RESEARCH ARTICLE

International Journal of Agriculture, Environment and Food Sciences 2023; 7(2): 298-304
DOI: https://doi.org/10.31015/jaefs.2023.2.7

The sensitivity of radish cultivars to high temperatures during germination and seedling growth stages

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Abstract
A laboratory experiment was conducted at constant temperatures of 20, 23, 26, 29, 32, 35, 38, and 41^{0}C to identify the response of six radish cultivars with different root sizes and colors to high-temperature stress during germination, emergence, and early seedling growth stage. Also, the optimal temperature was determined by calculating the relationship between seedling length and temperature via a polynomial regression model. The results showed that no seed germination was detected at 41^{0}C, while emergence and seedling growth were not observed at 38 ^{0}C and above. Similar germination percentages, mean germination time, and germination index were obtained between 20 ^{0}C and 35 ^{0}C. The root length reduced at 32 ^{0}C and it was more sensitive to high temperatures than shoots because the root/shoot length ratio showed a decreasing trend by increasing temperatures and longer root length was recorded at lower temperatures than 32 ^{0}C. There were genotypic variations among radish cultivars for temperatures and 'Kırmızı İnci', 'Beyaz İnci', and 'Siyah İnci' produced a better performance than the others under high temperatures. The regression analysis predicted the optimal temperatures as 21.5 ^{0}C and 22.6 ^{0}C for root and shoot length, respectively. This study indicates that high temperatures inhibited seedling growth rather than seed germination performance of radishes.

Keywords: *Raphanus sativus* L., Germination, Seedling growth, High temperature

Citation: Kaya, G. (2023). The sensitivity of radish cultivars to high temperatures during germination and seedling growth stages. International Journal of Agriculture, Environment and Food Sciences, 7 (2), 298-304

Received: 26 January 2023
Revised: 28 March 2023
Accepted: 30 March 2023
Published Online: 09 June 2023

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INTRODUCTION

Radish (*Raphanus sativus* L.) is an important and common vegetable consumed directly or indirectly in salads by humans for its roots with high vitamin and mineral contents throughout the world (Banihani, 2017). There are several types of radish cultivars in terms of root shapes, colors, and vegetation periods (Gunay, 2005). It is successfully grown in cool climates and high temperatures negatively affect its growth and tuber yields (Jia et al., 2020). Its cultivation concentrates in the Mediterranean region during the autumn seasons in Türkiye. Nowadays, fast-maturing varieties with small-sized roots are grown in vials under greenhouse conditions, even in pots for kitchen gardening (Khan et al., 2022). Under these climatic conditions, it is frequently subjected to high temperatures during germination, emergence, and seedling growth stages, resulting in irregular plant density.

Seed germination is mainly controlled by several environmental factors such as temperature, water, and oxygen availability along with seed viability and vigor. Among these factors, the temperature has a key role in regulating water uptake by seeds, which affect adversely or favorably germination and seedling establishment (Bradford, 2002). Since extraordinary temperatures prevent the radicle protrusion from the seeds during germination in some plant species, the temperature requirements for germination are vital for a successful stand establishment and high-yielding production. In radish, Abdel (2015) announced that radish cultivars germinated better at 12 ^{0}C than 20 ^{0}C. Recently, Bakhshandeh and Gholamhossieni (2019) found that the base, optimum, and ceiling temperatures for radishes were 9.64, 21.3, and 33.0 ^{0}C, while Khan et al. (2022) reported these temperatures as 15, 20, and 40 ^{0}C, respectively. Studies on the existence of thermo-dormancy and germination responses of the radish cultivars with different sizes, colors, and vegetation periods to high temperatures are limited. Therefore, the study aimed to determine the germination, emergence, root, and shoot development of six radish cultivars with different root shapes and colors under eight constant temperatures starting from 20 ^{0}C and to calculate the optimum temperature using the polynomial regression model.

MATERIALS AND METHODS

A laboratory experiment was arranged to determine the optimum and high temperature for germination of radish cultivars with different root sizes at the seed sciences laboratory of Eskişehir Osmangazi University, Türkiye. The seeds of six radish cultivars namely 'Beyaz İnci', 'Siyah İnci', 'Kırmızı İnci', 'Alçin' (medium), 'Toros Beyazı' (big), and 'Cherry Belle' (small) produced by Sim Arzuman Seed Company in Türkiye were used, and their thousand seed weights were 8.20, 8.38, 8.67, 14.43, 8.83, and 7.40 g, respectively.

The germination test was arranged with 4×50 replication/seed at constant temperatures of 20, 23, 26, 29, 32, 35, 38, and 41^{0}C under continuous dark. The seeds were permitted to germinate between three layers of filter papers wetted with 21 mL distilled water. The rolled filter papers were placed in sealed plastic bags to prevent evaporation. They were put in incubators with respective temperatures. The criterion for germination was a radicle protrusion of 2 mm. At the end of the experimental period (7th day), the final germination percentage (GP, Eq. (1)), mean germination time (MGT, Eq. (2)), and germination index (GI, Eq. (3)) were calculated as follows.

GP = n/N × 100 (Eq. 1)

n represents germinated seeds and N total seeds.

MGT= Σ(Dn)/Σn, (ISTA, 2018) (Eq. 2)

n is germinated seeds on day D, and D is the day number from the start of the experiment.

GI = Number of germinated seeds/days of first count + . . . + Number of germinated seeds/days of final count (Salehzade et al., 2009). (Eq. 3)

The emergence test was also performed with 200 seeds from each cultivar and temperature in a seedling tray filled with a mixture of peat: perlite: vermiculite (3:1:1). They were exposed to constant temperatures in growth chambers with 70% relative humidity, and the 2 mm of hypocotyl length above the medium surface were considered as emergence criterion.

The optimal temperature was estimated by a polynomial regression equation between temperature and the lengths of the root and shoot. In this model, the independent variable (temperature) was assumed to X-axis and the dependent variable (length) on the Y-axis. The optimum temperature was calculated as the peak value (-b/2a) from the regression equation (y= ax^{2}+bx+c) to the minimum temperature of 20 ^{0}C (Fallahi et al., 2017; Wang et al., 2020).

RESULTS

Analysis of variance showed significant differences in germination parameters among radish cultivars, temperatures, and cultivar × temperature interaction (Table 1). 'Kırmızı inci' gave the highest germination percentage and germination index, while the lowest MGT was obtained from it. At 26 ^{0}C, the maximum germination percentage and index were recorded, but the shortest time for germination was obtained. Germination parameters were depressed at 38 ^{0}C. Moreover, the emergence percentage of radish cultivars reduced at 35 ^{0}C, and no emergence was observed at 38 ^{0}C.

All radish cultivars germinated at all temperatures except for 41^{0}C, but higher temperatures than 29 ^{0}C reduced germination percentage (Figure 1a). A clear difference among radish cultivars for germination percentage was observed at 38 ^{0}C. The differences among the temperatures may result from genotypic factors because we determined significant differences among radish cultivars concerning germination percentage and Kırmızı İnci had the highest germination at 38 ^{0}C, followed by Beyaz İnci and Toros Beyazı.

MGT varied relatively with radish cultivars by increasing temperatures (Figure 1b). Temperatures between 20 ^{0}C and 35 ^{0}C gave similar MGT, while Kırmızı İnci possessed shorter MGT than the other cultivars. A similar trend was observed for GI and the highest GI was calculated in Kırmızı İnci at all levels of temperature (Figure 1c). Although the emergence percentage of radish cultivars responded differently to high temperatures and Kırmızı İnci was slightly affected, fluctuated, and finally dropped at 38 ^{0}C when the temperature increased (Figure 1d).

The seedling growth of radish cultivars was significantly depressed by increasing temperatures. As expected, Toros Beyazı, which is the cultivar with the highest seed weight and root size, produced longer shoots and roots than the other cultivars and it had heavier seedling fresh weight. However, Cherry Belle and Alçin

Table 1. Germination parameters and emergence percentage of radish cultivars under increasing temperatures

Factor	Germination (%)	Mean germination time (day)	Germination index	Emergence (%)
Cultivar (A)				
Beyaz İnci	94.9^{b}	1.22^{d}	42.9^{b}	94.3^{ab}†
Kırmızı İnci	96.6^{a}	1.16^{e}	44.9^{a}	96.3^{a}
Siyah İnci	93.1^{c}	1.56^{a}	36.7^{e}	93.2^{bc}
Toros Beyazı	94.1^{bc}	1.32^{b}	41.1^{cd}	97.0^{a}
Alçin	90.4^{d}	1.27^{c}	41.7^{c}	90.9^{c}
Cherry Belle	91.0^{d}	1.35^{b}	40.8^{d}	93.3^{b}
Temperature (B)				
20⁰C	97.3^{a}	1.46^{b}	37.4^{d}	96.0^{ab}
23⁰C	97.2^{a}	1.09^{d}	46.6^{b}	93.8^{b}
26⁰C	98.2^{a}	1.04^{ef}	$47.\ 9^{a}$	95.0^{ab}
29⁰C	97.6^{a}	1.04^{f}	47.8^{a}	96.6^{a}
32⁰C	95.0^{b}	1.09^{de}	46.1^{b}	96.0^{ab}
35⁰C	96.8^{ab}	1.14^{c}	44.9^{c}	87.2^{c}
38⁰C	70.2^{c}	2.33^{a}	18.8^{e}	-
Analysis of Variance				
A	**	**	**	**
B	**	**	**	**
A×B	**	**	**	**

**: significant at 1%. †: Letter(s) connected with the means in each column show the significance levels at 5%.

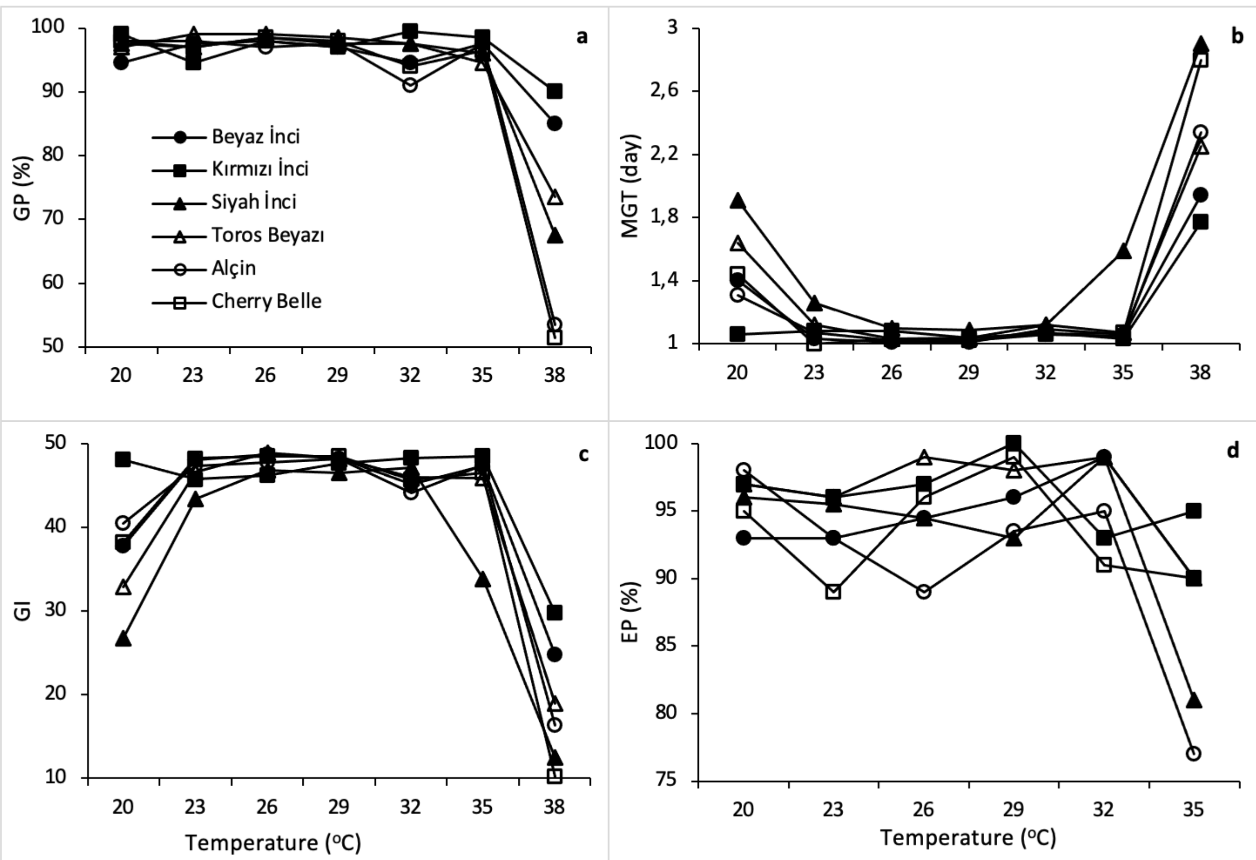

Figure 1. The interaction effects of radish cultivar × temperature on germination percentage (GP, a), mean germination time (MGT, b), germination index (GI, c), and emergence percentage (EP, d).

Table 2. Seedling growth parameters of radish cultivars under increasing temperatures

Factor	Shoot length (cm)	Root length (cm)	Seedling fresh weight (mg plant^{-1})	Seedling dry weight (mg plant^{-1})	Root/Shoot ratio
Cultivar (A)					
Beyaz İnci	6.07^{b}	8.53^{a}	118^{b}	1.44^{b}	1.44^{b}†
Kırmızı İnci	5.80^{b}	7.60^{bc}	103^{c}	1.28^{c}	1.28^{c}
Siyah İnci	5.32^{c}	7.34^{c}	88^{d}	1.43^{b}	1.43^{b}
Toros Beyazı	8.28^{a}	8.83^{a}	194^{a}	1.00^{d}	1.01^{d}
Alçin	5.10^{c}	8.01^{b}	103^{c}	1.52^{ab}	1.52^{ab}
Cherry Belle	4.13^{d}	6.60^{d}	86^{d}	1.57^{a}	1.57^{a}
Temperature (B)					
20^{0}C	5.68^{d}	10.80^{a}	113^{c}	2.05^{a}	2.05^{a}
23^{0}C	7.49^{a}	10.18^{b}	135^{a}	1.40^{bc}	1.39^{bc}
26^{0}C	6.92^{b}	8.83^{c}	137^{a}	1.36^{c}	1.36^{c}
29^{0}C	6.21^{c}	8.98^{c}	127^{b}	1.50^{b}	1.49^{b}
32^{0}C	4.73^{e}	5.96^{d}	98^{d}	1.32^{c}	1.32^{c}
35^{0}C	3.66^{f}	2.18^{e}	82^{e}	0.62^{d}	0.63^{d}
38^{0}C	-	-	-	-	-
Analysis of Variance					
A	**	**	**	**	**
B	**	**	**	**	**
A×B	**	**	**	**	**

**: significant at 1%. †: Letter(s) connected with the means in each column show the significance levels at 5%.

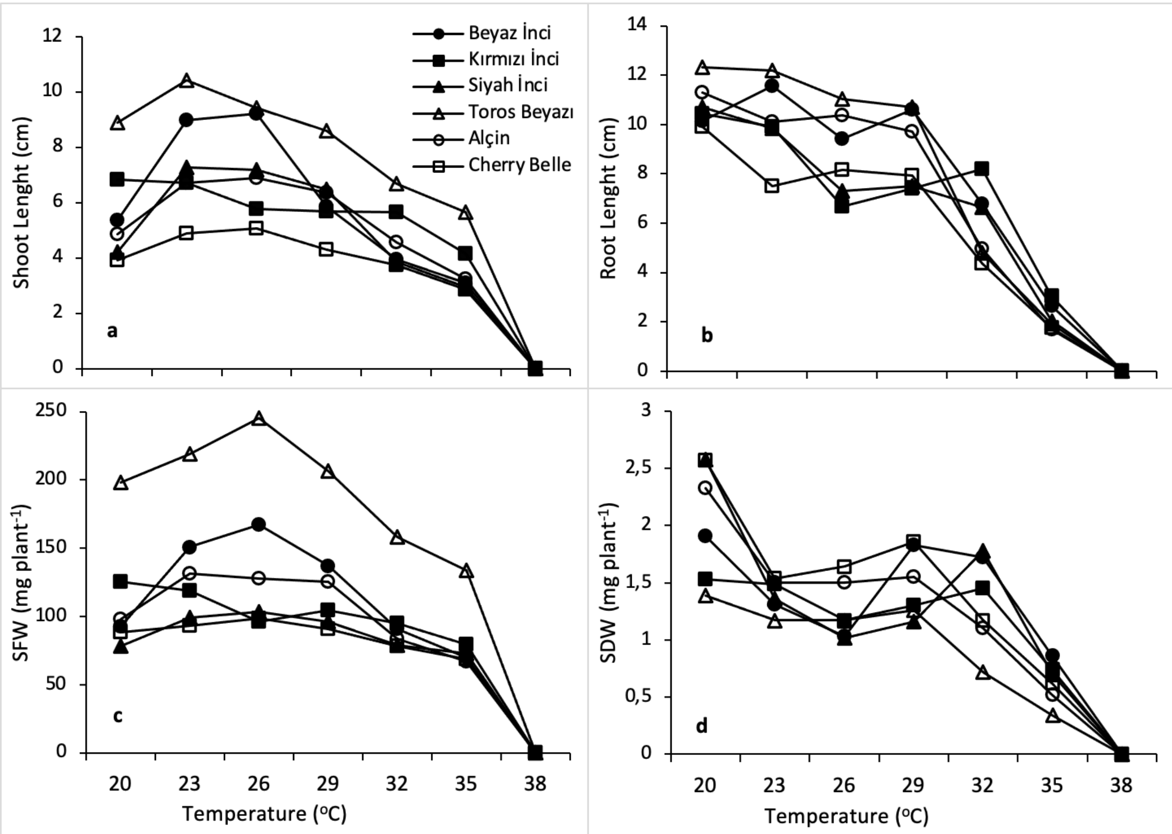

Figure 2. The interaction effects of radish cultivar × temperature on shoot length (a), root length (b), seedling fresh weight (c), and seedling dry weight (d).

cultivars accumulated more dry weight compared to the others; reflecting that the cultivars were influenced by high temperatures. Shoot length reached the highest level at 23 ^{0}C and a dramatic reduction occurred at 32 ^{0}C although root length was diminished with each increase in temperature. Similar trends were determined for seedling fresh and dry weights that were reduced at 32 ^{0}C. It was confirmed by the reduction in root/shoot length ratio that was lessened by increasing temperature. The ratio showed that low temperatures prominently inducted the root growth and each increase in temperature led to inhibition in root length.

The shoot length of radish cultivars was significantly changed by increasing temperatures and Toros Beyazı exhibited the highest shoot length at all levels of temperatures. A temperature of 38 ^{0}C did not allow the seedling growth of radish cultivars. None of the radish cultivars produced the shoots at 38 ^{0}C. Temperatures of 23 ^{0}C and 26 ^{0}C resulted in an increase in the shoot length of the cultivars except for Kırmızı İnci (Figure 2a). On the other hand, the root length of radish cultivars except for Beyaz İnci was reduced by each increase in temperature, Toros Beyazı with high-sized roots and seed weight had higher root length until 29 ^{0}C than the others (Figure 2b). No longer root length than germination criterion occurred at 38 ^{0}C. Seedling fresh weight peaked at 26 ^{0}C for Toros Beyazı, Beyaz İnci, Siyah İnci, Alçin, and Cherry Belle (Figure 2c) and it was considerably decreased at higher temperatures than 26 ^{0}C. The lower seedling dry weight was observed at temperatures above 20 ^{0}C and the horizontal course was observed between 23 ^{0}C and 29 ^{0}C (Figure 2d). There was a significant drop in seedling dry weight at 23 ^{0}C. The root/shoot length ratio showed that increased temperature led to a reduction in root growth; indicating the roots of radish were more sensitive to high temperatures rather than shoot growth (Figure 3).

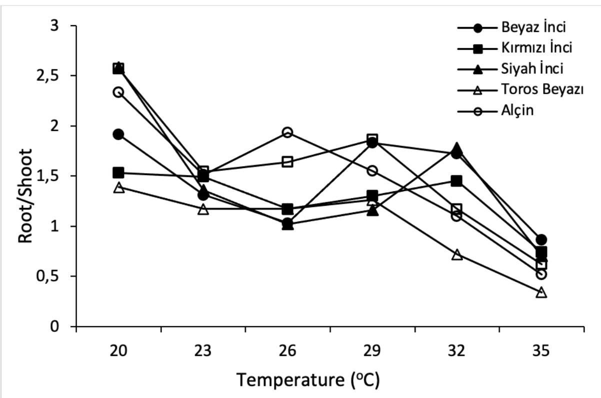

Figure 3. The root/shoot length ratio of radish cultivars as affected by temperatures

The relationship between temperature and root and shoot length was determined by a polynomial regression equation and significant relationships were calculated (P <0.01) (Figure 4). Shoot length increased with the temperature of 22.6 ^{0}C computed by the equation of $y=-0.3223x^2+1.7117x+4.681$, $R^2=0.907^{**}$. The shoot length gradually reduced at higher temperatures. However, the relationship between root length and the temperature was significant and root length was shortened at higher temperatures than 21.5 ^{0}C which was calculated by the equation of $y = -0.4018x^2+1.2219x+9.642$, $R^2= 0.964^{**}$.

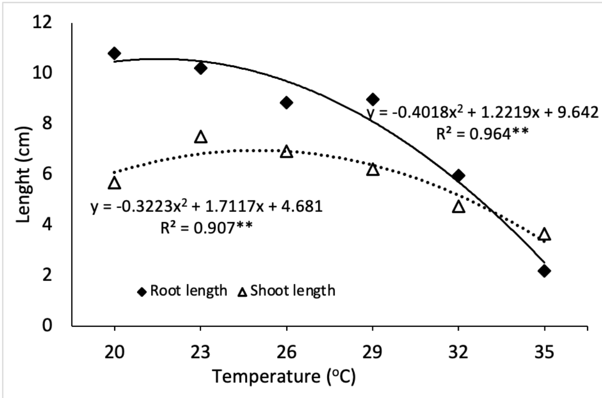

Figure 4. The relationship between the length of shoot and root and increasing temperatures for radish cultivars.

DISCUSSION

Temperature is a critical factor for seed germination of several plants especially those grown all seasons. Radishes are exposed to various temperatures from germination to harvest because it is easily adapted to different environmental conditions using varieties with short maturating, root sizes, and colors in both open fields and greenhouse. In this study, the responses of different radish cultivars to high temperatures were investigated during germination and early seedling growth stages. The temperature of 41 ^{0}C did not allow the seeds of all radish cultivars to germinate, but they showed differences in germination percentage at 38 ^{0}C. Kırmızı İnci and Beyaz İnci germinated better, while Alçin and Cherry Belle had the minimum germination percentage at this temperature. Similar results were reported by Cavusoglu and Kabar (2007) who found a 22.0% germination percentage of radish at 38 ^{0}C. Also, it was not determined as thermo-dormancy temperature for radish, which is consistence with the findings of Steiner et al. (2009) who reported no significant changes in germination with temperatures between 10 ^{0}C and 35 ^{0}C, but Bakhshandeh and Gholamhossieni (2019) and Shah et al. (2022) demonstrated the inhibitory effects of temperature at 33 ^{0}C and 40 ^{0}C, respectively. Also, Dell'Aquila (2005) determined a significant reduction in germination percentage at 35 ^{0}C in radishes and Elson et al. (1992) found 63% germination at 35 ^{0}C and zero at 40 ^{0}C in broccoli. The variation in temperatures may result from genotypic factors because there were distinct results for the germination of radish cultivars at 38 ^{0}C in this study. The result revealed that the most suitable temperature for separating germination performance was 38 ^{0}C which was higher than that reported by Steiner et al. (2009), 35 ^{0}C. The higher MGT or lower GI were recorded at 20 ^{0}C and 38 ^{0}C, with differences in radish cultivars. These findings are in agreement with the results of Khan et al. (2022) and Dell'Aquila (2005), who determined retardation in mean germination time and reduction in germination index at 40 ^{0}C. Although the emergence percentage was changed by radish cultivars and temperatures, it was inhibited at 35 ^{0}C without any significant decrease in Kırmızı İnci when the temperature increased.

Seedling growth of radish cultivars was also restricted by increasing temperature; however, shoot and root parts were differently influenced. An increase in temperature from 20 ^{0}C to 23 ^{0}C enhanced shoot length and seedling fresh weight, and then, they began to drop at 26 ^{0}C. Contrarily, root length, and seedling dry weight declined with increasing temperature. This tendency was confirmed by the polynomial regression models for shoot and root length (Figure 4). Rowse and Finch-Savage (2003) calculated a similar curve for GR_{50} in carrots. In addition, decreased root/shoot length ratio reflects that root growth was reduced more severely than shoot growth, and a lower temperature for root length (21.5 ^{0}C) than shoot length (22.6 ^{0}C) was calculated. This result supports the findings reported by Steiner et al. (2009) who demonstrated that the root system development was negatively influenced by high temperatures.

CONCLUSION

Extreme temperatures are harmful abiotic stress factors affecting germination of the crop plants (Bakhshandeh et al. 2020). In this study, radish cultivars responded differently to increasing temperatures for germination performance and seedling growth. Among the radish cultivars, Kırmızı İnci showed the best germination and seedling growth performance under high temperatures. The results revealed that there was no thermo-dormancy in the radish. Seedling growth was more sensitive to high temperatures than germination. Furthermore, root length was much more negatively influenced by high temperatures than shoot length, which limited emergence performance. For these reasons, the optimum temperature for radish was calculated using root and shoot lengths that were at 21.5 ^{0}C and 22.6 ^{0}C. It was concluded that emergence failure in radish under high temperatures resulted from the inhibition of shoot and root growth rather than germination inability and insensitive cultivars such as Kırmızı İnci should be preferred for high temperatures.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author contribution

The author read and approved the final manuscript. The author verifies that the Text, Figures, and Tables are original and that they have not been published before.

Ethical approval

Ethics committee approval is not required.

Funding

No financial support was received for this study.

Data availability

Not applicable.

Consent for publication

Not applicable.

Acknowledgments

The author is thankful to the staff of the Seed Science and Technology Laboratory, Department of Field Crops, Eskişehir Osmangazi University, Dr. N. Ergin, and Ph.D. student P. Harmancı for their kind help.

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