EXPERIMENTAL PAPER

Estimation of the cardinal temperatures for germination of four *Satureja* species growing in Iran

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S u m m a r y

Introduction: Seed germination is a complex physiological process regulated by genetic and environmental factors including temperature, water, oxygen, light and pH. Among them, temperature is one of the most important factors controlling the maximum rate and percentage of diaspore germination. **Objective:** The aim of the study was to determine the cardinal temperatures (T_b , T_o , T_c) of four *Satureja* species growing in Iran. **Methods:** Seeds of *Satureja mutica* Fish. et C. A. Mey., *S. macrantha* C. A. Mey., *S. sahandica* Bornm and *S. bachtiarica* Bunge were germinated at nine constant temperatures (from 0 to 40°C) with 5°C intervals. A factorial experiment based on completely randomized design with four replications was applied to determine the cardinal temperatures estimated by three regression models including intersected-lines (ISL), quadratic polynomial (QPN) and five-parameters beta (FPB). **Results:** The highest germination percentage (GP) occurred at 20°C for *S. mutica* (86%), *S. macrantha* (55%), *S. sahandica* (81%) and *S. bachtiarica* (89%), but there was no significant difference between 20 and 25°C, except *S. sahandica*. Germination stopped at 0°C and 40°C. The highest germination rate (GR), the lowest mean germination time (MGT) and time to 50% germination (D_{50}) were obtained at 20–25°C for all species. The GR_m for *S. bachtiarica* was significantly ($p \leq 0.05$) higher than for three other species

in all temperatures. None of the species did reach to 50% germination at temperatures higher than 30°C. **Conclusion:** Obtained results revealed the superiority of *S. bachtiarica* over the other species, v.s. *S. macrantha* was inferior. FPB and ISL models were most reliable for predicting cardinal temperatures, because of higher R^2 value and the lower root mean square error (RMSE). *S. macrantha* and *S. mutica* showed the lowest and the highest cardinal temperatures, respectively, in all three models.

Key words: cardinal temperatures, germination, *Satureja*, regression models

INTRODUCTION

The *Satureja* genus is a well-known medicinal and aromatic plant (*Lamiaceae*, *Labiatae*) that is comprised of 200 species widely distributed in the Mediterranean Area, Asia and boreal America [1, 2]. The *Satureja* genus has 16 species in Iran, of which nine are endemic and mostly extended in Irano-Turanian phytogeographical region in the northern, northwestern, western, southwestern, and central parts of Iran [3, 4]. They are low-growing herbs and subshrubs, reaching heights of 15–50 cm. The leaves are 1 to 3 cm long, with flowers forming in whorls on the stem, white to pale pink-violet [4].

The presence of secondary metabolites such as essential oils, steroids, flavonoids, and tannins, in *Satureja* genus have made it as one of the valuable herbs for pharmaceutical, perfume and food industries [1]. Recent experiments have confirmed anti-HIV [5], antioxidant [6], cytotoxic activities [7, 8], dental anesthetic [9], antiviral [10], antinociceptive and antiinflammatory [11], antibacterial and antifungal [12, 13], antispasmodic and antidiarrhea [14] effects for different *Satureja* spp.

Main essential oil constituents of *Satureja* spp. are phenolic compounds, carvacrol and thymol, as well as γ -terpinene, *p*-cymene, β -caryophyllene, linalool and other terpenoids [15, 16]. The main components of *S. mutica*, *S. macrantha* and *S. intermedia* growing in Iran were found to be carvacrol (30.9%), *p*-cymene (25.8%) and thymol (32.3%), respectively [16]. The main component of essential oil of *S. bachtiarica* is carvacrol and thymol [17]. Isolation of oleanolic acid is reported from *S. mutica*. Oleanolic acid is a ubiquitous triterpenoid in medicinal herbs, and is integral part of the human diet [8].

Germination is a critical stage in the life cycle of plants responsible for regeneration and survival of plants in modern agricultural and natural ecosystems [18]. Seed germination is a complex physiological process regulated by genetic and environmental factors including temperature, water potential, oxygen, light and pH [19-21]. Among them, temperature is the single most important factor governing the maximum rate and percentage of germination [22, 23] and successful establishment of plants with optimum density [24]. Temperature has an impact on a number of processes that regulate seed germination, including membrane permeability and the activity of membrane-bound and cytosolic enzymes [25].

In the experiments dealing with germination, clear variation existed in temperature requirement for germination of different species. It has been reported that seeds of a particular species are able to germinate over a range of temperature considered as cardinal temperatures, i.e., the base or minimum temperature (T_b), that is threshold below which no germination is possible, the optimum temperature (T_o) at which germination is the fastest, and maximum or ceiling temperature (T_c) above which germination is prevented [20, 26-28]. In general, cardinal temperatures of a particular seed depend on environmental conditions in which it is adapted and vary significantly among species and genotypes [22, 28, 29].

Quantification of germination response of seeds to temperature and estimate cardinal temperatures are considerably progressed in order to present models that can predict seed germination and emergence. It is useful for the selection of suitable planting time and also enables to select species and genotypes that can tolerate low or high temperatures and to determine geographical regions where plant species and genotypes can germinate and establish successfully [30-32].

Most studies have reported an inverse linear relation between time taken for cumulative germination to reach 50% of its maximum and the temperature during germination [21, 26, 28]. Furthermore, some reports have used Maguire formula for the calculation of speed of germination [29, 33].

There are various mathematical models describing germination responses to temperature, among which three have been used more often: intersected lines (ISL), quadratic polynomial (QPN) and five-parameters beta (FPB) [22, 28, 34, 35].

Satureja species are among endangered medicinal plants, so it is essential to have complete understanding of growth requirements, especially seed germination that are important for re-establishment and domestication projects. While countless studies have been conducted on germination parameters of plants, there have been few research studies performed on germination parameters of *Satureja*, majority of which have focused on *Satureja hortensis*. Therefore, a purpose of this study was to evaluate seed germination traits and determining cardinal temperatures of four *Satureja* species: *S. mutica*, *S. macrantha*, *S. sahendica*, and *S. bachtiarica*.

MATERIAL AND METHODS

This experiment was performed to determine cardinal temperature of four *Satureja* species at Genetic and Physiology Laboratory of Khorasan-e-razavi Agricultural and Natural Resources Research Center, Mashhad, Iran. Mature seeds were randomly collected in 2012, from North Khorasan (*Satureja mutica* Fish. et C. A. Mey), East Azerbaijan (*S. macrantha* C. A. Mey and *S. sahendica* Bornm) and Yazd (*S. bachtiarica* Bunge) provinces (tab. 1). Then, immature and damaged seeds were removed. Four replicates of fifty seeds of each species were germinated on Whatman No. 1 filter papers moistened with 5 ml distilled water in 90 mm

sterilized Petri dishes. Distilled water was added as required to ensure moisture was not limiting for germination. Batches of 50 seeds were incubated at nine constant temperatures (from 0 to 40°C) at 5°C intervals, in temperature-controlled incubator (Binder GmbH, Germany). The Petri dishes were enclosed and sealed in polyethylene bags to prevent desiccation. Germination was monitored over 21 days, until the cumulative number of germinated seeds became stable during three consecutive days or when reached 100% germination. A seed was considered germinated if the radicle was about 2 mm long and visible. Petri dishes were re-randomised after each count. Germinated seeds were counted every 24 h and cumulative germination percentage was plotted against time. From this curve, the time to 25% and 50% germination (D_{25} and D_{50}) was determined by fitting a logistic model of cumulative germination percentage (G) against time (t), as described by Eq. (1) and (2) [36, 37]:

$$y = \frac{G}{1 + be^{-at}} \tag{1}$$

$$t = \text{Ln} \frac{(G - y) / (y \cdot b)}{-a} \tag{2}$$

where y : germination percentage in each time
 G : maximum germination percentage
 e : the base of the natural logarithm
 t : the time to each germination percentage
 a, b : constant regression coefficient

Table 1

Geographical coordinates of collection areas for four species of *Satureja*

Species	Longitude (E)	Latitude (N)	Altitude (m.a.s.l)	Localization
<i>S. mutica</i>	56° 54' 12"	37° 30' 54"	1120	North Khorasan
<i>S. macrantha</i>	46° 50' 34"	39° 02' 15"	851	East Azerbaijan
<i>S. sahandica</i>	46° 19' 07"	37° 51' 46"	2200	East Azerbaijan
<i>S. bachtiarica</i>	54° 18' 56"	31° 31' 02"	2090	Yazd

Germination percentage (GP), mean germination time (MGT) [38] and germination rate of maguire (GR_m) were calculated by Eq. (3) to (5) [33]:

$$GP = \frac{\sum_{i=1}^k n_i}{N} \tag{3}$$

$$MGT = \frac{\sum_{i=1}^k n_i t_i}{\sum_{i=1}^k n_i} \tag{4}$$

$$GR_m = \sum_{i=1}^k \frac{n_i}{t_i} \quad (5)$$

where N: number of total seeds

n_i : number of seeds germinated in the i_{th} time

k : last time (day) of experiment

t_i : time (day) for start of experiment to the i_{th} observation

Then, germination rates (GR_m) were plotted against incubation temperature to estimate cardinal temperatures by means of three models including intersected-line model (ISL), quadratic polynomial model (QPN) and five parameters beta model (FPB) (tab. 2). Sigmasat® ver. 1.01 was used to fit the models using the nonlinear regression procedure [39].

Table 2

Intersected, quadratic, and beta models that were fitted to model germination rate at different constant temperatures

Function	Formula	Reference
Intersected-line model (ISL)	$f = \text{if } (T < T_o, \text{ Region 1 } (T), \text{ Region 2 } (T))$ $\text{Region 1 } (T) = b (T - T_b)$ $\text{Region 2 } (T) = c (T_c - T)$	35
Quadratic polynomial model (QPN)	$f = a + bT + cT^2$ $T_o = b + 2cT$	35
Five parameters beta model (FPB)	$f = \exp(\mu)(T - T_b)^\alpha (T_c - T)^\beta$ $T_o = (\alpha \cdot T_c) + (\beta \cdot T_b) / (\alpha + \beta)$	35

T: mean temperature, T_b : base temperature, T_o : optimum temperature, T_c : ceiling temperature;

a, b, c, μ , α , β : constant regression coefficient. T_o in QPN and FPB models is the first derivative of germination rate (f).

The quality of fitted models was evaluated by comparing the values of coefficients of determination (R^2) and root mean square error (RMSE). RMSE was calculated by the following equation [40]:

$$RMSE = \sqrt{\sum (Y_{obs} - Y_{pred})^2 / (n - 1)} \quad (6)$$

where Y_{obs} : observed value

Y_{pred} : predicted value

n: number of samples

Smaller RMSE values indicate better agreement between predictions and observations [40]. Germination data were normalized by (arcsin $\sqrt{\%}$) transformation. Data were analyzed using SAS 9.1.3 [41] statistical package. A factorial experiment in completely randomized design was carried out with four replications (4x50 seeds at each temperature), and means separated by Duncan's multiple range test.

Ethical approval: The conducted research is not related to either human or animal use.

RESULTS AND DISCUSSION

Germination traits of four *Satureja* species were significantly ($p \leq 0.05$) affected by temperature. As temperature increased or decreased from optimum (20°C), GP and GR_m reduced and MGT increased. Rate of changes was higher at temperatures below 20°C (tab. 3). Similar results have been reported for GP, MGT and GR_m of most plant species [20, 22, 26, 42, 43]. Most reports showed that increased temperature up to optimum followed by increased GR but declined thereafter [35, 44, 45].

Table 3

The effect of temperature on germination percentage (GP), mean germination time (MGT), germination rate of maguire (GR_m), and times to 25 and 50% germination (D₂₅, D₅₀)

Species	Temperature [C°]	GP [%]	MGT [days]	GR _m	D ₂₅ [days]	D ₅₀ [days]
<i>S. mutica</i>	0	0.0 ^P	—	—	—	—
	5	8.0 ^o	17.0 ^b	0.12 ^o	—	—
	10	13.0 ^{mno}	17.4 ^{ab}	0.20 ^o	—	—
	15	51.0 ^{efg}	9.6 ^{fg}	1.54 ^{kl}	9.2 ^b	14.9 ^b
	20	86.0 ^a	4.9 ^l	5.52 ^{cd}	2.7 ^{ghi}	4.0 ^d
	25	82.0 ^{ab}	4.2 ^{lmn}	6.70 ^b	1.9 ^{hi}	3.5 ^d
	30	69.0 ^{cd}	4.4 ^{lmn}	5.83 ^{bc}	2.2 ^{ghi}	4.8 ^d
	35	32.6 ^{ijk}	4.7 ^{lm}	3.20 ^{gh}	5.3 ^{de}	—
	40	0.0 ^P	—	—	—	—
<i>S. macrantha</i>	0	0.0 ^P	—	—	—	—
	5	15.0 ^{mn}	14.7 ^c	0.36 ^{no}	—	—
	10	30.9 ^{jk}	10.2 ^{ef}	1.16 ^{klmn}	13.3 ^a	—
	15	42.0 ^{ghi}	10.1 ^{ef}	1.21 ^{klmn}	10.5 ^b	—
	20	55.0 ^{ef}	7.7 ^{ij}	2.67 ^{hi}	6.4 ^{cd}	15.5 ^{ab}
	25	44.0 ^{fgh}	8.9 ^{gh}	1.77 ^{ijk}	9.6 ^b	—
	30	26.0 ^{kl}	7.5 ^j	1.38 ^{klm}	10.2 ^b	—
	35	12.2 ^{mno}	8.6 ^{hi}	0.59 ^{mno}	—	—
	40	0.0 ^P	—	—	—	—
<i>S. sahandica</i>	0	0.0 ^P	—	—	—	—
	5	10.6 ^{no}	18.0 ^a	0.20 ^o	—	—
	10	19.7 ^{lm}	11.0 ^e	0.64 ^{lmno}	—	—
	15	58.0 ^{de}	7.0 ^{jk}	2.56 ^{hij}	5.2 ^{de}	7.5 ^c
	20	81.0 ^{ab}	4.6 ^{lm}	5.81 ^{bc}	2.5 ^{ghi}	3.7 ^d
	25	67.0 ^{cd}	6.17 ^k	4.37 ^{ef}	3.58 ^{fg}	7.53 ^c
	30	49.7 ^{efg}	5.0 ^l	3.84 ^{fg}	3.23 ^{fgh}	7.38 ^c
	35	24.2 ^{kl}	4.12 ^{lmn}	3.22 ^{gh}	—	—
	40	0.0 ^P	—	—	—	—

Species	Temperature [C°]	GP [%]	MGT [days]	GR _m	D ₂₅ [days]	D ₅₀ [days]
<i>S. bachtiarica</i>	0	0.0 ^p	—	—	—	—
	5	18.6 ^{lm}	13.4 ^d	0.49 ^{mno}	—	—
	10	44.7 ^{fgh}	7.6 ^j	2.01 ^{ijk}	7.2 ^c	—
	15	83.0 ^{ab}	4.7 ^{lm}	4.89 ^{de}	3.3 ^{fgh}	4.3 ^d
	20	89.0 ^a	4.3 ^{lmn}	6.57 ^b	2.3 ^{ghi}	3.6 ^d
	25	88.0 ^a	3.8 ^{mn}	8.01 ^a	1.5 ^{ij}	2.7 ^{de}
	30	72.0 ^{bc}	4.5 ^{lm}	5.56 ^{cd}	2.5 ^{ghi}	4.4 ^d
	35	37.9 ^{hij}	3.5 ⁿ	5.15 ^{cde}	4.3 ^{ef}	—
	40	0.0 ^p	—	—	—	—

Values followed by different letters are significantly different at $p \leq 0.05$ level according Duncan's multiple range test

Germination process reacts differently to various temperatures, because temperature increased up to the optimum leads to increased enzyme activity and thus increases the efficiency of enzymatic reactions that it would improve the rate and percentage of germination. However, very low and very high temperatures inactivate enzymes and slow down reactions and thus reduce germination [46]. Besides, high temperatures, especially prolonged, lead to protein degradation and subsequent disruption of membranes and finally reduces germination rate [47, 48]. As well as high and low temperatures negatively affect sensitive embryo and finally seed germination by altering the amount of abscisic acid [49].

Maximum germination percentage (GP) was observed at 20°C for all four *Satureja* species, although there was no significant difference between 20 and 25°C, except *S. sahandica* ($p \leq 0.05$). At these temperatures (20–25°C), no significant difference was observed among species, except *S. macrantha* that showed the lowest GP (tab. 3). Minimum value of mean germination time (MGT) and maximum value of germination rate of maguire (GR_m) were also recorded at 20°C (*S. macrantha* and *S. sahandica*), and 25°C (*S. mutica* and *S. bachtiarica*). Among studied species, *S. bachtiarica* showed the highest value of GP and GR_m, and the minimum value of MGT at all temperatures (tab. 3). According to data in table 3, maximum GP was consistent with maximum GR_m and minimum MGT. Recently, MGT has been shown to be highly indicative of seed emergence performance [38, 45, 50].

There have been little studies conducted on temperature requirements for seed germination and cardinal temperatures of *Satureja* species, majority of which are related to annual savory. For instance, base, optimum and ceiling temperatures of annual savory (*S. hortensis*) were reported to be 7.56, 23.98 and 40°C [51] as well as 8, 24.77 and 41°C [43], respectively. The optimum and maximum temperatures for seed germination of most species have been reported between 15–30°C and 30–40°C, respectively [52]. Optimum temperature for maximum germination of *Plantago ovate* and *Plantago psyllium* were 15 and 25°C, respectively [53]. In other germination tests on some medicinal plants (*Lamiaceae*), the optimum thermal

range for seed germination have been reported for *Thymus kotschyanus* (15–30°C), *Nepeta binaludensis* and *Nepeta crassifolia* (20–30°C), *Nepeta glomerulosa* (20–25°C) and *Zataria multiflora* (15–20°C) [54]. Generally, each plant has a specific range of optimum temperature and exact value depends on the species or variety and other growth conditions [55]. Adam *et al.* [32] also reported various GR in several species.

Cumulative germination percentage curves have been fitted for different species of *Satureja* at different temperatures. Curve-fitting methods have been used to characterize the germination of seeds, compare seed pretreatments, and measure seedlot differences [56, 57]. Fitted curves offer a better description of the time-course of germination than single-value indices; and the original data can be reconstructed with minimal distortion and loss of information [58].

Figure 1
Effect of different constant temperatures on germination rate of (A) *S. mutica* and (B) *S. macrantha* based on three fitted models (a) intersected-line (b) quadratic polynomial (c) five parameters beta

Figure 2

Effect of different constant temperatures on germination rate of (A) *S. sahandica* and (B) *S. bachtiarica* based on three fitted models (a) intersected-line (b) quadratic polynomial (c) five parameters beta

Analysis of variance showed that time to 25% and 50% germination (D_{25} , D_{50}) were not significantly ($p \leq 0.05$) different at 20, 25 and 30°C for all species except *S. macrantha*, which reached to 50% germination only at 20°C. The D_{50} of *S. macrantha* was significantly ($p \leq 0.05$) higher than other species, which was associated with lowest GP and GR_m (tab. 3). Results also indicated that none of the *Satureja* species reached 50% germination at temperatures lower than 15 and higher than 30°C.

Figures 1 and 2 showed the regression equations of germination rate (GR_m) over nine temperatures separately for the sub- and supra-optimal temperatures ranges in four species. Germination rate is more sensitive to temperature than germination percentage. That is why the response of germination rate to temperature is used to determine the cardinal temperatures [59]. It is suggested that the energy of water increases in response to the elevation of temperature, provoking an increase in diffusion pressure, which concomitantly elevates the metabolic activity and diminishes the internal potential of a seed, promoting increased absorption of water. Thus, hydration occurs more rapidly at higher temperatures through physical processes that could accelerate germination [60]. Rapid germination means rapid radicle emergence and more available water for seedling to be established easier [61].

Cardinal temperatures (T_b , T_o and T_c) were estimated based on the regression relations between germination rate and temperature, using three models including intersected-line (ISL) ($R^2>0.81$), quadratic polynomial model (QPN) ($R^2>0.68$) and five-parameters beta (FPB) ($R^2>0.81$). All three models were able to reliably predict the rate of germination (tab. 4). Based on these estimations, the cardinal temperatures (T_b , T_o and T_c) were estimated in ranges of 2–5.4°C, 23.8–26.5°C and 42.2–45.7°C for *S. mutica*, 0.7–2.7°C, 20.8–21.4°C and 39.4–40°C for *S. macrantha*, 2–4.5°C, 22.1–24.3°C and 41.7–45.1°C for *S. sahandica* and 2–3.8°C, 22.8–25.2°C and 41.8–44.8°C for *S. bachtiarica*, respectively (tab. 4). There was disparity between cardinal temperatures estimated by different regression models. Such disparity has also been reported for cardinal temperatures of two seed lots of *Thymus transcaspicus*, estimated by different models [34].

Table 4.

Calculated cardinal temperatures for four species of *Satureja* for three fitted models based on germination rate of maguire (GR_m)

Species	Intersected-line model						Quadratic polynomial						Five parameters beta					
	t _b	T _c	T _o	R ²	SE	RMSE	T _b	T _c	T _o	R ²	SE	RMSE	T _b	T _c	T _o	R ²	SE	RMSE
<i>S. mutica</i>	5.4	42.2	26.5	0.90	1.27	0.69	4.9	42.6	23.8	0.68	2.01	1.80	2.0	45.7	25.8	0.85	1.34	0.95
<i>S. macrantha</i>	2.4	39.8	20.8	0.95	0.25	0.18	2.7	39.4	21.1	0.85	0.43	0.40	0.7	40.0	21.4	0.89	0.41	0.29
<i>S. sahandica</i>	4.5	43.5	22.1	0.87	1.03	0.69	4.2	41.7	22.9	0.78	1.34	1.22	2.0	45.1	24.3	0.81	1.18	0.84
<i>S. bachtiarica</i>	3.0	42.1	25.2	0.93	1.04	0.61	3.8	41.8	22.8	0.86	1.56	1.46	2.0	44.8	24.0	0.92	1.13	0.80

T_b , T_o and T_c are base, optimum, ceiling temperatures, respectively, R^2 is determination coefficient, SE is standard error, RMSE is root mean square error

Results represented that *S. macrantha* and *S. mutica* had the lowest and the highest cardinal temperatures, respectively, in all three models. The calculated base and optimum temperatures of *S. macrantha* confirmed its adaptation to low temperatures. Nadjafi *et al.* [20] stated, germination behaviour is highly related to the ecological conditions of a species' natural habitat.

Results revealed that five-parameters beta (FPB) and intersected-line (ISL) models were the most reliable ones for predicting cardinal temperatures, because of the higher R^2 value and the lower RMSE, yet all the three models showed a good predicting ability (tab. 4). Khalili *et al.* [43] and Heidari [28] reported Beta model to be the best one for interpreting germination rate of savory (*Satureja hortensis*) and milk thistle (*Silybum marianum* L.). Beta function model have been used by Jame and Cutforth [30], Dashti *et al.* [35] and Parmoon *et al.* [62] as the best-fitting output for cardinal temperatures, by its higher R^2 and lower RMSE. Tabrizi *et al.* [34] also reported that FPB and ISL were the best fitted models for cultivated and natural stand seeds of *Thymus transcaspicus*.

Determination of cardinal temperatures could be a useful guidance to introduce these species in a new area or in selection of the sowing time [22]. A clear understanding of cardinal temperatures could also be the first step for domestication of these species.

CONCLUSIONS

1. Decreased germination was observed at temperatures higher than and lower than 20°C, for all species.
2. The wide range of temperatures that produced final germinations greater than 70% (tab. 3) indicated that the potential germination of *S. bachtiarica* was high.
3. Our results revealed that five-parameters beta (FPB) and intersected-line (ISL) were applicable models to calculate cardinal temperatures.
4. The results also confirmed that in the absence of other limiting factors (e.g., water, light and media), the seed germination of studied *Satureja* species was influenced by temperature.
5. Measured germination parameters in the present study indicated superiority of *S. bachtiarica* over the other species, *S. macrantha* was inferior.

Conflict of interest: Authors declare no conflict of interest.

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OCENA TEMPERATUR GŁÓWNYCH KIEŁKOWANIA CZTERECH GATUNKÓW CZĄBRU ROSNĄCYCH W IRANIE

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Streszczenie

Wstęp: Kiełkowanie nasion jest złożonym procesem fizjologicznym regulowanym przez czynniki genetyczne i środowiskowe, w tym temperaturę, wodę, tlen, światło i pH. Wśród nich, temperatura jest jednym z najważniejszych czynników wpływających na maksymalną szybkość i procent kiełkowania diaspor. **Cel:** W niniejszej pracy określono temperatury główne (T_b , T_o , T_i) kiełkowania nasion dla czterech gatunków cząbrz występujących w Iranie. **Metody:** Nasiona *Satureja mutica* Fish. et C. A. Mey., *S. macrantha* C. A. Mey., *S. sahandica* Bornm i *S. bachtiarica* Bunge inkubowano w dziewięciu stałych temperaturach (od 0 do 40°C), w przedziałach co 5°C. Wykonano doświadczenie czynnikowe w układzie całkowicie losowym z czterema powtórzeniami, a dla określenia temperatur głównych zastosowano trzy modele regresji: segmentową regresję liniową (ISL), wielomianu kwadratowego (QPN) oraz regresję pięcioparametrową (FPB). **Wyniki:** Najwyższy procent kiełkowania (GP) odno-

towano w temperaturze 20°C, odpowiednio: u *S. mutica* (86%), *S. macrantha* (55%), *S. sahandica* (81%) i *S. bachtiarica* (89%). Z wyjątkiem *S. sahandica*, nie stwierdzono jednak istotnej różnicy między 20 a 25°C. Kiełkowanie ustało w 0°C i w 40°C. Najwyższa zdolność kiełkowania (GR), najkrótszy średni czas kiełkowania (MGT) oraz czas kiełkowania 50% nasion (D_{50}) obserwowano przy 20–25°C u wszystkich gatunków. Zdolność kiełkowania diaspor *S. bachtiarica* była istotnie ($p \leq 0.05$) wyższa niż u trzech pozostałych gatunków we wszystkich analizowanych temperaturach. Żaden z gatunków nie osiągnął 50% kiełkowania w temperaturach wyższych niż 30°C. **Wnioski:** Uzyskane wyniki pokazały przewagę *S. bachtiarica* nad innymi gatunkami, a *S. macrantha* charakteryzowała się najniższymi parametrami opisującymi kiełkowanie. Modele FPB i ISL najdokładniej przewidywały poziom temperatur głównych, ze względu na wyższą wartość współczynnika determinacji R^2 i niższą wartość średniej kwadratowej błędów (RMSE). We wszystkich trzech modelach najniższe i najwyższe temperatury główne (T_b , T_o , T_c) zanotowano odpowiednio u *S. macrantha* i *S. mutica*.

Słowa kluczowe: temperatury główne, kiełkowanie, cząbker, modele regresji