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Research Article

Effect of temperature and water potential on *Capparis spinosa* seed germination: Quantification of the cardinal temperatures and hydrothermal time

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Abstract: This study was conducted to quantify the germination response of Capers *Capparis spinosa* L. to temperature and water potential. The seeds were germinated at seven temperatures (5, 10, 15, 20, 25, 30, and 35 °C) and six water potentials (zero, -0.3, -0.6, -0.9, -1.2 and -1.5 MPa). Increased water potential and temperature decreased germination percentage and increased germination time. The results revealed that the dent-like function (RMSE = 0.24, R^2 = 0.82, and r = 0.86) is suitable for describing the response to temperature and water potential. Based on the dent-like model base, optimum and ceiling temperatures were estimated as 8.81 to 11/13, 21.30 to 24.88, and 35.22 to 37.55 °C, respectively. Biological hours for the control treatment (zero potential water) were calculated as 52.11 hours. The hydro time constant for SSG (θH), the middle value for the base water potential (Ψb(50)), the standard deviation in base water in the water potential (σyb), and the thermal time constant for SSG (θT) spanned the values of 0.63–243.48 MPa h, −0.3–2.59 bar and 343.3–1344.3 °C h, respectively. The hydrothermal time parameters were 445.12 bar °C h, −2.274 MPa, and 8.28 °C for θHT, and Ψb(50), Tb in temperatures and water potentials, respectively.

Keywords: Capers, Germination rate, Regression model, Dent-like model, Thermal time

Introduction

Capers *Capparis spinosa* L. is one of the most important species of the family of Capparidaceae. This plant is found in tropical or subtropical and arid regions and is almost everywhere. The main production areas are in harsh environments. Capers is found in southeastern Morocco, Turkey, and the Iberian Peninsula (Yang *et al.*, 2010).

Capers is a xerophytic shrub adaptable to harsh environments. This plant species has pharmacological/medicinal properties and Capers culinary uses. Its phytochemical importance relies on many bioactive components in different organs, and its cultivation can be of considerable economic value. The economic importance of the Capers plant (young flower buds, known as capers, are greatly favored for seasoning, and different parts of the plant are used in the manufacture of medicines and cosmetics) led to a significant increase in both the area under cultivation and production levels during the late

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1980s. *C. spinosa* is a medicinal plant. In Greek popular medicine, herbal tea made of capers root and young shoots are beneficial against rheumatism (Ageel *et al.*, 1986; Tlili *et al.*, 2010). Different flavonoids were identified in caper bush and capers: rutin (quercetin 3-rutinoside), quercetin 7-rutinoside, quercetin 3-glucoside-7-rhamnoside, kaempferol-3-rutinoside, kaempferol-3- glucoside, and kaempferol-3-rhamnorutinoside. Rutin is a potent antioxidant bioflavonoid in the body and is a dietary supplement for capillary fragility. Rutin has no known toxicity (Lam *et al.*, 2009; Tlili *et al.*, 2009; Yang *et al*., 2010). Capers contain more quercetin per weight than other plants (Darwish and Aburjai 2010; Yang and Wang, 2010).

Seed germination is a critical stage in plant life and establishment. In this stage, plants are susceptible to drought (Ahari *et al.*, 2009). Seed germination is a complex biological process that responds to numerous environmental elements, including water potential and temperature (Qiu *et al*., 2006). Temperature and water potential are the main factors in the successful germination of non-dormant seeds (Soltani *et al*., 2013). Salinity is an important factor that could negatively impact the germination process since high salinity causes a reduction in water availability (low water potential), which inhibits the process (Khan and Ungar, 1997).

The response of germination to temperature is base, optimal, and ceiling temperatures. At the optimum temperature, the highest germination rate occurs. The base and ceiling temperatures germination is zero (Alvarado and Bradford, 2002).

Seed germination modeling determines cardinal temperatures for most plant species, but these methods have limitations due to seed biological changes. Understanding the seed germination response helps us to select plants that tolerate crops and cultivars at low or high temperatures, and cardinal temperatures can be used to identify the geographical areas appropriate to a species or genotype that can germinate and establish (Kamkar *et al.*, 2012). Models have been used to predict biological processes. Models have been used to predict biological processes. The thermal time model indicates the relationship between the germination rate and temperature. So far, this model has been used in various seed plants such as *Sinapis arvensis* L. (Soltani *et al.*, 2013), safflower (Ostadian Bidgoly *et al*., 2018), *Papaver somniferum* L. (Kamkar *et al*., 2012), and Lathyrus (Jami Alahmadi *et al.*, 2015). The parameters of the thermal time model have biological concepts such as base temperature, the inherent germination (seedling emergence) rate, and other cardinal temperatures. Therefore, thermal time models can obtain base temperature and prepare prediction models of germination and seedling emergence. Also, it helps select the planting dates, screen species and genotypes for tolerance to low or high temperatures, and determine the areas where species and genotypes can germinate (Ostadian Bidgoly *et al*., 2018).

Given that in recent years, the consumption of medicinal plants has increased all over the world, the cultivated area of these plants is also growing. It is a necessity to have enough information about the ecophysiological behaviors of these plants. Cultivation of this plant requires basic information, especially the ecological needs, which have not been well studied. This data is necessary to increase the area under cultivation of these plants. This investigation was conducted to determine the effect of temperature and water potential on the seed germination response of *C. spinosa* and to find the cardinal temperatures of germination.

Materials and Methods

Seed source: The mature seeds of *C. spinosa* were collected from Zarand Kerman in central Iran (Lat: 390 49/520 N; Lon: 560 35/280 E) in 2021. The experiment was conducted in a completely randomized design and a factorial arrangement and at four replications. The seeds were germinated at different temperatures (5, 10, 15, 20, 25, 30 and 35 °C). Five water potentials (Ψw) of the imbibition solutions were studied: 0 (control), 0.3, -0.6, -0.9, -1.2, and -1.5 MPa. The saline solutions at the five water potentials were prepared by dissolving 0.0, 3.5, 7.1, 10.6, and

14.2 g L-1 of NaCl, respectively, in distilled water with references to Coons *et al.* (1990).

The Petri dishes were sterilized for 24 h in an oven at 120 °C. Twenty-five seeds were germinated in 9-cm-diameter Petri dishes on two layers of Whatman No. 1 (9 cm diameter) filter paper (Lemes and Lopes, 2012).

Germinated seeds were counted three times a day and were considered germinated if radicle length reached ≥ 2 mm. The germin (version 1) software was used to calculate the percentage and rate of seed germination. The program calculates the time to 10 (D10), 50 (D50), and 90% (D90) germination. This program calculates these parameters for each replication and each seed treatment by linear interpolating the increasing germination versus time. The following model was used to quantify the germination response to the temperature and determine the cardinal temperatures (Covell *et al*., 1986).

$R50 = f(T)R\text{max}$

Where f(T) is a temperature function and varies from zero at the base to one at optimal temperature(s), and Rmax is the inherent maximum rate of germination at the optimal temperature; 1/Rmax shows the minimum time required for germination, which is known as the biological time required for germination (G_0). To quantify the response of germination rate to temperature and also to determine cardinal temperatures and physiological hour requirements for germination, segmented, dent-like, and beta functions were used to quantify the response of germination rate to temperature and determine cardinal temperatures and physiological hour requirements for germination (Piper *et al*., 1996; Ritchie and NeSmith 1991; Yin *et al*., 1995). Dent-like (Piper *et al*., 1996), segmented (Ritchie and NeSmith, 1991), and beta models (Yin *et al*., 1995) (Table 1).

Fixing Tc was necessary due to the declining standard error estimation for other parameters of the particular function. The parameters were estimated by the least squares method using the nonlinear (NLIN) regression (R50 as y and T as x) procedure in SAS (SAS Institute, Inc. Cary, NC) (Jame and Cutforth, 2004).

Hydrothermal time model characterization Bradford (2002) showed the proceeding, corresponding, and equations that portray the thermal time model.

$\theta H = (\Psi - \Psi b\ (g))tg$ (4)

$GRg = 1/tg = (\Psi - \Psi b\ (g))/\theta H$ (5)

Where θH, Ψ, Ψb(g), tg, and GRg are the hydro time constant (MPa h), true seed water potential (MPa), base water potential (MPa) representative of a particular germination fraction g (%), time (hours) for g(%) of the seed population to experience radicle appearance, and germination rate undergone by g (%) of the seed population, respectively. Assuming that the variation in Ψb within a seed population follows a normal distribution, hydro time parameters were estimated by repeated probit analysis of Eq. (6) and varying the parameter θH until the best fit was attained (Gummerson, 1986; Bradford, 2002).

$\text{probit}\ (g) = [\Psi - (\theta H/tg) - \Psi b\ (50)]/\sigma\Psi b$ (6)

In this function, Ψb(50) is the middle value of Ψb, and σΨb represents the standard deviation in base water in Ψb between the seeds contained in the population. This process was utilized to separately approximate each of the three hydro time criteria for individual temperature regimes. The germination rates are characterized by a joint hydrothermal time scale model, as both the sub-optimal temperature and Ψ change (Gummerson 1986; Bradford 2002).

$\theta HT = (\Psi - \Psi b\ (g))(T - Tb)tg$ (7)

In this function, θHT is an expression for the joined accrued thermal time at temperatures greater than Tb and accrued hydro time at Ψ quantities higher than Ψb(g), described as the hydrothermal time constant (MPa °C h). Germination time course data were analyzed, and the parameters were estimated for the thermal time, hydro time, and hydrothermal time models using repeated profit regression analysis as described previously, by the least squares method using the nonlinear fitting (NLIN) regression procedure in the Statistical Analysis System (SAS Institute Inc, 2011).

Results

Evaluation of germination models

The results of analysis of variance showed a significant difference ($P < 0.01$) between the treatment water potential and germination temperature for the mean germination time (Table 2).

At 5 °C, the maximum time was observed at the potential level of 1.2 MPa. At 10 °C, no significant difference was observed between the -0.3 water potential levels and the control. At 15, 20, 25, and 30°C, the highest mean germination time was observed respectively at potentials -0.9 and -1.2 MPa. Termination time was observed in the control treatment at 20 °C (3.21 day), indicating the highest germination rate at this temperature. At 35 ° C, seed germination was observed in two water potentials of -0.3 and -0.6 MPa, and the maximum germination time was 9.33 days at -1.2 MPa (Table 3).

At 5 °C, the highest germination percentage was observed in the control treatment with decreasing water potential, the germination percentage decreased significantly, So at 1.5 MPa potential, no seeds germinated. At 10 °C, the highest germination percentage was observed in the control treatment. The germination percentage decreased at 15 °C in the control treatment and -0.2 MPa, 100% germination, and decreased water potential. At 15 °C, all seeds germinated except -1.2 MPa (83%). Also, the temperature from 15 to 20 °C increased the germination percentage of potential levels. At 15, 20, and 25 °C, no significant difference was observed between the control treatments and the three levels of -0.3, -0.6, and -0.9 Mpa (100% germination percentage), an increase in drought stress resistance at these temperatures. At 30 °C, a significant difference was observed between the control and other potential levels, and the highest germination percentage was observed in the control. At 35 ° C, the highest percentage of germination was observed in the control, and with increasing water potential, the percentage of germination decreased (Table 3).

Table 1 Dent-like, segmented, and beta models were fitted to germination rate vs. different constant temperatures.

Function	Formula
Segmented	$f(T) = (T - T_b)/(T_o - T_b)$ if $T_b < T \leq T_o$ $f(T) = (T_c - T)/(T_c - T_o)$ if $T_o < T < T_c$ $f(T) = 0$ if $T \leq T_b$ or $T \geq T_c$
Dent-like	$f(T) = (T - T_b)/(T_{o_1} - T_b)$ if $T_b < T < T_{o_1}$ $f(T) = (T_c - T)/(T_c - T_{o_2})$ if $T_{o_2} < T < T_c$ $f(T) = 1$ if $T_{o_1} \leq T \leq T_{o_2}$ $f(T) = 0$ if $T \leq T_b$ or $T \geq T_c$
Beta	$f(T) = \left(\frac{Tc-T}{To-Tb} \times \frac{T-Tb}{To-Tb}\right)^{((To-Tb)/(TC-TO))}$ if $T_b < T < T$ $f(T) = 0$ if $T \leq Tb \text{ or } T \geq Tc$

T: temperature, T_b: minimum temperature, T_o: optimum temperature, To_1: lower optimum temperature (for dent- like function), To_2: upper optimum temperature (for dent-like function), T_C: maximum temperature.

Table 2 Analysis of variance for the effect of temperature and water potential on mean germination and germination percentage.

Source of variation	df	Mean germination time	Germination percentage
Temperature (T)	6	2013**	2314.20**
Water potential (W)	5	9412**	412.23**
W × T	30	213**	86.23**
Error	126	4	0.35
CV	-	4.12	5.62

** Significantly at 0.01 probability level.

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The root mean square of deviations (RMSD) in the three functions varied from 0.13 to 0.55 . The average RMSD in segmented, dent-like, and beta were 0.28, 0.24, and 0.29, respectively. RMSD was lower in dent- the like function; the correlation coefficient (r) varied from 0.38 to 0.96 in three functions, but r quantities were higher in the dent-like compared to the beta and segmented functions. Due to lower average RMSD (0.24), lower average significance a (0.18) and b (0.33), higher average (0.86), and higher average R^2 (0.82) values for the dent-like function, this function was suitable for use in describing Capers germination response to temperature and water potential (Table 4).

For germination, there are specified cardinal temperatures and biological hour requisites in Table 5. In the superior model (the segmented function), the base temperature was 8.81 to 11.13 °C under various water potentials. In other words, the range temperature was 2.32 °C for potential water loss.

Table 5 show specified cardinal temperatures and biological hour requisites for germination. Using the dent-like function, a ceiling temperature of 35.22 °C, a base temperature of 8.8 °C at 0 MPa potential, an optimum temperature of 21.30 °C, and the value of go, 52.11 h, were obtained (Table 5). Biological time to germination varied between 52.11 to 125.37 h under various water potentials.

The coefficient R^2 ranged from 0.34 to 0.95. For each temperature regime, the estimated values of Ψb(50), σΨb, and θH were specific (Table 6). At each temperature, the base water potential was different for seed germination. Values of base water potential for seed germination are various between 0.13 MPa (at temperature 35 °C) and −2.59 MPa (at temperature 20 °C). Water potential starts to decrease when the temperature rises from 5 to 20 °C, the base value, but base water potential increases with the temperature from 20 °C to 35 °C (Table 4).

Comparing the standard deviation of the base water potential coefficient (σΨb), the tested temperatures, at 5 °C and 35 °C showed that germination (σΨb = 0.21 and 0.13 MPa) were of higher uniformity than at other temperatures, and the lowest uniformity of the germination temperatures were at 15 °C and 20 °C (σΨb = -0.86 and -0.77 MPa). In these conditions, θH (MPa h) describes a fixed seed germination rate of a seed population. Uniform germination indicates a smaller numerical value of the coefficient. In our experiment, the highest value (243.48 MPa h) at 10 °C and the lowest coefficient of hydro time (23.12 MPa h) at 35 °C demonstrate the highest germination rate at this temperature.

Estimated values of the thermal time constant (θT) and base temperature (Tb) were specific for each water potential regime (Table 7). At -1.2 MPa and 0 MPa, the highest and lowest base temperatures (Tb) were respectively 14.06 and 8.37 MPa. The Tb increased from 8.37 (0 MPa) to 14.06 (-1.2 MPa). The highest thermal time contest θT was observed at -1.2 MPa, and the thermal time contest increased from 340.3 °C h (at 0 MPa) to 1334.3 °C h (at -1.2 MPa). The R^2 was greater than 0.90 at 0, -0.3, and -0.6 MPa; the lowest R^2 was observed at -1 MPa (0.64%). Final germination percentages and germination rates were reduced with increasing water potential (Table 7).

Hydrothermal time parameters were determined for different temperatures and water potentials. For (θHT), Ψb (50) (T_b) were, respectively, 445.12 MPa °C h, −2.274 MPa, and 8.28 °C (Table 8).

Discussion

The results indicated, that decreasing water potential increased the mean germination time and decreased germination percentage.

Temperature and water potential affect germination percentages and rate (Baskin and Baskin, 1998). Bidgoly *et al*. (2018) reported that in safflower with increasing temperature and water potential, the germination percentage also decreases, and the mean germination time increases. Germination rates were calculated as the reciprocal of the time needed for 50% of maximum germination for evaluating the correlation between germination and temperature and water potential. Segmented, beta, and dent-like were used to describe temperature and water potential effects on germination rate (Table 4). In another study, results indicated that the segmented model was the best model to describe the germination response of fenugreek seed under different temperatures and water potentials (Teimori *et al*., 2020). Zaferanieh *et al*. (2020) reported that in Alyssum homolocarpum the segmented function (RMSD = 0.28, R2 = 0.82, and r = 0.90) is suitable for describing the response to temperature and water potential.

Table 3 Mean comparison for the effect of water potentials in different germination temperatures for seed germination of Capper.

	Temperature (ºC)	Water potential (Mpa)					
		0	-0.3	-0.6	-0.9	-1.2	-1.5
Mean germination time (days)	5	7.35d	7.92d	8.41c	9.11b	10.50a	-
	10	5.06d	5.65d	6.88c	7.23b	9.43a	-
	15	4.13c	4.83b	4.92b	4.98b	5.74a	
	20	3.21c	3.42b	3.78b	3.96b	4.83a	-
	25	2.41c	2.67c	3.14b	3.89b	4.16a	-
	30	4.32d	5.28c	7.65b	8.14a	8.55a	-
	35	6.45e	7.00d	7.67c	8.68b	9.33a	-
Germination (%)	5	24a	19b	12c	5d	3d	-
	10	68a	60b	55c	43d	22e	-
	15	100a	100a	100a	100a	83b	-
	20	100a	100a	100a	100a	91b	-
	25	100a	100a	100a	100a	62c	-
	30	82a	73b	50 c	21d	6e	-
	35	32a	26b	18 c	10d	3e	-

Means in each column, followed by a similar letter(s), are not significantly different at 1% probability level.

Table 4 Coefficient of determination (R2) and Root mean square of deviations (RMSD) for the relationship between germination rate with water potential and temperature in *Capparis spinosa* L, as described by segmented, beta, and dent-like functions, as well as regression coefficients (a and b, ± SE) and predicted hours to germination and the correlation coefficient (r) between observed.

Function	Water potential (MPa)	RMSD	R^2	a	b	R
Segmented	0	0.42	0.79	0.15	0.28	0.81
	-0.3	0.40	0.83	0.80	0.19	0.87
	-0.6	0.21	0.55	0.30	0.22	0.53
	-0.9	0.13	0.48	0.12	0.18	0.38
	-1.2	0.24	0.62	0.20	0.09	0.70
	-1.5	-	-	-	-	
Dent- like	0	0.24	0.92	0.09	0.9	0.96
	-0.3	0.20	0.94	0.18	0.11	0.94
	-0.6	0.22	0.78	0.15	0.23	0.87
	-0.9	0.35	0.63	0.34	0.33	0.66
	-1.2	0.22	0.84	0.18	0.1	0.91
	-1.5	-	-			
Beta	0	0.44	0.87	0.21	0.31	0.91
	-0.3	0.55	0.88	0.14	0.20	0.84
	-0.6	0.20	0.93	0.38	0.31	0.52
	-0.9	0.16	0.47	0.23	0.22	0.70
	-1.2	0.11	0.35	0.18	0.18	0.46
	-1.5	-	-	-	-	-

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Table 5 Estimates of base temperature, optimum temperature (lower optimum temperature and upper optimum temperature for the dent-like function only), ceiling temperature, and biological hour (go), for the emergence of *Capparis spinosa* L cultivar using segmented, beta, and dent- like functions in different water potentials.

Function	Water potential (MPa)	Estimates of cardinal temperatures			
		T_b (°C)	T_o (°C)	T_c (°C)	g_o (h)
Segmented	0	8.31	22.06	33.08	48.17
	-0.3	9.11	23.42	34.13	58.53
	-0.6	10.92	23.96	34.13	79.60
	-0.9	14.14	24.38	35.43	95.50
	-1.2	13.82	25.67	37.13	149.48
Dent- like	0	8.81	21.30	35.22	52.11
	-0.3	9.54	22.53	35.54	73.29
	-0.6	9.73	23.14	36.22	85.63
	-0.9	10.52	24.26	37.41	90.14
	-1.2	11.13	24.88	37.55	125.37
Beta	0	7.13	23.71	34.12	45
	-0.3	8.91	25.00	36.78	63.14
	-0.6	9.37	26.17	37.34	76.31
	-0.9	11.55	24.1	38.19	96.2
	-1.2	13.07	26.49	40.37	148.3

Table 6 For different water potentials at eight germination temperatures describing seed germination of *Capparis spinosa* parameter estimates of the hydro time model.

Temperature	$\psi_{b(50)}$(MPa)	$\sigma_{\psi b}$	θH (MPa h)	R^2	GR(%)
5	-0.6	0.21	0.63	0.49	0.17
10	-2.18	0.59	243.48	0.91	72.64
15	-2.32	0.86	183.98	0.73	76.48
20	-2.59	0.77	119.72	0.95	88.69
25	-1.07	0.47	94.69	0.82	53.68
30	-0.9	0.35	42.38	0.88	28.92
35	-0.3	0.13	23.12	0.34	0.15

σΨb is the standard deviation in base water potential; Ψb(50) is the median base water potential; R2 is the coefficient of determination of the regression Hydro time model at each temperature θH is the hydro time constant;, GP is the average germination percentage for every temperature.

Table 7 Parameter estimates of the thermal time model at six water potentials describing seed germination of *Capparis spinosa* for different temperatures.

Water potential (MPa)	Tb (°C)	θT (°C h)	RMSE	R^2	GP (%)	GR (h−1)
0	8.37	340.3	13.13	0.83	92	0.194
-0.3	9.17	468.3	11.64	0.97	94	0.142
-0.6	10.63	838.4	29.16	0.88	90.5	0.08
-0.9	15.01	987.3	78.1	0.64	67.3	0.016
-1.2	14.06	1334.3	148.65	0.89	22.3	0.015
-1.5	-	-	-	-	-	

θT is the thermal time constant; Tb is the median base temperature; R2 is the coefficient of determination of the regression thermal time model at water potential; GP and GR are the average germination percentage and germination rate for water potentials.

Table 8 Parameters estimate of the hydrothermal time model, describing SSG at various temperatures and water potentials.

θHT (MPa °C h)	Ψb(50)(MPa)	Tb (°C)	R^2
445.12	-2.274	8.28	87

θHT is the hydrothermal time constant; Ψb(50) is the median base water potential; Tb is the base temperature; R2 is the coefficient of determination of the hydrothermal time model.

Generally, decreasing the water potential increases the biological time for germination. Water stress increases the biological time to germination at optimal temperatures. Ostadian Bidgoly *et al*. (2018) reported that the biological time to germination of safflower seeds had an incremental trend under reduced water potentials, and its maximum value occurred at -1.6 MPa, which agrees with our results.

In addition, our estimates for Tb, To and Tc compare with the literature data, respectively as follows: *Carthamus tinctorius* L (3.9-1.6, 39.3-25, and 45-33.6 °C; Ostadian Bidgolya *et al*., 2018), *Cuphea vis-cosissima Jacq* (6–10, 18–24 and 33-38 °C; Berti and Johnson 2008), *Alyssum holocarpum* (6.37-4.96, 15-14.75 and 30-28.5°C Zaferanieh *et al*., 2020), *Plantago ovata Forssk* (3.3, 21.2 and 35.0 °C; Ghaderi-Far *et al*., 2012), and *Kochia scoparia* L. (3.5, 24 and 50 °C; Al-Ahmadi and Kafi, 2007).

The coefficient of R2 was determined using the regression hydro time model at each temperature for each temperature specified. Usually, increasing the temperature from 10 to 35 °C reduces the thermal Coefficient. The highest germination percentage was observed at 20 °C (88.69%), the lowest germination percentage was at 5 and 35 °C, respectively 0.17 and 0.15, and increasing the temperature from 10 to 35 °C increased the germination percentage. Windauer *et al.* (2007), in *Lesquerella fendleri* seeds, showed that the median base water potential varied from −1.13 to−0.92 MPa, and the hydro time constant for germination ranged from 39 to 43 MPa h. Ostadian Bidgoly *et al*. (2018) in *Carthamus tinctorius* L. seeds showed that the hydro time constant germination ranged from 137.1 to 2.54 MPa h, Zaferanieh *et al*. (2020) reported that median base water potential varied from -0.09 to -1.18 Mpa.

Many reports use these models to portray seed germination (Table 9).

C. spinosa is a suitable plant compared to other plants for desert areas and with water deficit. With this germination rate and proper growth, this plant can germinate at low temperatures and water potentials.

Table 9 Some reports using hydrothermal time seed germination and emergence.

Researchers	Year	Species	Hydrothermal time (MPa °C h)
Bidgoly *et al.*	2018	*Carthamus tinctorius*	397.7
Teimori *et al.*	2021	*Trigonella foenum-graecum*	547
Bloomberg *et al.*	2009	*Pinus radiate*	149-176
Parmoon *et al.*	2015	*Silybum marianum*	276.6
Watt *et al.*	2010	*Buddleja davidii*	105
Zaferanieh *et al.*	2020	*Alyssum homolocarpum*	845.12

Conclusion

The dent-like model was recognized as the superior model for describing the effect of temperature on germination rate and was used to estimate the cardinal temperatures. Under different water potentials the biological time of germination linearly increased by the decrease in water potential at the base, optimal, and ceiling temperatures of 8.81 to 11.13, 21.30 to 24.88, and 35.22 to 37.55 °C respectively. In the dent-like function, the biological time of germination linearly increased by the decrease in water potential. The biological hour requirements for germination of these species ranged between 52.11 and 125.37 h under different water potentials. As the water potential decreases, the temperature time and the base water potential increase. The results showed that the hydro time value decreased when the temperature increased.

Parameters estimate of the hydrothermal time model for germination of *C. spinosa*, the hydrothermal time, base water potential, and base temperature for germination were measured to be 445.12 MPa °C h, -2.274 MPa, and 8.28 °C, respectively. Thus *C. spinosa* can be cultivated under the conditions of low soil moisture and low temperature.

Author contributions MZ and MS grew seeds, performed the experiments, and also prepared the first draft of the manuscript. MZ analyzed the data. MS designed and guided the experiments and wrote the manuscript in the final version. All authors reviewed and approved the manuscript.

Compliance with ethical standards

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

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اثر دما و پتانسیل آب بر جوانه‌زنی بذر *Capparis spinosa*: تعیین کمّیت دماهای اصلی و زمان هیدروترمال

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چکیده: این مطالعه به‌منظور کمّی‌سازی پاسخ جوانه‌زنی کپر (*Capparis spinosa* L.)به دما و پتانسیل آب انجام شد. بذرها در هفت دما (۵، ۱۰، ۱۵، ۲۰، ۲۵، ۳۰ و ۳۵ درجه سانتی‌گراد) و شش پتانسیل آبی (صفر، ۰/۳-، ۰/۶-، ۰/۹-، ۱/۲- و ۱/۵- مگاپاسکال) جوانه زدند. افزایش پتانسیل و دما باعث کاهش درصد جوانه‌زنی و افزایش زمان جوانه‌زنی شد. نتایج نشان داد که مدل دندان‌مانند (RMSE = 0.24 ، R2 = 0.82 وr = 0.86) برای توصیف پاسخ به دما و پتانسیل آب مناسب است. براساس مدل دندان‌مانند دمای پایه، دمای بهینه و سقف به‌ترتیب ۸/۸۱ تا۱۱/۱۳، ۲۱/۳۰ تا ۲۴/۸۸ و ۳۵/۲۲ تا ۳۷/۵۵ درجه سلسیوس برآورد شد. ساعت بیولوژیکی برای تیمار شاهد (آب با پتانسیل صفر) ۵۲/۱۱ ساعت محاسبه شد. ثابت هیدروتایم برای SSG (θH)، برای پتانسیل آبپایه (Ψb(50)، انحراف استاندارد در آبپایه در پتانسیل آب (σyb) و ثابت زمانی حرارتی برای SSG (θT) مقادیر ۰/۶۳ تا ۴۸/۲۴۳- مگاپاسکال، ۰/۳ تا ۲/۵۹ بار و ۳,۳۴۳-تا ۱۳۴۴/۳ درجه سلسیوس، به‌ترتیب. در مدل هیدروترمال‌تایم، ثابت هیدروترمال پتانسیل پایه آب و دمای پایه به‌ترتیب ۴۴۵/۱۲ مگاپاسگال درجه سلسیوس در ساعت، ۲/۲۷۴- مگاپاسگال و ۸/۲۸ درجه سلسیوس تخمین زده شد. از داده‌های به‌دست آمده از این مدل‌ها می‌توان در استقرار و مدیریت بهتر گیاه کپر برای کشت در مناطق مختلف استفاده نمود.

واژگان کلیدی: کپر، سرعت جوانه‌زني، مدل رگرسیوني، مدل دندانه‌مانند، زمان حرارتی

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