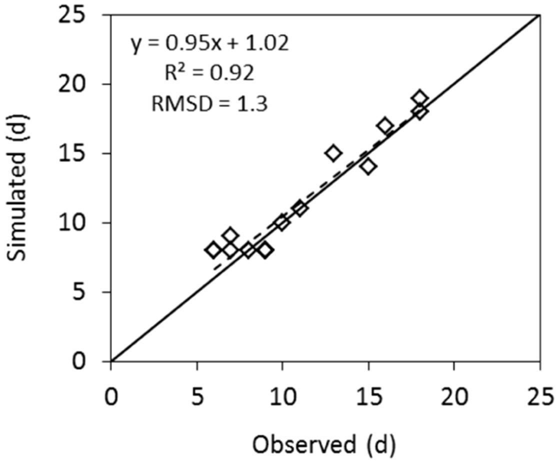

Figure 6. Predicted vs. observed days to emergence for safflower under the different sowing dates using the independent datasets. The solid line is a 1:1 line and the dash line is the regression line.

Conclusion

The findings of the present study indicated that the final emergence percentage was decreased in the high temperatures. The response of safflower emergence rate to temperature was the best described by a segmented function. There was no significant difference across the cultivars in terms of cardinal temperatures. Cardinal temperatures for emergence were estimated 3.4 °C for base temperature, 22 °C for optimum temperature and 35 °C for ceiling temperature. The biological day requirement for emergence was estimated 8.6 days. Based on these findings, a seedling emergence model was conducted to predict the days to emergence that was successful.

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