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A predictive model for the effects of temperature on the germination period of flax seeds (*Linum usitatissimum* L.)

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Abstract: Temperature is the most important factor in regulating the germination of nondormant seeds at the beginning of the growth season. The present study was conducted to produce simple regression models to predict how temperature affects the time it takes for 50% of a selection of flax seeds to germinate. R-square (r^2) values of regression coefficients of the equations established for flax cultivars varied from 0.899 (Antares) to 0.886 (Bionda). The optimum temperature for the time to germination for both cultivars was calculated using the coefficients obtained from the regression models. The optimum temperatures were found to be between 22.10 and 22.05 °C for Antares and Bionda, respectively.

Key words: Flax, germination time, predicted model, temperature

Introduction

Environmental factors such as temperature, water, and light influence seedling survival and germination. Although all the factors affecting plant growth and development may be at an optimal level, obtaining a higher yield depends on seed quality (Probert 1992). Besides ecological factors, some seed characteristics such as germination rate, the time necessary for 50% of the seeds to germinate, emergence rate, and the time until emergence are important factors affecting yield and quality (Uzun et al. 2000).

Seed germination is a complicated event, with different phases of the process affected by temperature, moisture, and oxygen. Temperature is the most important factor regulating the germination of nondormant seeds in irrigated, annual agro-ecosystems at the beginning of the growth season where light, nutrients, and moisture are typically not growth limiting (Ritchie and NeSmith 1991).

Several researchers have studied minimum, optimum, and maximum temperatures of germination for various crops. Kurt and Bozkurt (2006) found that a soil temperature of 20 °C is better than a lower temperature for flax seedling emergence. Similarly, Lorenz and Maynard (1980) found 5, 26, and 30 °C to be the minimum, optimum, and maximum temperatures, respectively, with regard to the germination of pea seeds. However, Vural et al. (2000) found 8–10 °C and 20–25 °C to be the minimum and optimum temperatures, respectively, for the germination of cowpea seeds.

Predictive models have been used to determine plant growth and development (Phelps and Finch-Savage 1997). Several studies on this subject have concentrated on the specification of different plant phases to describe plant growth and development. Plant development phases include germination, active growth, the reproductive stage, and

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physiological maturity. Temperature and light affect plant developmental phases. The elapsed time from seed sowing to seedling emergence has been regarded as an indication of a plant's development (Ellis et al. 1990).

Having a reasonable estimate of a crop's developmental stage without visiting the field can save considerable time and expenses. This is the main advantage of the predictive model proposed. Additionally, a predictive model may be used to assist in the determination of the most suitable time to fertilize and to apply herbicides, pesticides, or insecticides for the optimum activity, efficiency, and control. Finally, a predictive model facilitates the accurate comparison of crop development across different years.

In this study, the relationship between temperature and the time until the germination of flax cultivar seeds was investigated. The primary objective of this research was to determine equations that can relate time to germination and temperature.

Materials and methods

Experiments were performed in a growth chamber with temperature and photoperiod controls to study flax seed germination using 2 cultivars, 1 having brown seeds (Antares) and 1 having yellow seeds (Bionda). The seeds were surface sterilized using sodium hypochlorite (20%) for 1 min, followed by a thorough rinsing (repeated 5 times) with distilled water and air-drying.

A growth chamber with automatic controls for temperature, light, and humidity was used in all germination experiments. The temperatures at which germination was tested were constant from 0 to 42 °C for 2 days, with also 4 °C intervals in the dark. Each experiment was duplicated simultaneously in 5 replications for each temperature value. These 5 replicates of 50 seeds were germinated in 2 layers of moistened Whatman No. 1 filter paper, and these papers were placed in petri dishes (100 × 100 × 15 mm). The dishes were monitored daily for water loss and refilled with distilled water as necessary. Seeds that had 1-cm-long radicles were counted as germinated (Samimy et al. 1987). They were checked for germination 3 times a day at the beginning of each experiment when germination was rapid, and once a day by the end of each experiment when germination had slowed (Yeh and Atherton 2000). Any germinated seeds were removed from the dishes once the radicles had extended more than 1 cm beyond the seed coat.

The resulting seed germination data were analyzed to determine the time necessary for 50% of the seeds to germinate for each temperature regime. In order to predict the time necessary for 50% of the seeds treated with different temperatures regimes to germinate, the model $D = a - b \times T + c \times T^2$, which was produced by Uzun et al. (2000) in order to predict the time elapsed from seed sowing to emergence for some vegetable crops, was adapted to the data obtained from the present study by carrying out a multi-regression analysis based on constant temperature (T) and square temperature (T^2). In the above model ($D = a - b \times T + c \times T^2$), D is the time (in days) that elapsed between seed sowing and emergence, T is the mean daily temperature (°C), and a, b, and c are cultivar-specific constants. The dependent variable of the above model (the time elapsed from seed sowing to emergence as days) changed to the time (in days) necessary to reach 50% germination (DG) for some crops. The subsequent model was $DG = a - b \times T + c \times T^2$.

The optimum temperatures for the time in days to germination for the seeds of the flax varieties tested were determined by using the submodel $T_o = b/2 \times c$ (T_o represents the optimum temperature for the shortest time to 50% germination). In other words, the minimum point of the curve resulted from plotting DG (as T and T^2) and b and c, which are the coefficients of $DG = a - b \times T + c \times T^2$. The data obtained from the present study were analyzed by multi-regression analysis and the analysis was continued until the mean square residual for the regression was minimized (Yang et al. 1995). The Excel 7.0 package program was used for the analysis.

Results

When the data for DG of both flax cultivars were plotted against temperature, it was observed that DG declined curvilinearly with an increase in temperature (Figure 1). In other words, depending on the particular cultivar, DG decreased with increasing

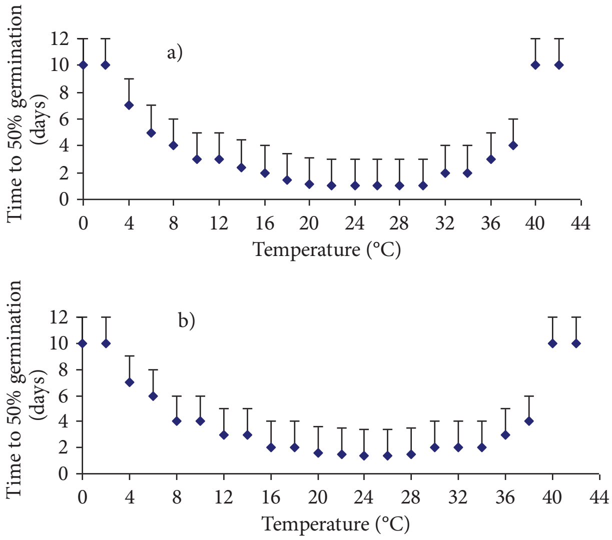

Figure 1. The changes in DG with temperature (°C) for (a) Antares, (b) Bionda, the species examined.

temperatures to a point where DG was the shortest, and then increased thereafter. As is clear from Figure 1, the range of temperatures, from minimum to maximum, in relation to DG was similar for the 2 cultivars. For both cultivars, DG decreased from 0 to 22 °C and remained stable between 22 and 30 °C and increased thereafter.

After seeing the effects of temperature on DG in both cultivars, multiple regression analysis was applied to the data in order to determine the relationship between these parameters. When DG was regressed against temperature (T) (as T and T^2, because of non-linearity), the best curvilinear fits among indices across cultivars, as indicated by r^2, were chosen as the determination. The coefficients for cultivars were derived from the model $DG = a - b \times T + c \times T^2$, and their standard errors and degree of significance are given in the Table. The optimum temperatures for DG were also calculated for both cultivars through the model $To = b/2 \times c$, derived from $DG = a - b \times T + c \times T^2$ (Table). As seen in the Table, the regression coefficients (r^2) of the equations produced for DG for both flax varieties changed between 0.899 (Antares) and 0.886 (Bionda). In general, in terms of predicting time to germination in response to temperature, Antares ranked first and Bionda second according to their coefficients of determination (Table).

The results show that the effect of temperature on the time to seed germination explained most of the variation in the time to seed germination and that this variation was cultivar dependent. When actual values for the time to germination in response to temperature for the studied flax varieties were plotted against those predicted by the models produced in the present study, it was noted that the models predicted the time to germination reasonably well (Figure 2). Optimum temperatures for DG differed depending on the cultivar (Table), and the optimum temperatures for the time to seed germination were found to be between 22.10 and 22.05 °C for the Antares and Bionda cultivars, respectively.

Table. The coefficients (a, b, and c), their standard errors (SE), r^2 values, and optimum temperatures for the examined flax cultivars, which were calculated by using the equations developed to predict DG ($DG = a - b \times T + c \times T^2$).

Varieties	Constants for species and cultivars			r^2 (Coefficient of determination)	Predicted optimum germination temperature (°C) ($T_o = b/2 \times c$).
	a	b	C		
Antares	10.663	0.920	0.021	0.8992***	22.10
SE	(0.648)***	(0.072)***	(0.002)***		
Bionda	10.719	0.882	0.020	0.8855***	22.05
SE	(0.659)***	(0.073)***	(0.002)***		

***Significant at the level of $P < 0.001$

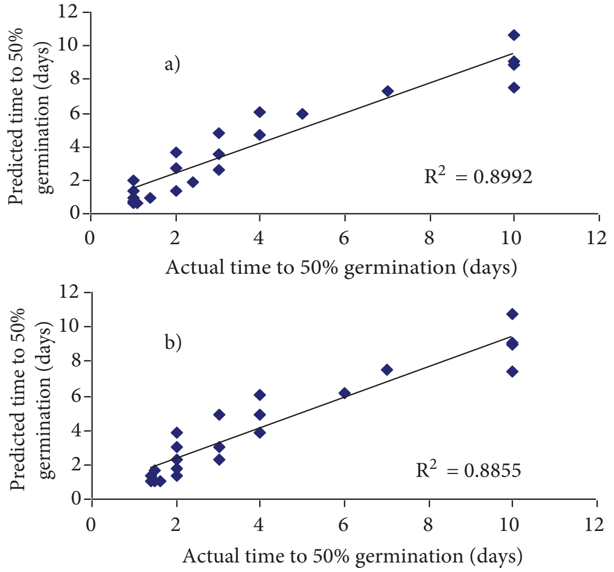

Figure 2. The relationship between actual DG and those predicted by the model, $DG = a - b \times T + c \times T^2$, for (a) Antares and (b) Bionda, the species examined.

Discussion

In the present study, a curvilinear decline in DG was observed with increasing temperature between a minimum and maximum range, the exact values of which were dependent upon the particular flax cultivar. To date, predominantly linear relations between germination rate and temperature (over specific ranges) have been found among the main crop plants. However, consistent deviations from a linear model for some cultivars occurred especially at low temperatures, such that the germination time at 5 °C was found to be up to twice as fast as at the predicted temperature (Marshall and Squire 2001). Marshall and Squire (2001) also indicated that the consequence of non-linearity was to increase the spread of time over which seeds germinated at low temperatures, which indicated the margin of error likely to follow from applying linear rate/temperature models to whole populations such that there was a marked non-linearity in the response of germination to temperature for 4 oilseed rape cultivars. It was reported that germination rates increased linearly with temperature between 15 and 30 °C for 9 different weed species (Scott et al. 2000). Finch-Savage and Phelps (1993) also indicated that the time to germination increases as temperature decreases but, if given sufficient time, essentially all viable seeds will complete germination.

The minimum temperature was found to be 0 °C for both flax cultivars tested in the present study. It has been reported that several problems may arise with methods that rely on linear models, including lack of fit (Phelps and Finch-Savage 1997). The results of the present study showed that the effect of temperature on the time to seed germination explains most of the variation in the time to seed germination for both flax cultivars tested and that this variation was cultivar dependent. The maximum temperature for DG was 42 °C for both of flax cultivars. Values for DG plotted against temperature result in "germination characteristic curves" (Finch-Savage and Phelps 1993). Species differ in their minimum, optimum, and maximum germination temperatures. Toyomasu et al. (1993) reported that high temperature inhibits germination by maintaining high endogenous abscisic acid contents without affecting endogenous gibberellic acid contents. When the seeds sense that the temperature is too high to germinate, abscisic acid biosynthesis is enhanced and high abscisic acid content is maintained to prevent germination. If the temperature continues to rise, the seeds increase their sensitivities to abscisic acid, thereby maintaining the enhanced abscisic acid biosynthesis, but not affecting the bioactive gibberellic acid contents.

Optimum temperatures for the time to seed germination were found to be 22.1 and 22.05 °C for Antares and Bionda, respectively. Finch-Savage and Phelps (1993) indicated that the median germination rates (the inverse of the time necessary to reach 50% germination) are often linear below and above the optimum temperature. This finding, when considered in terms of time to germination, is in accordance with the present results.

In the study, the R-square (r^2) values of regression coefficients of the produced equations for flax cultivars varied from 0.899 (Antares) to 0.886 (Bionda). In addition, the optimum temperature for the time to germination for both cultivars was calculated using the coefficients obtained from the regression models. The optimum temperatures were found to be 22.10 and 22.05 °C for Antares and Bionda, respectively.

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