Agrotechniques in Industrial Crops

Journal Homepage: https://atic.razi.ac.ir

Effect of Seed Color and Size on Cardinal Temperatures of Castor Bean (*Ricinus Communis* L.) Seed Germination

Seyed Amir Moosavi[*1], Seyed Ataollah Siadat[1], Ahmad Koochekzadeh[1], Ghasem Parmoon[2], Samaneh Kiani[1]

[1]*Department of Plant Production and Genetics, Faculty of Agriculture, Agricultural Sciences and Natural Resources University of Khuzestan, Iran*

[2]*Department of Agronomy, Faculty of Agriculture, University of Mohaghegh Ardabili, Ardabil, Iran*

ARTICLE INFO

Original paper

Article history:
Received: 25 Jan 2022
Revised: 27 Feb 2022
Accepted: 25 Mar 2022

Keywords:
Base temperatures
Germination rate
Regression
Seed morphology

ABSTRACT

Many studies have focused on the cardinal temperatures and thermal time requirements of seed germination, but how seed size and color affect germination rate and thermal thresholds is poorly understood. In this study, nonlinear regression models were used to examine the relationships among seed size, seed color, and germination rate, and assess the extent to which these seed traits influence cardinal temperature and thermal time requirements for seed germination. The beta-modified model was found to be the best model for predicting the required time to reach 50% germination. Based on the model output, the base, optimum, and maximum temperatures were 4.49-8.59, 19.76-21.88 and 34.12-41.68 °C, respectively. Larger seeds have a higher base and ceiling temperatures compared to smaller seeds. The thermal time of 50% germination was 1890, 954, 1551, and 1188 degree-hours for small and large greenish-gay and reddish-brown seeds, respectively. The lower germination rate in greenish-gray seeds compared with reddish-brown colored seeds could be due to the lower seed vigor or viability. Not all castor seeds are produced at the same time during the growing season. Therefore, the last produced grains lose ideal grain filling conditions, which cause them to be smaller, less dense, and have low vigor.

DOI: 10.22126/ATIC.2022.7417.1041

1. Introduction

Seed germination is a key process in the successful establishment of a plant in a given habitat, and it can be dramatically influenced by seed traits and environmental factors (Wang *et al*., 2016). Seed size is a plastic trait that has a direct impact on the quality of seed germination (Souza and Fagundes, 2014). Seed size can interact with many environmental factors which affect successful seedling establishment in the field (Saeed and Shaukat, 2000; Baskin and Baskin, 2014; Steiner *et al*., 2019). Seed size in the Kingdom of Plantae varies from species to species, but it is possible to find variations within plant species. The relationship between seed size and the thermal threshold of seed germination is poorly understood. However, there are some reports that investigate the effect of seed size on the germination properties of some plant species. It has been previously reported that seed mass may affect germination percentage (Soriano *et al.*, 2011; Xu *et al.*, 2014). Some reports suggest that smaller oat seeds germinate more rapidly than larger ones (Willenborg *et al.*, 2005). However, studies showed that the larger the seed of safflower, the higher the number of seeds that germinated (Sadeghi *et al.*, 2011). It was reported that the large seeds of *Senna occidentalis* L. exhibited a higher germination percentage compared with small seeds (Saeed and Shaukat, 2000). It has been reported that larger seeds germinate faster than small seeds in winterfat (*Eurotia lanata* (Pursh) Moq.), possibly due to the ability of large seeds to provide higher energy and nutrients for greater germination capacity (Vaughton and Ramsey, 1998; Humara *et al.*, 2002).

* Corresponding author.
E-mail address: amirmoosavi@asnrukh.ac.ir

It has been shown that seeds of darker color exhibited lower electrical conductivity compared with light-colored seeds, which was correlated with their higher seed germination potential (Mavi, 2010). It was reported that rape seeds with red or black seed coat color exhibited higher seed germination quality than yellow-colored ones. The superiority of dark-colored rape seeds to light may be attributed to a higher amount of melatonin pigment (Zhang *et al*., 2006). The previous report showed that at the various incubation temperatures, the yellow-colored seeds of *lotus halophilus* have a lower germination index than the green seeds (Bhatt *et al*., 2016).

Previous findings revealed that size and color are two influential factors for oilseed rape germinability. It has been shown that the larger seeds of oilseed rape have higher germinability when compared with small-sized seeds. It was also noted that seeds with a darker coat exhibited higher seed quality after a certain number of storage periods (Knežević *et al*., 2019).

Seeds need to germinate under suitable thermal, moisture, and light conditions so that the chances of seedling survival and establishment are increased (Biswas *et al*., 2019). Temperature is regarded as the most prominent environmental factor regulating seed germination and the rate of its progress towards seedling development (Fenner, 2012; Bita and Gerats, 2013). The seed requires a certain amount of heat to initiate the germination process. This temperature is called the base temperature, and the germination rate linearly increases as the temperature becomes higher and eventually reaches the maximum seed germination at the optimum temperature (Alvarado and Bradford, 2002; Fenner, 2012). The effect of temperature on seed germination is characterized by cardinal temperatures: minimum or base (T_b), maximum or ceiling (T_c), and optimum (T_o). Seed germination occurs between T_b and T_c, which are the lowest and highest temperatures, respectively, at which seeds can complete their germination (Alvarado and Bradford, 2002). The seed germination rate starts to decline when the temperature increases from the optimum and there is no seed germination at the ceiling temperature. Cardinal temperatures are therefore defined as base, optimum, and ceiling temperatures (Shafii and Price, 2001; Hardegree, 2006; Kamkar *et al*., 2006; Bewley *et al*., 2012). Many researchers use the thermal time to quantify the impact of temperature on plant and seed physiology (Lonati *et al*., 2009; Del Monte *et al*., 2014; Cochrane, 2017). Thermal time is also widely used to determine the planting date and time of emergence of plant species (Miller *et al*., 2001; Cleland *et al*., 2007).

It is unclear to what extent seed size and seed color influence the thermal thresholds of seed germination. Quantifying the cardinal temperatures of seed germination in plant species can help farmers identify the optimal sowing period at their geographic location and predict field establishment under different thermal scenarios (Kamkar *et al*., 2012; Motsa *et al*., 2015). Castor bean (*Ricinus communis* L.) is an annual or perennial shrub belonging to the euphorbiaceous family (Bauddh *et al*., 2015). It is native to East Africa, the southeastern Mediterranean Basin, and India, but is widespread throughout tropical regions and widely used as an ornamental plant (Severino *et al*., 2012). Castor is one of the main sources of non-edible vegetable oil in the arid and semi-arid regions (Sadashiv, 2011; Khan Marwat *et al*., 2017). Because it is a species of economic or agricultural interest, it is important to understand the thermal thresholds of the different varieties.

The fatty acid composition of castor bean seed oil mainly consists of ricinoleic acid. Seed meal contains 21–48% crude protein (Annongu and Joseph, 2008; Matos Júnior *et al*., 2011; Akande *et al*., 2016). Regarding medicinal properties, this plant can be used in inflammation treatment, liver disorders, hypoglycemia, and as a laxative (Kuete, 2014; Gusamo and Jimbudo, 2015). Castor bean has an intraspecific variation in seed size and seed color. Because this plant is a species of economic and agricultural interest, it is important to understand the thermal threshold of the different varieties.

A wide array of different effects of seed size in non-stressful and stressful conditions has been reported for seed germination, seedling emergence, and establishment in many crop species (Steiner *et al*., 2019). However, it is unclear to what extent seed size and seed color influence ecological thresholds for seed germination. A large number of reports have focused on the effect of seed size on germination percentage and seedling growth, but there is a lack of information about the effect of seed size and color on thermal thresholds of seed germination.

This study aimed to evaluate the effect of seed size and seed coat color on the thermal thresholds of castor bean seed germination.

2. Materials and methods

2.1. Seed source and processing

In this experiment, two genotypes of castor beans namely green and red leaf color with distinct seed colors were purchased from Pakan Bazr Co., Isfahan, Iran, 2019. The first genotype had a light greenish-gray-colored seed coat, and the second genotype had a reddish-brown colored seed coat. Seed lots were divided into two size classes: small (2 – 2.5 mg with a mean weight of 2.02 mg) and large (3 – 3.5 mg with a mean weight of 3.02 mg). The experiment started right after the acquisition of the seeds during fall 2019 using germinators with controlled environments in the Seed Technology Laboratory, Faculty of Agriculture, Agricultural Sciences and Natural Resources, University of Khuzestan, Iran.

2.2. Seed germination and temperature

Castor bean seeds were germinated under fully dark conditions according to the International Seed Testing Association (ISTA, 2017). Three replicates of 25 seeds from each treatment: small greenish-gray seeds, large greenish-gray seeds, small reddish-brown seeds, and large reddish-brown seeds were germinated in 12-cm diameter Petri dishes between two layers of Whatman No. 1 (12 cm diameter) filter paper containing 9 mL of distilled water in each of eight constant temperature ranges from 5°C to 40°C at 5°C intervals. Germination was monitored every 6 h during the first 4 days (96 h) and every 12 h until 14 days of evaluation. Seeds were considered to have germinated once the radicle had protruded at least 2 mm from the seed coat (Tobe *et al.*, 2004). Replicates were arranged in a completely randomized design. Seeds that showed signs of fungal growth were removed from the Petri dishes. Germinated seeds were counted, removed and expressed as a percentage of the total number of tested seeds.

2.3. Data analysis

The cumulative germination percentage per treatment was plotted against time. From the curve, the duration, or the required time to completion of seed germination fractions (D_{10}, D_{50}, and D_{90}), was determined using a logistic model as described by (Eq.1) (Soltani, 2007):

$$G = \frac{\text{Gmax}}{1 + \exp[s(t - b)]} \qquad (1)$$

Where G_{max} is the maximum germination percentage, b is a constant, s is the slope of the line, t is the time (h), and G is the germination. A germination rate (Gr) was determined for each germination fraction as the reciprocal of the time taken for a given fraction of the seeds to complete germination. The impact of temperature on seed germination rate was quantified using the following equation:

$$Gr= f(h)/f_o \qquad (2)$$

Where f (h) is the temperature (reduction factor) that ranges between zero at the base and ceiling temperatures to 1 at the optimal temperature, and 1/fo is the inherent maximum rate of germination at the optimal temperature. This function is the ratio of the germination rate at each temperature to the maximum seed germination rate as a function of temperature. In other words, fo represents the minimum number of hours required for completion of seed germination at the optimum temperature (Soltani *et al.*, 2006).

Sigma Plot, *Ver.* 14 software was used to calibrate the models (beta, beta modified, segmented, and dent-like) using an iterative optimization method. Nonlinear models used for the quantification of germination response to temperature are presented in (Fig. 1).

T is the temperature, T_b is the base temperature, T_o the optimum temperature, T_{o1} represents the lower optimum temperature for a 3-piece segmented function, and T_{o2} represents the upper optimum temperature for a 3-piece segmented function, T_c the maximum temperature, c, a shape parameter for the beta function that determines the curvature of the function, and d, the parameter of the beta modified function that indicates the sensitivity of the germination rate to temperature. The daily thermal time (DTT) was calculated as DTT= $(T_o-T_{b)}\times f(h)$, where f(h) is the T function, T_{o1} is the lower optimum T, and T_b is the base T. To determine the best estimates of the parameters, Root Mean Square (RMSE) (Timmermans *et al.*, 2007) and the coefficient of determination (R^2) were used (Butler and King, 2004; O'Meara *et al.*, 2006). Low *RMSE* and R^2 *values* close to 1 correspond to better model estimation.

3. Results

Seeds with a greenish-gray seed coat germinated slower than seeds with a reddish-brown seed coat at all temperature regimes (Fig. 2). The segmented model output showed that the base temperature (T_b) of small seeds in greenish-gray seeds was 4.72 ºC for 50% of the total seed population, which was slightly higher than larger seeds (4.29 ºC). In seeds with a reddish-brown seed coat, the base temperature for germination of 50% of the total population was 4.99 and 4.56 for small and large seeds, respectively. 21 ºC is the optimum for both small and large Greenish-gray seeds, while it was 19 and 20 ºC for small and larger reddish-brown, respectively (Table 1). The segmented model fitted on relative germination rate against mean temperature for three germination fractions (10%, 50% and 90%) is presented in Fig. 2.

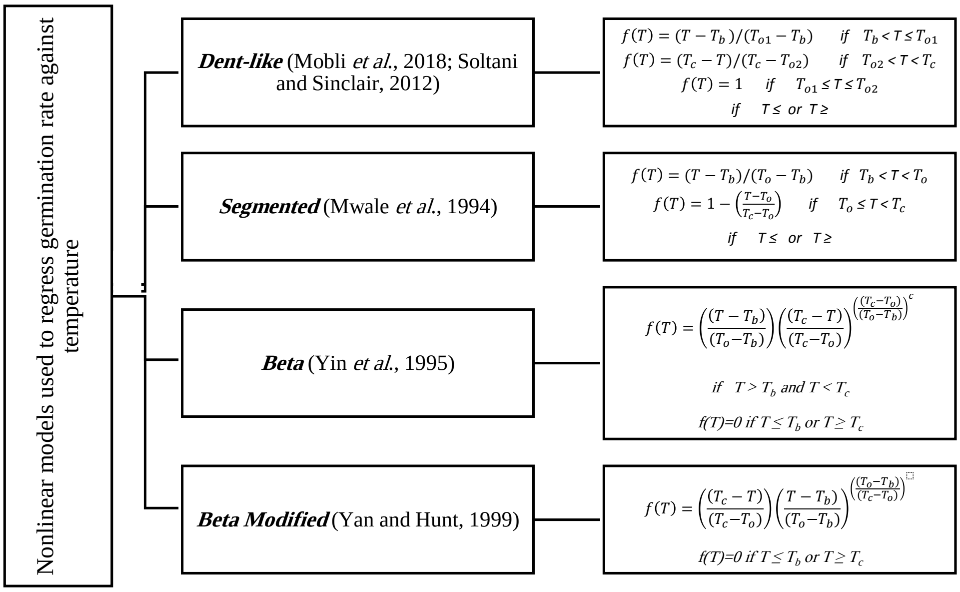

Figure 1. Nonlinear models used to regress germination rate against temperature.

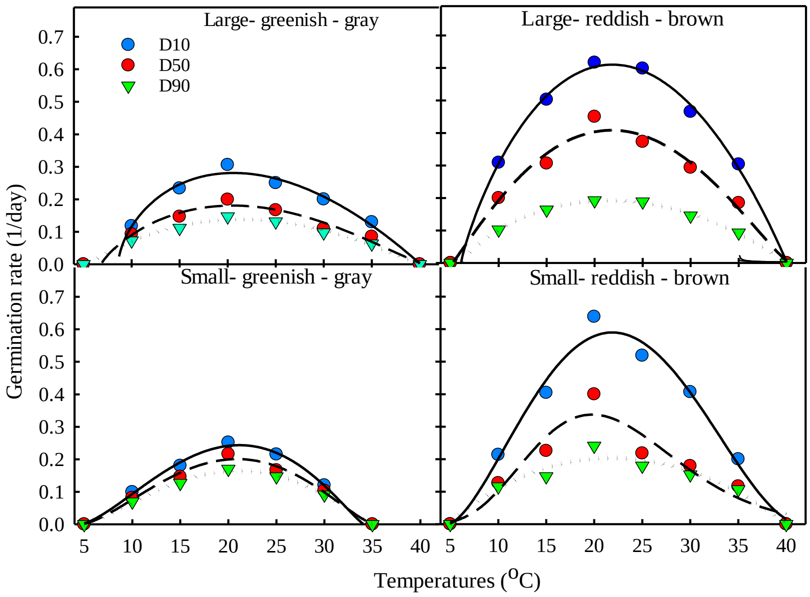

Figure 2. Predicted (lines) vs. observed (symbols) germination rate of *Ricinus communis* seeds at different constant temperatures using non-liner models.

T_b was estimated for a germination fraction of 50% using a dent-like model in small and large size greenish-gray seeds, and was 4.63±0.27 and 2.43± 0.18. The optimum temperature of seed germination fraction 50% for small and large-sized reddish-brown seeds was 5.02 ± 0.43; 3.30 ± 0.59, respectively. This suggests that small-sized seeds require a higher temperature for initial seed germination compared with larger ones. The calculated R^2 and RMSE values from the segmented model for different seed germination fractions of 10, 50, and 90% in larger reddish-brown seeds were 0.993, 0.956, and 0.941, respectively.

Table 1. Estimated parameters for the segmented model for different germination fractions of *Ricinus communis* seeds.

Types	Size	Fraction	T_b	T_o	T_c	fo	R^2	RMSE
Greenish-gray	Small	10%	4.55±0.52	21.80±0.43	35.19±0.44	3.47±0.10	0.995	0.010
		50%	4.72±0.63	21.25±0.56	35.40±0.60	4.24±0.15	0.992	0.010
		90%	4.43±0.88	21.90±0.70	35.41±0.74	5.04±0.23	0.986	0.011
	Large	10%	3.77±1.50	22.09±1.20	41.23±1.56	1.34±0.09	0.958	0.066
		50%	4.29±1.03	21.16±0.91	41.17±1.26	2.04±0.10	0.976	0.034
		90%	3.52±1.67	22.02±1.30	41.14±1.68	4.23±0.29	0.951	0.023
Reddish-brown	Small	10%	5.04±0.52	20.83±0.94	40.48±0.65	2.97±0.16	0.975	0.024
		50%	4.99±1.34	19.24±1.12	40.21±1.69	4.64±0.27	0.971	0.016
		90%	4.15±1.61	21.40±1.03	41.90±2.26	5.94±0.33	0.969	0.013
	Large	10%	4.55±1.00	21.19±0.50	41.34±1.36	1.47±0.04	0.993	0.026
		50%	4.56±1.08	20.00±1.69	41.68±1.48	2.78±0.19	0.956	0.036
		90%	3.87±1.23	20.62±1.48	41.04±1.37	4.03±0.33	0.941	0.027

Tb, To, Tc, and fo are base temperature, optimum temperature, maximum temperature, minimum time to reach a given percentile, and coefficient of regression, respectively

Table 2. Estimated parameters for a dent-like model for different germination fractions of *Ricinus communis* seeds.

Types	Size	Fraction	T_b	T_{o1}	T_{o2}	T_c	fo	R^2	RMSE
Greenish-gray	Small	10%	4.28±0.25	17.78±1.50	25.27±1.80	35.00±0.79	4.83±0.98	0.988	0.019
		50%	4.63±0.27	19.55±1.52	22.43±1.19	35.40±0.72	4.81±0.80	0.992	0.013
		90%	5.87±0.38	18.24±1.41	23.83±1.07	35.41±0.71	4.84±0.80	0.991	0.011
	Large	10%	1.75±0.11	14.27±2.07	28.20±1.63	40.51±1.25	5.00±0.97	0.974	0.06
		50%	2.43±0.18	17.92±2.00	26.41±2.20	40.43±1.39	4.49±1.34	0.971	0.042
		90%	5.50±0.28	13.87±1.57	27.97±1.41	40.47±1.05	5.00±0.78	0.982	0.016
Reddish-brown	Small	10%	3.60±0.25	19.21±1.94	26.60±2.00	39.97±1.10	4.99±1.05	0.976	0.027
		50%	5.02±0.43	18.14±1.91	22.12±2.39	40.08±3.51	4.56±1.13	0.976	0.017
		90%	7.18±0.45	16.97±1.49	26.24±1.95	40.67±2.69	4.49±1.08	0.979	0.012
	Large	10%	1.73±0.10	16.88±1.53	25.75±1.93	40.50±1.30	4.91±1.12	0.981	0.049
		50%	3.30±0.59	18.23±5.01	25.00±6.40	41.12±1.51	4.80±3.17	0.854	0.076
		90%	5.29±0.67	13.17±3.31	28.27±3.42	40.51±1.23	5.00±1.79	0.894	0.042

Tb, To_1, To_2, Tc, and fo are base temperature, upper limit of optimum temperature, lower limit of optimum temperature, maximum temperature, minimum time to reach a given percentile, and coefficient of regression, respectively

Results related to Dent-like models indicated that this model was less reliable than a segmented model due to lower R^2 and RMSE (Table 2). The estimated To_1 and T_{O2} from greenish-gray seeds obtained from the dent-like model were To_1=17.78, T_{O2} =25.27 ºC, To_1=19.55, To_2=22.43 ºC and To_1=18.24, To_2=23.83°C for D_{10}, D_{50}, and D_{90}, respectively. According to the Beta model, the optimum temperature for a fraction of 50% of total seed germination varied between 20 and 21 ºC for castor bean seeds. Based on the statistical evidence (R^2 and RMSE), the Beta-modified and segmented models were more reliable than the dent-like model to estimate the cardinal temperatures of germination fraction in two groups of colored castor bean seeds. Because the highest average R^2 and the lowest RMSE values were in the beta modified function, this function was used to determine the cardinal temperature and thermal time requirement of castor bean seed germination. The base temperature estimated by the beta function was slightly higher than the other models. For instance, the estimated T_b of 10% germination fraction for small greenish-gray and reddish-brown seeds was 7.13±2.39, (R^2=0.97) and 7.00±6.92 ºC, (R^2=0.98) while for the same fraction, the segmented model estimated 4.55±0.52, R^2=0.99 and 5.04±0.52 ºC, R^2=0.97 (Table 3). Based on the output from the beta modified function, the estimated cardinal temperatures of fraction 50% of total seed germination in large seeds of greenish-gray were: T_b=4.49±3.24, To=21.75±1.62, T_c=40.34±1.93 ºC; (R^2=0.97), (RMSE=0.037) and for and reddish-brown type were (Tb=2.00±9.81, To=19.76±2.04, Tc=40.57±9.48 ºC; R^2=0.89, RMSE=0.064) (Table 4).

Table 3. Estimated parameters for the beta model for different germination fractions of *Ricinus communis* seeds.

Types	Size	Fraction	T_b	T_o	T_c	fo	R^2	RMSE
Greenish-gray	Small	10%	6.85±1.99	20.75±0.90	34.83±0.45	4.26±0.18	0.983	0.016
		50%	7.13±2.39	20.62±1.18	34.87±0.60	5.16±0.29	0.970	0.017
		90%	6.35±1.46	20.96±0.57	34.93±0.28	6.16±0.17	0.993	0.007
	Large	10%	5.80±1.04	21.92±0.41	40.05±0.23	1.64±0.03	0.997	0.016
		50%	6.91±2.46	21.44±1.30	39.93±0.74	2.49±0.12	0.968	0.033
		90%	5.74±0.86	21.56±0.33	40.05±0.18	5.18±0.06	0.998	0.004
Reddish-brown	Small	10%	7.00±3.07	21.49±1.13	39.90±0.64	3.61±0.15	0.976	0.020
		50%	7.00±6.92	20.59±1.63	39.96±0.94	5.65±0.33	0.955	0.017
		90%	5.00±0.59	21.12±0.90	39.98±0.51	7.27±0.24	0.985	0.008
	Large	10%	7.00±2.08	21.99±1.63	39.48±0.86	1.82±0.12	0.948	0.061
		50%	7.00±3.01	20.65±3.71	39.46±1.99	3.47±0.48	0.809	0.067
		90%	6.65±1.84	21.82±1.38	40.10±1.10	4.91±0.35	0.943	0.026

Tb, To, Tc, and fo are base temperature, optimum temperature, maximum temperature, minimum time to reach a given percentile, and coefficient of regression, respectively

Table 4. Estimated parameters for beta modified model for different germination fractions of *Ricinus communis* seeds.

Types	Size	Fraction	T_b	T_o	T_c	fo	C	R^2	RMSE
Greenish-gray	Small	10%	6.09±1.87	21.16±0.82	34.12±3.76	4.11±0.16	1.54±0.61	0.993	0.012
		50%	5.16±7.02	20.89±0.88	35.26±2.05	4.98±0.34	1.62±0.80	0.985	0.018
		90%	6.14±1.50	21.12±0.40	35.03±0.66	6.05±0.18	1.40±0.26	0.997	0.007
	Large	10%	4.49±1.82	21.86±0.59	40.02±0.25	1.64±0.03	0.85±0.24	0.997	0.018
		50%	4.49±3.24	21.75±1.62	40.34±1.93	2.45±0.15	1.10±1.06	0.970	0.037
		90%	4.78±1.14	21.47±0.49	40.02±0.19	5.19±0.08	0.80±0.19	0.998	0.004
Reddish-brown	Small	10%	8.59±1.60	20.61±1.30	40.08±0.78	3.56±0.17	0.61±0.32	0.983	0.020
		50%	6.84±5.73	20.47±2.08	40.57±2.58	5.53±0.41	0.82±0.91	0.958	0.019
		90%	5.45±4.61	21.37±1.20	40.19±1.04	7.20±0.30	0.96±0.63	0.986	0.008
	Large	10%	4.68±4.18	21.88±0.97	41.64±4.58	1.70±0.11	1.70±1.06	0.980	0.050
		50%	2.00±9.81	19.76±2.04	40.57±9.48	2.96±0.46	5.78±37.23	0.898	0.064
		90%	5.00±0.65	21.83±1.65	40.09±1.46	4.91±0.48	0.92±0.36	0.943	0.031

Tb, To, Tc, fo and c are base temperature, optimum temperature, maximum temperature, minimum time to reach a given percentile, and coefficient of regression, respectively

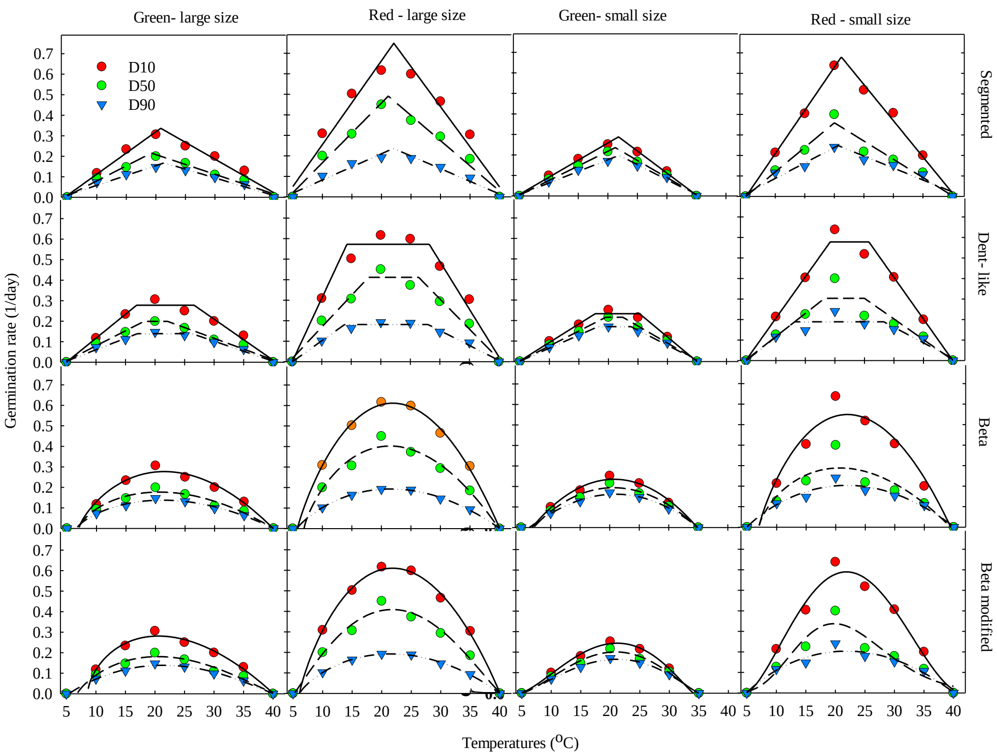

Figure 3. Thermal time (degree hours) required for different germination fractions based on pooled data, when T = To. Observed (filled circles) and predicted (solid line). F(t) values for different constant temperatures based on the beta model.

The ceiling temperature was very similar for larger seeds as for small seeds, and it was in the range of 34 to 35 ºC, while reddish-brown seeds germinated at approximately 5 ºC higher temperature than small seeds, in the range of 40 to 41 ºC. A temperature function, or f (T), was calculated for small and large seeds of both greenish-gray and reddish-brown seeds (Fig. 3). Temperatures above 5 ºC cause an increase in the f (t) values of large seeds, which reaches a maximum at 20 ºC and then begins to decline. This suggests that the optimum temperature for large seeds is around 20 °C. The thermal time required for germination of Reddish-brown seeds was lower than that of greenish-gray seeds. The thermal time required for 60% seed germination of reddish-brown seeds was lower than 1500 degree hour, while small-sized greenish-gray seeds germinated below 30% at the thermal time of 1500 degree hour (Fig. 3).

4. Discussion

In this study, we show that the morphology of castor bean seeds impacts seed germination and that seed size has more impact on seed germination requirements of castor beans compared with seed coat color. Seeds with a greenish-gray color showed a lower germination rate than reddish-brown seeds (Fig. 2). The thermal time required for the germination of Reddish-brown seeds was lower than greenish-gray seeds. Additionally, with regard to seed color, smaller seeds showed a higher base temperature for germination. Results of the study suggest that castor seeds germinate faster at higher temperatures due to a high degree of thermo-plasticity. However, seed metabolite profiling at 35 ºC revealed some levels of heat stress in germinating seeds (Ribeiro *et al*., 2015).

The thermal times required for 50% germination were 1890, 954, 1551, and 1188 degree-hours for small and large greenish-gay and reddish-brown seeds, respectively. The lower germination rate in greenish-gray seeds compared with reddish-brown colored seeds could be due to the lower seed vigor or viability, which is related to the physiological status of seed lots.

It was revealed that the larger the seeds, the lower the time is required for completion of seed germination at the optimum temperature. The large seeds of both castor bean genotypes exhibited lower f_o than the smaller elios seeds, which showed faster germination for each fraction of seed germination. Not all castor seeds are produced at the same time during the growing season. Therefore, the last produced grains lose ideal grain filling conditions, which causes them to be smaller, less dense, and have low vigor (Marcos Filho, 2015). Our results are in agreement with those of (Drumond *et al*., 2019), who reported that denser castor bean seeds exhibited higher germination performance than the lighter seeds. A previous study revealed that the quality of castor seed germination is highly dependent on seed coat properties (Veloso *et al*., 2017). Seed response to temperature varies according to seed coat treatment. Castor seeds germinated faster and higher when scarified and relived from seed coat imposed dormancy (Mendes *et al*., 2009). The ceiling temperature was 34 to 35 ºC in larger seeds. These findings were in agreement with Wang et al. (2004) who reported that larger seeds of winterfat (*Eurotia lanata*) exhibit a lower base temperature compared with smaller seeds. However, there was no difference between sizes for the thermal time requirement of 50% seed germination fraction of winterfat.

Elaiosome removal improved castor seed germination (Martins *et al*., 2006) as chemicals inside the elaiosome are responsible for its inhibitory effects on germination (Sasidharan and Venkatesan, 2019). The thermal response of castor bean seeds is directly influenced by the age of the seeds. At alternating temperatures, germination of fresh castor seeds was enhanced, while seed germination of old seeds did not improve at the same experimental conditions (Martins *et al*., 2009).

In all cases, except for small-sized reddish-brown seeds, there was a decline in the rate of germination and in the maximum germination above optimum temperature.

5. Conclusion

The outputs of this study will be useful for the characterization of the ecophysiology of seed germination of castor bean seeds and identifying the optimal sowing dates for this industrial plant in a range of climates and regions. Such findings from morphological seed features may also be useful for computer-aided image analysis in seed biology.

Conflict of Interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No human or animals were used in the present research.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

All authors had an equal role in study design, work, statistical analysis and manuscript writing.

Informed Consent

The authors declare not to use any patients in this research.

Funding/Support

This study was supported by University of Khuzestan, Iran.

Acknowledgment

The authors wish to thank the Agricultural Sciences and the Natural Resources University of Khuzestan for financial support (Grant #981/04).

References

Akande T.O., Odunsi A.A., Akinfala E.O. 2016. A review of nutritional and toxicological implications of castor bean (*Ricinus communis* L.) meal in animal feeding systems. Journal of Animal Physiology and Animal Nutrition 100(2): 201-210. https://doi.org/10.1111/jpn.12360

Alvarado V., Bradford K.J. 2002. A hydrothermal time model explains the cardinal temperatures for seed germination. Plant, Cell & Environment 25(8): 1061–1069. https://doi.org/10.1046/j.1365-3040.2002.00894.x

Annongu A.A., Joseph J.K. 2008. Proximate analysis of castor seeds and cake. Journal of Applied Sciences and Environmental Management 12(1). https://doi.org/10.4314/jasem.v12i1.55567

Baskin C.C., Baskin J.M. 2014. Seeds: ecology, biogeography and evolution of dormancy and germination., (2nd in)(Academic Press: San Diego, CA, USA).

Bauddh K., Singh K., Singh B., Singh R.P. 2015: Ricinus communis: a robust plant for bio-energy and phytoremediation of toxic metals from contaminated soil. Ecological Engineering 84: 640–652. https://doi.org/10.1016/j.ecoleng.2015.09.038

Bewley J.D., Bradford K., Hilhorst H. 2012. Seeds: physiology of development, germination and dormancy, Springer Science & Business Medi. 133-181 https://doi.org/10.1007/978-1-4614-4693-4_4

Bhatt A., Gairola S., El-Keblawy, A.A. 2016. Seed colour affects light and temperature requirements during germination in two Lotus species (Fabaceae) of the Arabian subtropical deserts. Revista de Biología Tropical 64(2): 483-492. https://doi.org/10.1139/cjb-2019-0096

Biswas P.S., Rashid M.M., Khatun H., Yasmeen R., Biswas J.K. 2019. Scope and Progress of Rice research harnessing cold tolerance. Advances in Rice Research for Abiotic Stress Tolerance 225–264. https://doi.org/10.1016/B978-0-12-814332-2.00011-3

Bita C., Gerats T.2013. Plant tolerance to high temperature in a changing environment: scientific fundamentals and production of heat stress-tolerant crops. Frontiers in plant science 4, 273. https://doi.org/10.3389/fpls.2013.00273

Butler M.A., King A.A. 2004. Phylogenetic comparative analysis: a modeling approach for adaptive evolution. The American Naturalist 164(6): 683–695. https://doi.org/10.1086/426002

Cleland E.E., Chuine I., Menzel A., Mooney H.A., Schwartz M.D. 2007. Shifting plant phenology in response to global change. Trends in ecology & evolution 22(7): 357–365. https://doi.org/10.1016/j.tree.2007.04.003

Cochrane A. 2017. Modeling seed germination response to temperature in Eucalyptus L'Her. (Myrtaceae) species in the context of global warming. Seed Science Research 27(2): 1–11. https://doi.org/10.1017/S0960258517000010

Drumond A.A.L., Sales J. de F., Zuchi J., Camelo G.N., Souza M.M.V. 2019. Physiological quality of castor seeds (*Ricinus communis* L.) after processing. Journal of Seed Science 41, 224–232. https://doi.org/10.1590/2317-1545v41n2215551

Fenner M.W. 2012. Seed ecology, Springer Science & Business Media.

Gusamo B.K., Jimbudo M. 2015. Tree-borne Oilseed Crops: Jatropha curcas, Ricinus communis, Anacardium occidentale and Some Native Trees for Oil Production for Bio-energy Source in Papua New Guinea. Journal of Agriculture and Environmental Sciences 4(2): 113–123. https://doi.org/10.15640/jaes.v4n2a13

Hardegree S.P. 2006. Predicting germination response to temperature. I. Cardinal-temperature models and subpopulation-specific regression. Annals of Botany 97(6): 1115–1125. https://doi.org/10.1093/aob/mcl071

Humara J.M., Casares A., Majada J. 2002. Effect of seed size and growing media water availability on early seedling growth in Eucalyptus globulus. Forest ecology and management 167(1-3): 1–11. https://doi.org/10.1016/S0378-1127(01)00697-1

ISTA .2017. International rules for seed testing.

Kamkar B., Al-AlahKamkar B., Al-Alahmadi M.J., Mahdavi-Damghani A., Villalobos F.J. 2012. Quantification of the cardinal temperatures and thermal time requirement of opium poppy (*Papaver somniferum* L.) seeds to germinate using non-linear regression models. Industrial Crops and Products 35(1): 192-198. https://doi.org/10.1016/j.indcrop.2011.06.033

Kamkar B., Koocheki A., Nassiri Mahallati M., Rezvani Moghaddam P. 2006. Cardinal temperatures for germination in three millet species (*Panicum miliaceum*, *Pennisetum glaucum* and *Setaria italica*). Asian Journal of Plant Science 5(2): 316–319. https://doi.org/10.3923/ajps.2006.316.319

Khan Marwat S., Khan E.A., Baloch M.S., Sadiq M., Ullah I., Javaria S., Shaheen S. 2017. Ricinus cmmunis: Ethnomedicinal uses and pharmacological activities. Pakistan journal of pharmaceutical sciences 30.

Knežević J., Tomić D., Jovanović D., Tmušić N., Štrbanović R., Poštić D., Stanisavljević R. 2019. Seed quality of oilseed rape varieties with different size and colors after three and fifteen months storage. Tarim Bilimleri Dergisi 25(4): 449–458. https://doi.org/10.15832/ankutbd.442650

Kuete V. 2014. Physical, hematological, and histopathological signs of toxicity induced by African medicinal plants. Toxicological Survey of African Medicinal Plants 635–657. https://doi.org/10.1016/B978-0-12-800018-2.00022-4

Lonati M., Moot D.J., Aceto P., Cavallero A., Lucas R.J. 2009. Thermal time requirements for germination, emergence and seedling development of adventive legume and grass species. New Zealand Journal of Agricultural Research 52(1): 17–29. https://doi.org/10.1080/00288230909510485

Marcos Filho J. 2015. Seed vigor testing: an overview of the past, present and future perspective. Scientia Agricola 72, 363–374. https://doi.org/10.1590/0103-9016-2015-0007

Martins V.F., Guimarães P.R., Silva R.R. Da, Semir J. 2006. Secondary seed dispersal by ants of Ricinus communis (Euphorbiaceae) in the Atlantic forest in southeastern Brazil: Influence on seed germination. Sociobiology 47, 265–274.

Martins V.F., Haddad C.R.B., Semir J. 2009. Seed germination of *Ricinus communis* in predicted settings after autochorous and myrmecochorous dispersal. The Journal of the Torrey Botanical Society 136(1): 84–90. https://doi.org/10.3159/08-RA-092R.1

Matos Júnior J.B., Dias A.N., Bueno C.F.D., Rodrigues P.A., Veloso Á.L.C., Faria Filho D.E. de 2011. Metabolizable energy and nutrient digestibility of detoxified castor meal and castor cake for poultry. Revista Brasileira de Zootecnia 40, 2439–2442. https://doi.org/10.1590/S1516-35982011001100022

Mavi K. 2010. The relationship between seed coat color and seed quality in watermelon Crimson sweet. Horticultural Science 37, 62–69. https://doi.org/10.17221/53/2009-HORTSCI

Mendes R. de C., Dias D.C.F. dos S., Pereira M.D., Berger P.G. 2009. Tratamentos pré-germinativos em sementes de mamona (*Ricinus communis* L.).: Revista Brasileira de Sementes 31, 187–194. https://doi.org/10.1590/S0101-31222009000100021

Miller P., Lanier W., Brandt S. 2001. Using growing degree days to predict plant stages. Ag/Extension Communications Coordinator, Communications Services, Montana State University-Bozeman, Bozeman, MO 59717, 994–2721.

Mobli A., Ghanbari A., Rastgoo M. 2018. Determination of cardinal temperatures of Flax-leaf Alyssum (*Alyssum linifolium*) in response to salinity, pH, and drought stress. Weed Science 66(4): 470-476. https://doi.org/10.1017/wsc.2018.19

Del Monte J.P., Aguado P.L., Tarquis A.M. 2014. Thermal time model of *Solanum sarrachoides* germination. Seed Science Research 24(4): 321 - 330. https://doi.org/10.1017/S0960258514000221

Motsa M.M., Slabbert M.M., Van Averbeke W., Morey L. 2015. Effect of light and temperature on seed germination of selected African leafy vegetables. South African Journal of Botany 99, 29–35. https://doi.org/10.1016/j.sajb.2015.03.185

Mwale S.S., Azam-Ali S.N., Clark J.A., Bradley R.G., Chatha M.R. 1994. Effect of temperature on the germination of sunflower (*Helianthus annuus* L.). Seed Science and Technology 22, 565–571.

O'Meara J.M., Burles S., Prochaska J.X., Prochter G.E., Bernstein R.A., Burgess K.M. 2006. The Deuterium-to-Hydrogen Abundance Ratio toward the QSO SDSS J155810. 16–003120.0. The Astrophysical Journal Letters 649, L61. https://doi.org/10.1086/508348

Ribeiro P.R., Willems L.A.J., Mutimawurugo M.C., Fernandez L.G., de Castro R.D., Ligterink W., Hilhorst H.W.M. 2015. Metabolite profiling of Ricinus communis germination at different temperatures provides new insights into thermo-mediated requirements for successful seedling establishment. Plant Science 239, 180–191. https://doi.org/10.1016/j.plantsci.2015.08.002

Sadashiv P.S. 2011. Acute toxicity study for Ricinus communis. Der Pharm Lett 3, 132–137.

Sadeghi H., Khazaei F., Sheidaei S., Yari L. 2011. Effect of seed size on seed germination behavior of safflower (*Carthamus tinctorius* L.). ARPN Journal of Agricultural and Biological Science 6, 5–8.

Saeed S., Shaukat S.S. 2000. Effect of seed size on germination, emergence, growth and seedling survival of Senna occidentalis Link. Pakistan Journal of Biological Sciences 3(2): 292–295. https://doi.org/10.3923/pjbs.2000.292.295

Sasidharan R., Venkatesan R. 2019. Seed elaiosome mediates dispersal by ants and impacts germination in *Ricinus communis*. Frontiers in Ecology and Evolution 7, 1–8. https://doi.org/10.3389/fevo.2019.00246

Severino L.S., Auld D.L., Baldanzi M., Cândido M.J.D., Chen G., Crosby W., Tan D., He X., Lakshmamma P., Lavanya C. 2012. A review on the challenges for increased production of castor. Agronomy Journal 104(4): 853–880. https://doi.org/10.2134/agronj2011.0210

Shafii B., Price W.J. 2001. Estimation of cardinal temperatures in germination data analysis. Journal of agricultural, biological, and environmental statistics 6, 356–366. https://doi.org/10.1198/108571101317096569

Soltani A. 2007. Application of SAS in Statistical Analysis, JDM Press, Mashhad.

Soltani A., Robertson M.J., Torabi B., Yousefi-Daz M., Sarparast R. 2006. Modelling seedling emergence in chickpea as influenced by temperature and sowing depth. Agricultural and forest meteorology 138(1-4): 156–167. https://doi.org/10.1016/j.agrformet.2006.04.004

Soltani A., Sinclair T.R. 2012. Modeling physiology of crop development, growth and yield, CABi. https://doi.org/10.1079/9781845939700.0000

Soriano D., Orozco-Segovia A., Márquez-Guzmán J., Kitajima K., Gamboa-de Buen A., Huante P. 2011. Seed reserve composition in 19 tree species of a tropical deciduous forest in Mexico and its relationship to seed germination and seedling growth. Annals of Botany 107(6): 939–951. https://doi.org/10.1093/aob/mcr041

Souza M.L., Fagundes M. 2014. Seed size as key factor in germination and seedling development of *Copaifera* *langsdorffii* (Fabaceae). American Journal of Plant Sciences 5(17): 2566–2573. https://doi.org/10.4236/ajps.2014.517270

Steiner F., Zuffo A.M., Busch A., Sousa T. de O., Zoz T. 2019. Does seed size affect the germination rate and seedling growth of peanuts under salinity and water stress? Pesquisa Agropecuária Tropical 49. https://doi.org/10.1590/1983-40632019v4954353

Timmermans B.G.H., Vos J., Van Nieuwburg J., Stomph T.J., Van der Putten P.E.L. 2007. Germination rates of *Solanum sisymbriifolium* temperature response models, effects of temperature fluctuations and soil water potential. Seed science research 17(3): 221. https://doi.org/10.1017/S0960258507785628

Tobe K., Li, X., Omasa K. 2004. Effects of five different salts on seed germination and seedling growth of Haloxylon ammodendron (*Chenopodiaceae*). Seed Science Research 14(4): 345–353. https://doi.org/10.1079/SSR2004188

Vaughton G., Ramsey M. 1998. Sources and consequences of seed mass variation in *Banksia marginata* (Proteaceae). Journal of Ecology 86(4): 563–573. https://doi.org/10.1046/j.1365-2745.1998.00279.x

Veloso A.C.R., Silva P.S., Siqueira W.K., Duarte K.L.R., Gomes I.L. V, Santos H.T., Fagundes M. 2017. Intraspecific variation in seed size and light intensity affect seed germination and initial seedling growth of a tropical shrub. Acta Botanica Brasilica 31, 736–741. https://doi.org/10.1590/0102-33062017abb0032

Wang R., Bai Y., Tanino K. 2004. Effect of seed size and sub-zero imbibition-temperature on the thermal time model of winterfat (*Eurotia lanata* (Pursh) Moq.). Environmental and Experimental Botany 51(3): 183–197. https://doi.org/10.1016/j.envexpbot.2003.10.001

Wang Z., Wang L., Liu Z., Li Y., Liu Q., Liu B. 2016: Phylogeny, seed trait, and ecological correlates of seed germination at the community level in a degraded sandy grassland. Frontiers in Plant Science 7, 1532. https://doi.org/10.3389/fpls.2016.01532

Willenborg C.J., Wildeman J.C., Miller A.K., Rossnagel B.G., Shirtliffe S.J. 2005. Oat germination characteristics differ among genotypes, seed sizes, and osmotic potentials. Crop Science 45(5): 2023–2029. https://doi.org/10.2135/cropsci2004.0722

Xu J., Li W., Zhang C., Liu W., Du G. 2014. Variation in seed germination of 134 common species on the eastern Tibetan Plateau: phylogenetic, life history and environmental correlates. Plos One 9. https://doi.org/10.1371/journal.pone.0098601

Yan W., Hunt L.A. 1999. An equation for modeling the temperature response of plants using only the cardinal temperatures. Annals of Botany 84(5): 607–614. https://doi.org/10.1006/anbo.1999.0955

Yin X., Kropff M.J., McLaren G., Visperas R.M. 1995. A nonlinear model for crop development as a function of temperature. Agricultural and Forest Meteorology 77(1-2): 1–16. https://doi.org/10.1016/0168-1923(95)02236-Q

Zhang X.K., Yang G.T., Chen L., Yin J.M., Tang Z.L., Li J.N. 2006. Physiological differences between yellow-seeded and black-seeded rapeseed (*Brassica napus* L.) with different testa characteristics during artificial aging. Seed Science and Technology 34(2): 373–381. https://doi.org/10.15258/sst.2006.34.2.13

HOW TO CITE THIS ARTICLE

Moosavi S.A., Siadat S.A., Khuchekzade A., Parmoon Gh., Kiani S. 2022. Effect of Seed Color and Size on Cardinal Temperatures of Castor Bean (*Ricinus Communis* L.) Seed Germination. *Agrotechniques in Industrial Crops* 2(1): 1-10. 10.22126/ATIC.2022.7417.1041