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Quantification of Critical Temperature Thresholds and Thermal Time Required for Seedling Emergence of Spring Rapeseed

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ABSTRACT

Quantitative knowledge about temperature T effect on seedling emergence in spring rapeseed (*Brassica napus* L.) is rare. Therefore, the main purpose of the present study was to determine the critical T thresholds and thermal time required for seedling emergence of spring rapeseed. To do this, two field trials, each with 15 different planting dates, were performed to evaluate the seedling emergence responses of five spring rapeseed cultivars to a wide range of T environments. A Normal-based thermal time model was used to describe the relationship between time-to-emergence and T. In this model, a Normal distribution of both sub-optimal thermal time $\theta_{T(e)}$ and maximum temperature $T_{m(e)}$ was assumed while base temperature T_b and supra-optimal thermal time θ_{T_m} remained constant for all emergence fractions. The model correctly explained the emergence dynamics of various cultivars in response to T over sub- and supra-optimal ranges. The thermal thresholds for seedling emergence, T_b, sub-optimal thermal time to reach 50% emergence ($\theta_{T(50)}$), maximum emergence T for induction of 50% thermoinhibition in seeds ($T_{m(50)}$), and θ_{T_m} depended on the rapeseed cultivar studied. The values of T_b, $\theta_{T(50)}$, $T_{m(50)}$ and θ_{T_m} ranged from 3.90 to 5.94 °C, 71.44 to 76.67 °C d, 32.90 to 33.48 °C and 4.76 to 6.67 °C d, respectively. Within each cultivar, optimum T ($T_{o(e)}$) exhibited a slight variation among various emergence fractions. The value of $T_{o(50)}$ varied between 30.96 and 31.22 °C, depending on the cultivar. The outputs obtained from this work may be readily used in crop simulation models.

Keywords: Emergence rate; Modeling; Normal distribution; Temperature response; Time to emergence

INTRODUCTION

Seedling emergence is one of the most sensitive stages of the life cycle of plants, which affects their growth, development, and productivity (Forcella *et al*., 2000). Fast and uniform emergence of vigorous seedlings in the field can increase grain yields by reducing the time from planting to completing the groundcover and establishing the optimal canopy structure

(Derakhshan *et al*., 2014). The accuracy of predicting the timing of emergence in the field is also critical for the performance of growth simulation models (Bakhshandeh *et al*., 2017).

Some of the environmental inputs used in emergence models include soil (or air) temperature (T), moisture, texture, and compaction, and burial depth (Karimzadeh Soureshjani *et al*., 2019). Soil T and moisture are the most crucial variables in emergence modeling due to their high predictive power (Forcella *et al*., 2000). Thermal time units can be applied directly to predict the seedling emergence in the field because the seeds of the crop varieties are genetically homogeneous and are generally planted directly into moistened soil at a precise depth. The response of seedling emergence to T can be modeled based on the rate of seedling emergence and defined by three critical T thresholds: the base (T_b), optimum (T_o), and maximum (T_m) (Derakhshan *et al*., 2018). The T_b and T_m are the temperatures below or above which the seedling emergence will not occur, whereas the T_o is that at which seedling emergence is most rapid (Derakhshan *et al*., 2014).

Based on the thermal time approach, the rate of emergence for any given percentile (R_e) is often a linear function of T in the range between T_b and T_o (Derakhshan et al., 2014). This concept can be expressed in the form of the thermal time model as (Bradford, 2002):

$$\theta_{T(e)} = (T - T_b)t_e \tag{1}$$

or

$$R_e = 1/t_e = \left(T - T_b\right)/\theta_{T(e)} \tag{2}$$

where $\theta_{T(e)}$ is the thermal time to emergence of percentile *e* of the population, T is the average soil (or air) temperature from planting to completion of emergence, and t_e is the time to emergence of a specific percentile *e*. According to these equations, the time to completion of seedling emergence is a fixed value for each given percentile at the T range between T_b and T_o if expressed on a thermal time basis (Bradford, 2002). In the T range between T_o and T_m, the rate of seedling emergence declines almost linearly until complete emergence inhibition (Derakhshan *et al*., 2018). It is frequently observed that individual seeds in the population differ in their maximum temperatures (Bradford, 2002). This concept can be explained using the following model (Bradford, 2002):

$$\theta_{T_m} = (T_{m(e)} - T)t_e \tag{3}$$

or

$$R_e = 1/t_e = (T_{m(e)} - T)/\theta_{T_m} \tag{4}$$

where θ_{T_m} is the supra-optimal thermal time to complete seedling emergence, and $T_{m(e)}$ indicates that the values of maximum T differ amongst individual seeds. According to the above equations, the slope of decreases in R_e ($1/\theta_{T_m}$) with increasing T in the range between T_o and T_m will be identical for all percentiles, consequently, predicted lines intercept the T axis at various T_m values (Bradford, 2002).

Given the absence of quantitative data on spring rapeseed (*Brassica napus* L.) emergence, this study aimed to determine critical T thresholds and thermal time required for seedling emergence in spring rapeseed.

MATERIALS AND METHODS

Field trials

Two field trials with a range of planting dates were undertaken at the experimental site of the Agricultural Sciences and Natural Resources University of Khuzestan, Ahvaz (31°36′N and 48°53′E), Iran. The trials commenced in September 2015 and lasted until June 2017. In each of the two field trials, five spring rapeseed cultivars (Dalgan, Hyola 401, Jerry, RGS003, and Sarigol) were sown at 15 various planting dates. Each planting date was considered as a separate T environment, in which five spring rapeseed cultivars were arranged in a randomized complete block design with four replications. Planting dates of the first field trial were 23 September, 7 October, 23 October, 6 November, 22 November, 6 December, 22 December 2015, and 5 January, 21 January, 4 February, 20 February, 5 March, 3 April, 4 May and 4 June 2016. Planting dates of the second field trial were 22 September, 6 October, 22 October, 5 November, 21 November, 5 December, 21 December 2016, and 4 January, 20 January, 3 February, 19 February, 5 March, 4 April, 5 May and 5 June 2017. These planting dates have been chosen solely for creating various T regimes and evaluating the seedling emergence response of rapeseed cultivars to an extended range of temperatures. Physical properties of soil in the 0–30 cm top layer were: clay 43%, silt 40%, sand 17%, bulk density 1.38 g cm^3, and pH 7.3. The field trials were performed under optimal irrigation conditions so that there was no flooding or water shortage.

The size of each experimental plot was 3 m by 3 m. Seeds were planted at a density of 90 plants m^2 and a depth of 1.5 cm with a row spacing of 25 cm. The number of emerged seedlings per day was counted from two 1 m long rows placed in the center of each experimental plot. The minimum and maximum temperatures were recorded daily at a standard meteorological station a few meters from the experimental plots.

Data Analysis

Seed viability based on the standard germination test was above 95%, and the percentage of seedling emergence in the field varied between 35.3 and 80.0, depending on the cultivar and planting date. For each count-day, the cumulative emergence fraction (between 0 and 1) was calculated for each cultivar and planting date (T environment). The fraction of emerged seedlings for each cultivar at the best planting date (highest emergence percentage) was assumed to be equal to 1, based on this, data from other planting dates were normalized. For each cultivar studied, cumulative emergence fraction was plotted against time. From this curve, the time (t_e) to reach emergence fractions of 0.16 (E16), 0.50 (E50), and 0.84 (E84) were obtained by interpolation.

For each rapeseed cultivar, data were divided into two parts (sub-optimal and supra-optimal T ranges) for nonlinear regression analysis by visual inspection of the scatter plot of emergence rates ($R_e = 1/t_e$) versus T (Hardegree, 2006). The Normal-based thermal time model was fitted to the cumulative emergence data using the PROC NLMIXED procedure of SAS (SAS, 2009). Using Eqs. (2) and (4), and the outputs obtained from fitting the thermal time model to the data, the T_o value was calculated for different emergence fractions (Hardegree, 2006).

Table 1.Parameter estimates for the emergence of five spring rapeseed cultivars using the Normal-based thermal time model (Eqs. (5) and (6)).

Cultivar	Model parameters*						RMSE
	T_b (°C)	$\theta_{T(50)}$ (°C d)	σ_{θ_T} (°C d)	θ_{T_m} (°C d)	$T_{m(50)}$ (°C)	σ_{T_m} (°C)	
Dalgan	5.94 ± 0.04	73.21 ± 0.39	9.00 ± 0.20	5.07 ± 0.19	32.90 ± 0.04	0.41 ± 0.02	0.0632
Hyola 401	5.84 ± 0.03	71.44 ± 0.25	9.19 ± 0.13	5.72 ± 0.15	33.02 ± 0.04	0.48 ± 0.02	0.0514
Jerry	3.90 ± 0.05	76.67 ± 0.38	11.37 ± 0.18	6.67 ± 0.20	33.48 ± 0.05	0.56 ± 0.02	0.0430
RGS003	4.32 ± 0.04	71.73 ± 0.33	10.14 ± 0.16	4.76 ± 0.08	32.98 ± 0.02	0.33 ± 0.01	0.0390
Sarigol	4.15 ± 0.04	74.30 ± 0.30	9.77 ± 0.14	5.66 ± 0.08	33.30 ± 0.05	0.46 ± 0.02	0.0443

* Abbreviations: T_b, base temperature for seedling emergence; $\theta_{T(50)}$, median sub-optimal thermal time to emergence; σ_{θ_T} , standard deviation of $\theta_{T(e)}$ distribution; θ_{T_m}, supra-optimal thermal time to emergence; $T_{m(50)}$, median maximum temperature to inhibit 50% emergence; σ_{T_m} , standard deviation of $T_{m(e)}$ distribution; RMSE , Root Mean Square Error.

Model description

For each cultivar, if the total number of seeds sown in different planting dates (T regimes) is considered as a population, the variable time-to-emergence follows a binomial cumulative distribution function (CDF) within this population due to variation of each seed response to T. Therefore, the time-to-emergence data were simulated based on the CDF of the Normal distribution (Derakhshan *et al.*, 2018).

If a Normal distribution is assumed for both θ_T and T_m while T_b and θ_{T_m} remain fixed for all fractions of the population, the thermal time model for the sub-optimal T range is:

$$p\left(\theta_{T(e)}\right) = \Phi\left[\frac{\left(T - T_b\right)t_e - \theta_{T(50)}}{\sigma_{\theta T}}\right] \qquad (5)$$

where *p* is the fraction of emerged seedlings at a specific θ_T, Φ is the Laplace Integral (CDF of the standard Normal distribution), $\theta_{T(50)}$ is the median thermal time to emergence, and σ_{θ_T} is the standard deviation of the frequency distribution of thermal times ($\theta_{T(e)}$) in the population. The equation for the supra-optimal T range is:

$$p\left(T_{m(e)}\right) = 1 - \left[\Phi\left(\frac{\left(T + \left(\frac{\theta_{T_m}}{t_e}\right)\right) - T_{m(50)}}{\sigma_{T_m}}\right)\right] \qquad (6)$$

where *p* is the fraction of emerged seedlings at a specific T_m, Φ is the Laplace Integral, $T_{m(50)}$ is the median maximum T to inhibit 50% emergence, and σ_{T_m} is the standard deviation of the frequency distribution of maximum temperatures ($T_{m(e)}$) in the population.

RESULTS

The minimum T of the experimental site in the first year varied between -2.0 and 29.5 °C and in the second year ranged from -4.0 to 31.1 °C (Fig. 1). The maximum T ranged from 12.2 to 49.2 °C in the first year and from 10.0 to 51.2 °C in the second year (Fig. 1). During the field trials, the probability of occurrence of daily mean T was 5.04% for temperatures below 10 °C, 38.09% for 10–20 °C, 30.09% for 21–30 °C, and 26.78% for 31–40 °C.

In both years of the field trial, no seedlings emerged from the seeds sown in June. The average air T during the seedling emergence assessment period on the planting dates of 4 June 2016 and 5 June 2017 was 34.17 and 34.22 °C, respectively. The highest number of days to 50% emergence was recorded on 21 January 2016 sowing and varied between 9.84 (cv. RGS003) and 13.17 days (cv. Dalgan) depending on the cultivar. For all cultivars studied, the lowest time to 50% emergence (averaged 2.69 days) was observed on 7 October 2015 (with an average T of 30.86 °C). Therefore, this T was considered as T_o for the rate of seedling emergence and based on that, the data were divided into sub-optimal and supra-optimal T ranges.

The thermal time model (Eqs. (5) and (6)) well explained the emergence behavior of various spring rapeseed cultivars in response to T, so that there was a close match between the observed and predicted values of $\theta_{T(e)}$ and $T_{m(e)}$ (Fig. 2). The RMSE values were estimated to be between 3.90 and 6.32%, depending on the cultivar, which confirms that the model predicted seedling emergence in the field with a small error (Table 1).

The estimated values of T_b for the studied rapeseed cultivars varied from 3.90 (cv. Jerry) to 5.94 °C (cv. Dalgan). The $\theta_{T(50)}$, which represents the sub-optimal thermal time to 50% seedling emergence, varied from 71.44 to 76.67 °C d, depending on the rapeseed cultivar studied. The value of σ_{θ_T} indicated that the spread of θ_T for cv. Jerry (11.37 °C d) was slightly higher than that of cvs. Sarigol and RGS003 (averaged 9.95 °C d), and for these two cultivars, it was slightly greater than that for cvs. Hyola 401 and Dalgan (averaged 9.09 °C d) (Table 1). It is clear that the smaller σ_{θ_T}, the more uniform the emergence of seedlings in the field.

The supra-optimal thermal time to complete seedling emergence (θ_{T_m}) varied from 4.76 °C d in the cv. RGS003 to 6.67 °C d in the cv. Jerry. Above T_o, the parameter $T_{m(50)}$ represents the maximum T at which the probability of seedling emergence is 50%; That is, 50% of the seeds of the population exhibit thermoinhibition. The estimated value of this parameter for cvs. Jerry and Sarigol (averaged 33.39 °C) was significantly higher than that of the other cultivars, which had similar $T_{m(50)}$ values (averaged 32.97 °C). The σ_{T_m} value ranged from 0.33 °C in the cv. RGS003 to 0.56 °C in the cv. Jerry (Table 1). This parameter indicates the spread of $T_{m(e)}$ distribution within the population.

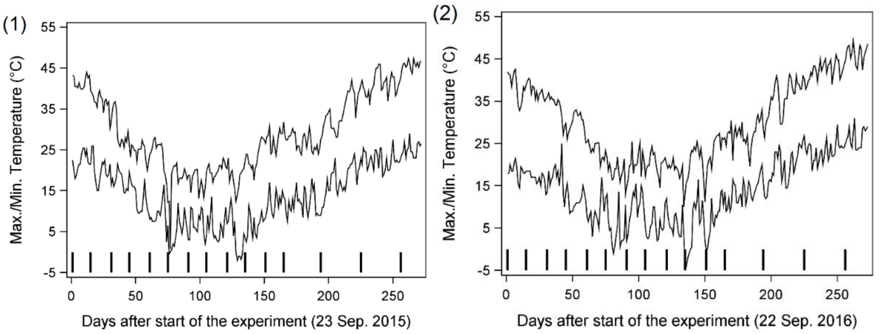

Figure1. Minimum and maximum air temperatures during field trials in 2015-2016 (1) and 2016-2017 (2) at Khuzestan. Short vertical lines indicate planting dates.

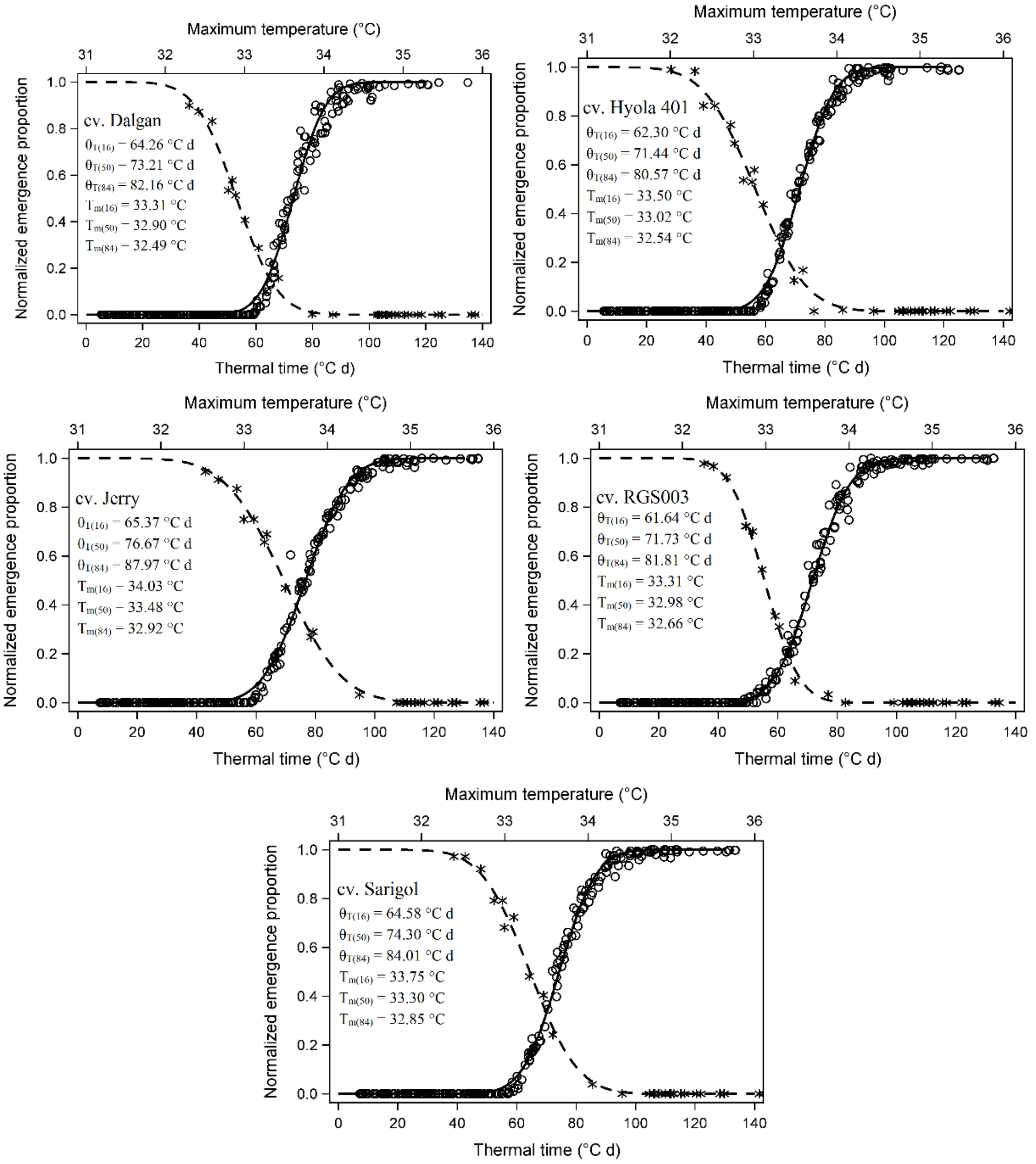

Figure 2. The relationship between normalized emergence and observed (circles) and predicted (line) sub-optimal thermal time for five spring rapeseed cultivars using the Normal distribution. Also shown is the relationship between normalized emergence and observed (asterisk) and predicted (line) maximum temperatures in the supra-optimal temperature range.

Sub-optimal thermal time and maximum temperature for various emergence fractions

The $\theta_{T(e)}$ and $T_{m(e)}$ were predicted based on the inverse cumulative distribution of the Normal distribution. The θ_T for the E16 fraction ranged from 61.64 to 65.37 °C d, according to the cultivar. The θ_T required to achieve the E84 fraction varied from 80.57 °C d in the cv. Hyola 401 to 87.97 °C d in the cv. Jerry (Figure 2). The value of T_m varied from 33.31 to 34.03 °C for the emergence fraction of E16 (84% thermoinhibition in seedling emergence) and from 32.49 to 32.92 °C for the emergence fraction of E84 (16% thermoinhibition in seedling emergence) (Figure 2).

Optimum temperature for various emergence fractions

Depending on the rapeseed cultivar studied, the calculated T_o varied between 31.14 and 31.35 °C for the emergence fraction of E16 ($T_{o(16)}$), between 30.96 and 31.22 °C for the emergence fraction of E50 ($T_{o(50)}$), and between 30.75 and 31.06 °C for the emergence fraction of E84 ($T_{o(84)}$) (Figure 3).

DISCUSSION

The T_b values estimated in this study were close to those estimated for the germination of spring rapeseed cultivars (between 4.86 and 7.10 °C) in the previous research (Derakhshan *et al*., 2018). However, the base T estimated by Andreucci *et al*. (2016) for seed germination of winter cultivars of *B. oleracea* (between 0 and 1 °C), *B. napus* (between 0 and 3 °C) and *B. rapa* (between 2 and 3 °C) are smaller than the range of T_b for seedling emergence found in this study. Genotypic variation for T_b in the present study is in agreement with the findings of Karimzadeh Soureshjani *et al*. (2019) in flax and sesame.

The $T_{m(50)}$ values obtained in present study are slightly smaller than those reported for seed germination of spring rapeseed cultivars (between 33.90 and 34.42 °C) (Derakhshan *et al*., 2018). The optimum T obtained in this study for seedling emergence of spring rapeseed cultivars was in agreement with the optimal T range of 29 to 33 found by Andreucci *et al*. (2016) for seed germination of winter rapeseed (*B. napus*) cultivars. In general, the response of seedling emergence rates to T varied among the seed fractions within the population. So that, fast-emerging seedlings (the lowest fractions) have higher values for T_o and T_m compared to slower emerging seedlings (the higher fractions), which reach T_o and T_m at lower temperatures.

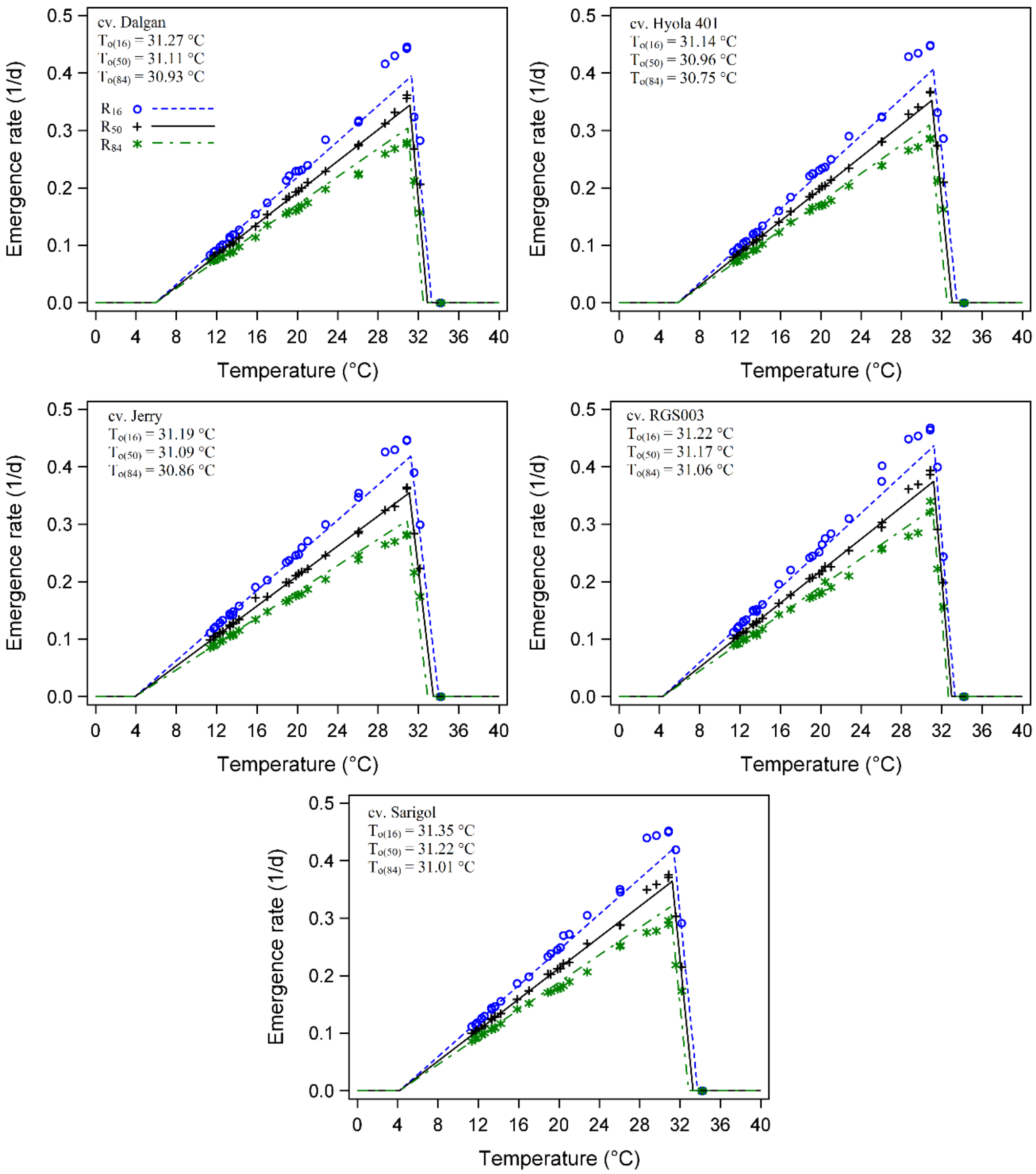

Figure 3. Predicted relationship between temperature and emergence rate using the thermal time model for the spring rapeseed cultivars studied.

The results of this work confirm that in the absence of other restricting factors (e.g., soil water content), the seedling emergence of rapeseed in the field is strongly controlled by T. According to the thermal time model, in general, in all rapeseed cultivars studied, the emergence rate increased linearly in response to the increase in T in the range between T_b and T_o and decreased linearly in the range between T_o and T_m. However, there were significant differences among them in terms of estimated critical T thresholds for seedling emergence. While seedling emergence of rapeseed cultivars occurred over a wide range of sub-optimal temperatures, the occurrence of thermoinhibition in this process was observed only in a small T range. This phenomenon might be considered as an adaptive strategy in the emergence response of rapeseed cultivars to T. Above T_o, as each unit of T increases, germination and the subsequent emergence of a larger fraction of seeds of the population are prevented. Two fates await these seeds: thermal death or temporary thermoinhibition of germination

(Derakhshan *et al*., 2018). In the latter case, the seeds remaining capable of germinating until the environmental conditions change.

The thermal model used in this study have parameters that are all biologically significant and considers both the rate and percentage of emergence at each count-time to estimate the parameters (unlike nonlinear regression models). This model provided a sufficient explanation of the seedling emergence properties of various spring rapeseed cultivars in response to T. The outputs obtained from fitting the thermal time model to the data in this study well explained the differences among rapeseed cultivars in terms of seedling emergence response to T. The thermal thresholds determined in the present study can be used to construct a simple model to predict the timing of seedling emergence in the field to optimize sowing management.

CONTRIBUTIONS

Conceptualization, M.M. and F.K.; writing—original draft preparation, M.H.; writing—review and editing, M.R and M.M.; supervision, F.K. All authors have read and agreed to the published version of the manuscript.

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DECLARATIONS

Conflict of Interest: The authors declare that they have no conflict of interest.

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