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Research Article

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Mitigation of Adverse Effects of Drought and Low Temperature Stresses by Seed Priming in Sunflower (*Helianthus annuus* L.) During Germination

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HIGHLIGHTS

- The study evaluated the effect of priming on sunflower germination under drought and low temperatures.
- Drought more severely reduced germination and seedling growth than low temperatures.
- Low temperatures at 15°C decreased shoot and root length by 63% and 59%, respectively.
- Hydration can ameliorate low temperatures and drought-induced damage in sunflower.

Abstract

The study aimed to determine the effects of seed priming on germination and seedling development in sunflowers exposed to drought and low-temperature stresses. The primed seeds (KNO_3, and hydration) of Sanbro MR were evaluated at low temperatures of 15 °C and 18 °C under drought conditions induced by PEG-6000 at the water potentials of 0 (distilled water), −0.2, −0.4, and −0.6 MPa. Unprimed seeds were used as a control, and a temperature of 25 °C was considered optimal. The results showed that germination was negatively affected by both stress factors, although this varies according to priming applications. Drought inhibited germination and seedling growth more than low temperatures. Seedling growth was also more adversely affected by low temperatures compared to germination. Under low temperatures, there was a 63% decrease in shoot length and a 59% decrease in root length. Drought stress resulted in an 85% reduction in shoot length, while roots were reduced by 65%. The primed seeds with KNO_3 gave the highest germination percentage at -6 MPa at 15 °C. However, hydration showed superiority under different drought levels at 18 °C and 25 °C. It was concluded that hydrated seeds could be recommended for increased germination and seedling growth under low temperatures and drought stresses in sunflowers.

Keywords: *Helianthus annuus* L.; hydropriming; potassium nitrate; low temperature; drought

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1. Introduction

Sunflower (*Helianthus annuus* L.) is an annual oilseed crop and is an economically significant commodity in Türkiye because of its substantial role in vegetable oil production. It has an area of 1 million hectares with an average production of 2.5 million tons (TUİK 2024), of which 70% of the sowing area is under rainfed conditions. For this reason, it is exposed to several abiotic stresses such as drought, low and high temperature, salinity, and heavy metals, which affect it from germination to harvest (Ali et al. 2017; Hussain et al. 2018; Haj Sghaier et al. 2023).

The germination process is mainly influenced by moisture, oxygen, and temperature, which are often combined with abiotic stress factors (Jiang et al. 2023). During germination, low temperatures limit water absorption by seeds, leading to the inhibition of germination and seedling growth (Hoppe and Theimer 1997; Chakraborty and Dwivedi 2021; Haj Sghaier et al. 2023). The lack of water restricts the seed's capacity to take in the necessary water and slows down the process of germination by inhibiting the enzymes that are essential for allowing energy for seedling development (Soleimanzadeh 2012; Wen 2015; Haj Sghaier et al. 2023).

Priming promotes germination by activating metabolic activities, enhances osmotic adjustment, strengthens cell membranes, and stimulates the production of protective proteins and antioxidants. As a result, primed seeds show better germination and seedling vigor in drought, salinity, and extreme temperatures (Harris et al. 1999; Kaya et al. 2006; Aswathi et al. 2021; Ghosh et al. 2024; Rehman et al. 2024; Sneha et al. 2024). Seeds can be primed in a variety of media, including water (hydropriming), aerated solutions with low water potential containing polyethylene glycol, or salt solutions ($CaCl_2$, KNO_3, KCl, K_3PO_4, $MgSO_4$, and NaCl) (osmopriming), solid matrix (matripriming), and priming with plant growth regulators and polyamines (Kaya et al. 2024; Rehman et al. 2024). The superiority of primed seeds has been found under drought stress in soybean (*Glycine max* Merril.) (Sintaha et al. 2022), wheat (*Triticum aestivum* L.) (Tabassum et al. 2018), maize (*Zea mays* L.) (Khan et al. 2015), safflower (*Carthamus tinctorius*) (Akbari et al. 2020), and sunflower (*Helianthus annuus* L.) (Kaya et al. 2006). Also, primed seeds have improved the germination performance of maize (*Zea mays* L.) (Guan et al. 2009), rapeseed (*Brassica napus* L.) (Zhu et al. 2021), cotton (*Gossypium hirsutum* L.) (Xia et al. 2023) and sugar beet (*Beta vulgaris* L.) (Kaya and Kulan 2020) under low temperatures. For these reasons, this study was conducted to investigate whether primed sunflower seeds improve germination and early growth under different combinations of low temperatures and drought.

2. Materials and Methods

This study was conducted at Eskişehir Osmangazi University, Seed Science and Technology Laboratory in 2023, Odunpazarı, Eskişehir. The seeds of sunflower hybrid Sanbro MR obtained from Syngenta Seeds Company were used. To create drought stresses, different water osmotic potentials of −0.2, −0.4, and −0.6 MPa were arranged using polyethylene glycol (PEG) 6000 with the formula described by Michel and Kaufmann (1973) for 15 °C, 18 °C, and 25 °C. Distilled water was used as a control (0 MPa).

2.1. Seed priming

Two seed priming were applied to the seeds, as defined by Kaya et al. (2006). For hydration, sunflower seeds were submerged in distilled water at 20 °C for 16 h in the dark. For KNO_3 treatment, the seeds were immersed in a 500 ppm KNO_3 solution at the same temperature and duration and then they were rinsed with tap water. The primed seeds were immediately surface-dried with paper towels and then they were dried to their initial moisture content at room temperature (roughly 22 °C, 45% relative humidity). Primed (hydration and KNO_3) and unprimed (control) seeds were left at room temperature for two days (Kaya et al. 2015).

2.2. Germination test

A germination test was conducted with 200 seeds (4×50) for each treatment to evaluate seed viability according to the ISTA (2003) guidelines. Fifty seeds were inserted into two-layer filter papers wetted with 7 mL of the distilled water for each paper. After filter papers with seeds were rolled, they were placed into a sealed plastic bag to avoid water loss. The packages were incubated at 25 °C in the dark, and seeds with 2 mm radicle were counted every 24 h for 10 d as germinated. To evaluate the speed of germination, mean germination time (MGT) was calculated according to ISTA (2003) rules. MGT= $\Sigma(Dn)/\Sigma n$, where n is the seed number germinated on day D and D is the number of days from the beginning of the germination test. On the 10th day, ten seedlings from each treatment were randomly selected to determine the seedling growth traits such as root length (RL), shoot length (SL), seedling fresh weight (SFW), and seedling dry weight (SDW). After the seedling fresh weight was directly weighed, the seedlings were transferred into an oven at 80 °C for 24 hours for the determination of dry weight (Ergin et al. 2021). The root/shoot ratio was determined by dividing the root length by the shoot length. The germination index (GI) was also calculated according to Salehzade et al. (2009) with the following formula 1:

$$GI = \text{Number of germinated seeds/days of first count} + \ldots + \text{Number of germinated seeds/days of the final count.} \quad (1)$$

Where n is the seed number germinated on day D, and D is the number of days from the beginning of the germination test.

2.3. Statistical analysis

All obtained data were analyzed according to a three factor in a completely randomized design with four replications using the MSTAT-C (Michigan State University, v. 2.10) statistical software. The means were separated by Tukey's test at $p<0.05$ level.

3. Results

In this study, the analysis of variance and main effects of seed priming, temperature, and drought level on germination and early seedling development of sunflower are shown in Table 1. The results showed that temperature, seed priming, drought, and all the combinations of the interactions were found to be significant for germination percentage, mean germination time, and germination index.

At low temperatures, germination percentage only decreased at 15 °C, while decreasing temperature caused a retardation in mean germination time and a reduction in germination index (Table 1). Hydrated seeds gave better results for germination percentage, mean germination time, and germination index than the control and KNO_3 treated seeds. As expected, increased drought stress resulted in increased germination time, while germination percentage and germination index decreased. Previous studies show that germination decreases as drought stress increases (Ahmad et al. 2009) and that priming applications increase germination percentage and germination index (Fatemi 2014; Čanak et al. 2014) are in line with the results of the current study.

Low temperatures caused a reduction in the shoot and root length, seedling fresh weight, and root/shoot ratio in sunflower, while hydration considerably stimulated them. The shoot length was significantly decreased by increasing drought stress. A similar observation was also determined in root length, except for -0.2 MPa PEG. In all treatments, the roots were longer than the shoots, which is proof that shoots are more sensitive than roots under low temperatures and drought stress (Table 2). Root length was not affected by the interaction between temperatures, priming, and drought. This result confirms the findings of Aboutalebian et al. (2021), who reported a reduction in root and shoot growth of canola (*Brassica napus* L.) varieties under drought stress. Similar results were also found in sunflower under drought stress (Nezami et al. 2008; Basit et al. 2024) and rice (*Oryza sativa* L.) under low-temperature stress (Doddagoudar et al. 2023).

Low-temperature stress significantly affected the fresh weight of sunflower seedlings. The fresh weight of sunflowers was significantly reduced at 15 °C. Of priming treatments, the highest seedling fresh weight (174 mg $plant^{-1}$) was recorded from hydration. Drought reduced seedling fresh weight, and a similar trend was also determined for dry weight. There was no significant effect of temperature on dry weight; hydrated seeds produced a lower dry weight of seedlings than the others. The root/shoot ratio decreased with decreasing temperature, but priming treatments helped to increase it significantly. Although they were in the same statistical group, higher values were measured with the application of hydration than with KNO_3. It was determined that under moderate drought stress, the roots developed more rapidly than shoots, which resulted in a higher root-to-shoot ratio than the control (Table 2). Kaya and Kulan (2020) determined that primed sugar beet seeds produced notably heavier seedlings than control. Moghanibashi et al. (2012) stated that lighter seedlings were formed in sunflowers with increasing drought stress levels. Szczerba et al. (2021) reported that seedling weights of soybean varieties at low temperatures were considerably lower compared to optimum temperatures, which is consistent with our results.

Table 1. The main effects of seed priming, temperature, and drought on germination properties of sunflower

	Germination percentage (%)	Mean germination time (day)	Germination index
Temperature (A)			
15 °C	88.1±1.5	4.17±0.16	12.3±0.61
18 °C	92.0±0.9	3.60±0.17	15.0±0.77
25 °C	89.6±2.2	2.69±0.14	21.2±.1.41
Priming (B)			
Control	89.0±2.39	3.72±0.18	14.5±0.87
Hydration	91.9±1.31	3.30±0.19	17.9±1.29
KNO_3	88.8±0.77	3.45±0.16	16.1±1.12
Drought (C)			
0	94.3±0.63	2.20±0.10	25.1±1.41
-0.2 MPa	94.6±0.63	2.98±0.10	17.3±0.61
-0.4 MPa	92.9±0.83	3.76±0.13	13.5±0.53
-0.6 MPa	77.8±2.75	5.02±0.13	8.7±0.37
Analysis of variance			
A	**	**	**
B	**	**	**
A×B	**	**	**
C	**	**	**
A×C	**	**	**
B×C	**	**	**
A×B×C	**	**	**

**: Significance level at $p<0.01$.

As can be seen in Figure 1A, the root length of the sunflower increased as the temperature increased. At all temperatures, the hydrated seeds developed the longest roots, while the unprimed seeds had the shortest root length. Similarly, the highest root length at all drought stress levels was achieved by hydrated seeds, followed by KNO_3-treated seeds. It increased considerably at -0.2 MPa and then decreased rapidly at higher drought levels, with the lowest reductions occurring in hydration application (Figure 1B). Additionally, increased drought stress had different effects on root length depending on temperature (Figure 1C). The longest root length was obtained at 25 °C under all drought severities, followed by 18 °C and 15 °C. At -0.2 MPa and -0.4 MPa, the root length was longer than that of the unstressed control seeds. This improvement resulted in an increase in root/shoot ratio under these drought stresses. Root growth under stress conditions is directly related to seedling survival (Haj Sghaier et al. 2023), and it can be promoted with priming. Rahimi (2013) demonstrated that seedlings grown from primed seeds developed longer roots under low-temperature stress.

Table 2. The seedling growth parameters of sunflower seeds under different levels of drought and temperatures

	Shoot length (cm)	Root length (cm)	Seedling fresh weight (mg plant^{-1})	Seedling dry weight (mg plant^{-1})	Root/shoot ratio
Temperature (A)					
15 °C	0.70±0.06	3.13±0.27	135±6.4	62.6±0.48	4.27±0.20
18 °C	0.92±0.09	4.77±0.37	148±7.8	61.3±0.58	5.78±0.44
25 °C	1.87±0.28	7.56±0.58	199±16.9	61.4±0.48	7.75±0.72
Priming (B)					
Control	0.96±0.10	3.67±0.35	147±7.8	62.7±0.43	4.41±0.35
Hydration	1.39±0.24	6.28±0.53	174±14.6	60.2±0.58	6.92±0.62
KNO_3	1.14 ±0.19	5.52±0.52	161±12.4	62.4±0.46	6.46±0.55
Drought (C)					
0	2.70±0.31	5.79±0.26	271 ±14.9	62.3 ±0.61	2.99±0.26
-0.2 MPa	0.95±0.06	7.89±0.66	159±6.5	62.4 ±0.50	8.31±0.44
-0.4 MPa	0.61±0.02	4.90±0.52	114±1.6	61.8±0.63	7.61±0.66
-0.6 MPa	0.40±0.02	2.03±0.27	98±0.8	60.6 ±0.62	4.82±0.60
Analysis of variance					
A	**	**	**	*ns*	**
B	**	**	**	**	**
A×B	**	**	**	*ns*	**
C	**	**	**	*	**
A×C	**	**	**	*	**
B×C	**	**	**	*ns*	**
A×B×C	**	*ns*	**	**	**

*, ** show significance level at p<0.05 and p<0.01, ns: non-significant.

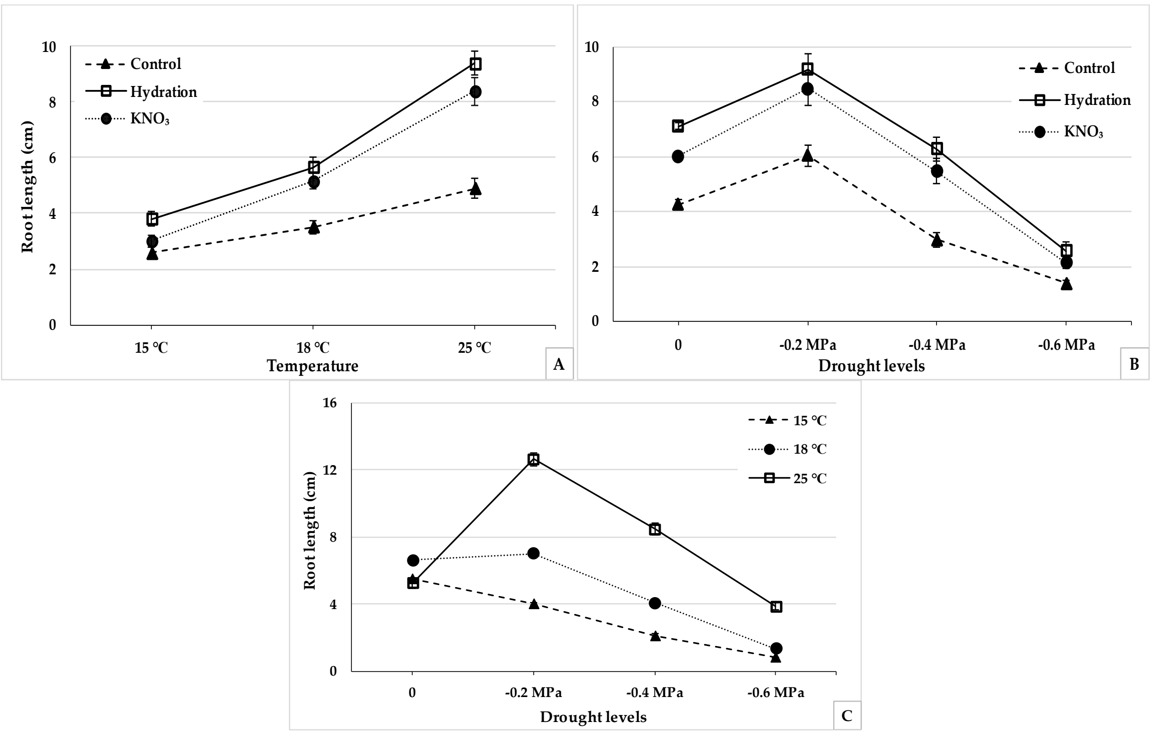

Figure 1. Changes in root length of sunflower under different temperatures (A) and drought levels (B and C)

Table 3. Changes in germination characteristics of sunflower seeds exposed to different seed priming under different drought levels and temperatures

		Germination percentage (%)			Mean germination time (day)		
	PEG (MPa)	**15 °C**	**18 °C**	**25 °C**	**15 °C**	**18 °C**	**25 °C**
Control	**0**	99^{a}±0.5	99^{a}±0.5	97^{abc}±1.5	2.98^{f}±0.02	2.31^{jk}±0.05	1.97^{k}*±0.01
	-0.2	97^{ab}±1.0	98^{ab}±0.5	96^{abc}±1.4	3.91^{d}±0.10	3.05^{f}±0.04	2.41^{h-k}±0.04
	-0.4	93^{abc}±2.2	92^{abc}±4.5	94^{abc}±1.4	5.33^{ab}±0.11	4.05^{cd}±0.06	2.88^{f-i}±0.08
	-0.6	73de±6.6	91^{abc}±4.5	42^{f}±5.0	5.83^{a}±0.07	5.42^{ab}±0.06	4.51^{c}±0.09
Hydration	**0**	93^{abc}±1.5	95^{abc}±1.3	96^{abc}±1.0	2.38^{ijk}±0.03	2.10^{k}±0.08	1.24^{l}±0.04
	-0.2	96^{abc}±1.5	95^{abc}±0.6	98^{a}±1.4	3.25^{ef}±0.05	2.96^{f}±0.03	2.18^{k}±0.05
	-0.4	96^{abc}±1.5	94^{abc}±1.8	98^{a}±1.2	3.99^{d}±0.05	3.64^{de}±0.13	2.82^{f-j}±0.07
	-0.6	67^{e}±5.3	85^{a-d}±4.5	93^{abc}±1.3	5.65^{a}±0.15	5.44^{ab}±0.08	3.94^{d}±0.30
KNO_3	**0**	89^{abc}±1.7	92^{abc}±1.0	93^{abc}±1.3	2.94^{fg}±0.08	2.44^{g-k}±0.09	1.42^{l}±0.02
	-0.2	88^{a-d}±1.4	93^{abc}±1.0	92^{abc}±1.9	3.73^{de}±0.11	3.10^{f}±0.06	2.25^{k}±0.07
	-0.4	87^{a-d}±3.0	91^{abc}±0.6	92^{abc}±2.3	4.52^{c}±0.06	3.68^{de}±0.07	2.92^{fgh}±0.04
	-0.6	83^{bcd}±3.5	82^{cde}±1.9	86^{a-d}±3.7	5.57^{ab}±0.08	5.06^{b}±0.10	3.78^{d}±0.08

*: Means followed by the same letter(s) are not significant at p<0.05.

Germination percentages of primed and unprimed seeds varied with temperatures and drought levels, and it was reduced by decreasing temperatures. At 15 °C, KNO_3-treated seeds germinated lower than the others, but they produced a stable germination percentage under all levels of drought. Moreover, it had the highest germination percentage at -0.6 MPa at 15 °C. An apparent decrease in the germination percentage of unprimed and hydrated seeds was detected at -0.6 MPa. A similar trend was observed at 18 °C (Table 3). It was found that hydrated seeds germinated faster than others at all temperatures and drought levels. Some researchers supporting the results of the current study have reported that priming applications can also alleviate stress-related negative effects on sunflower germination traits (Moghanibashi et al. 2012; Hamidi and Pirasteh-Anosheh 2013; Prayaga et al. 2017). Zhang et al. (2019) determined that germination percentage decreased and mean germination time was prolonged in rapeseed under low-temperature stress.

Table 4. Changes in germination index of sunflower seeds exposed to seed priming treatment under different drought levels and temperatures.

		Germination index		
	PEG (MPa)	**15 °C**	**18 °C**	**25 °C**
Control	**0**	17.1^{gh}±0.2	22.4^{cde}±0.5	25.1^{c}*±0.6
	-0.2	12.8^{jkl}±0.3	16.5^{gh}±0.2	20.9^{ef}±0.5
	-0.4	9.0^{mno}±0.3	11.7^{klm}±0.4	17.0^{gh}±0.3
	-0.6	6.4^{o}±0.6	8.5^{no}±0.3	6.9^{o}±0.9
Hydration	**0**	20.4^{ef}±0.5	24.2^{cd}±1.0	42.3^{a}±0.9
	-0.2	15.4^{hij}±0.3	17.3^{gh}±0.1	23.2^{cde}±0.3
	-0.4	12.4^{jkl}±0.4	13.5^{ijk}±0.6	18.6^{fg}±0.3
	-0.6	7.9^{no}±0.3	8.1^{no}±0.5	12.2^{kl}±0.5
KNO_3	**0**	16.6^{gh}±0.7	20.7^{ef}±0.5	37.5^{b}±0.4
	-0.2	12.4^{kl}±0.5	16.1^{ghi}±0.3	21.5^{def}±0.8
	-0.4	9.9^{lmn}±0.4	12.9^{jk}±0.2	16.8^{gh}±0.6
	-0.6	7.8^{no}±0.3	8.4^{no}±0.4	12.4^{kl}±0.6

*: Means followed by the same letter(s) are not significant at p<0.05.

The germination index decreased with an increase in drought stress at all temperatures. It increased when temperature and drought stress were increased. However, hydrated seeds produced a higher germination index at all levels of drought and temperature. It was determined that priming applications under low temperatures and -0.2 MPa PEG gave higher values than the control (Table 4). The germination index is a property that clearly demonstrates the impacts of temperature and drought stress. It provides valuable insights into the general health and viability of seeds under stress conditions. The efficacy of hydration in inducing low-temperature tolerance is noticeable (Doddagoudar et al. 2023) and an improvement in germination index was determined in canola under drought stress (Heshmat et al. 2011). Furthermore, hydrated seeds produced better results than osmopriming in sunflower (Pahoja et al. 2013), which is consistent with the findings of the present study.

Table 5. Changes in seedling characteristics of sunflower seeds exposed to priming treatments under different drought levels and temperatures.

Priming	PEG (MPa)	Shoot length (cm)			Root/shoot ratio		
		Temperature			Temperature		
		15 °C	18 °C	25 °C	15 °C	18 °C	25 °C
Control	0	1.40^{efg}±0.06	1.89^{de}±0.08	2.68^{c}±0.22	3.30^{klm}±0.24	2.89^{klm}±0.09	1.03^{m}*±0.13
	-0.2	0.74^{jkl}±0.05	0.61^{kl}±0.02	1.32^{f-i}±0.10	4.78^{g-l}±0.26	8.56^{def}±0.73	7.31^{e-i}±0.63
	-0.4	0.45^{l}±0.04	0.57^{kl}±0.02	0.64^{jkl}±0.02	3.10^{klm}±0.49	3.97^{j-m}±0.19	8.27^{def}±0.63
	-0.6	0.31^{l}±0.04	0.44^{l}±0.04	0.50^{l}±0.05	2.72^{lm}±0.24	2.74^{lm}±0.25	4.30^{i-l}±0.51
Hydration	0	1.34^{fgh}±0.08	2.42^{cd}±0.14	6.55^{a}±0.22	4.84^{g-l}±0.33	3.26^{klm}±0.15	1.08^{m}±0.04
	-0.2	0.75^{jkl}±0.03	0.79^{h-l}±0.04	1.85^{ef}±0.04	6.49^{f-j}±0.46	10.69^{bcd}±0.39	7.84^{d-g}±0.72
	-0.4	0.54^{l}±0.03	0.62^{kl}±0.04	0.70^{jkl}±0.02	5.86^{f-k}±0.18	8.41^{def}±0.91	15.07^{a}±0.41
	-0.6	0.31^{l}±0.01	0.38^{l}±0.02	0.42^{l}±0.01	2.71^{lm}±0.19	3.27^{klm}±0.52	13.54^{ab}±1.35
KNO_3	0	1.18^{g-j}±0.07	1.41^{efg}±0.09	5.41^{b}±0.20	4.73^{h-l}±0.41	4.67^{h-l}±0.09	1.10^{m}±0.11
	-0.2	0.63^{kl}±0.02	0.75^{jkl}±0.03	1.10^{g-k}±0.08	5.95^{f-k}±0.14	10.02^{cde}±040	13.15^{ab}±0.92
	-0.4	0.50^{l}±0.02	0.70^{jkl}±0.05	0.77^{i-l}±0.06	3.93^{j-m}±0.15	7.39^{e-h}±1.17	12.49^{abc}±0.65
	-0.6	0.30^{l}±0.01	0.48^{l}±0.02	0.50^{l}±0.02	2.76^{lm}±0.12	3.51^{j-m}±0.55	7.84^{d-g}±0.75

Priming	PEG (MPa)	Seedling fresh weight (mg plant^{-1})			Seedling dry weight (mg plant^{-1})		
		Temperature			Temperature		
		15 °C	18 °C	25 °C	15 °C	18 °C	25 °C
Control	0	208^{cde}±5.9	227^{bcd}±5.7	252^{b}±16.3	65.3^{ab}±1.18	64.0^{ab}±1.15	59.5^{bc}±2.12
	-0.2	131^{h-l}±1.4	140^{hij}±3.1	181^{efg}±10.3	62.5^{ab}±1.11	62.5^{ab}±1.31	62.5^{ab}±0.86
	-0.4	103^{i-l}±1.0	109^{h-l}±0.8	118^{h-l}±7.9	63.3^{ab}±1.21	63.8^{ab}±1.6	61.3^{ab}±2.74
	-0.6	99^{kl}±1.8	101^{i-l}±1.4	97^{kl}±3.1	62.8^{ab}±0.93	62.9^{ab}±0.21	62.0^{ab}±2.12
Hydration	0	224^{bcd}±6.3	257^{b}±7.6	448^{a}±9.8	62.8^{ab}±2.58	63.4^{ab}±1.23	60.3^{abc}±1.97
	-0.2	123^{h-l}±1.9	147^{fgh}±3.0	244^{bc}±16.1	59.9^{bc}±0.67	61.8^{ab}±0.61	62.3^{ab}±0.97
	-0.4	114^{h-l}±2.8	112^{h-l}±2.6	121^{h-l}±2.9	60.5^{ab}±1.58	57.3^{bc}±1.87	60.4^{ab}±2.67
	-0.6	92^{l}±1.4	100^{jkl}±1.7	100^{jkl}±2.8	60.7^{ab}±1.17	51.8^{c}±0.91	60.9^{ab}±1.48
KNO_3	0	187^{def}±6.9	221^{bcd}±5.9	411^{a}±21.5	60.0^{bc}±2.19	63.6^{ab}±2.09	62.0^{ab}±0.81
	-0.2	135^{h-l}±5.1	141^{ghi}±1.7	188de±9.5	68.6^{a}±1.45	60.9^{ab}±1.49	60.3^{ab}±0.46
	-0.4	105^{i-l}±2.7	117^{h-l}±2.2	126^{h-l}±4.9	62.5^{ab}±0.36	62.1^{ab}±0.29	64.8^{ab}±2.06
	-0.6	97^{kl}±2.8	101^{i-l}±1.8	99^{kl}±1.7	62.3^{ab}±0.7	61.3^{ab}±0.61	61.0^{ab}±0.87

*: Means followed by the same letter(s) are not significant at $p<0.05$.

The shoot lengths of the hydrated seeds were the longest under all of the combinations of temperature and drought stress. Increasing drought severity and decreasing temperature resulted in shortened shoot length, but hydration induced shoot growth. It has also been determined that the shoots of sunflowers are more sensitive to drought than the roots. As the drought levels increased, a rapid and significant drop was determined, particularly in the hydration, as shown in Table 5. In both drought and low-temperature stress, the roots grew more than the shoots. It was determined that hydration had the highest root/shoot ratio in seedlings exposed to a low drought level of -0.2 MPa at 15 °C. Our findings were supported by the results of Ping et al. (2015), who found that the impact of low-temperature stress on the roots of rapeseed is more significant than its impact on the development of shoots. Janmohammadi et al. (2008) also reported that hydropriming promoted the development of maize seedlings under drought-stress conditions.

The seed primings significantly enhanced the shoot fresh weight of the sunflower. However, the seedlings became more sensitive to drought as the temperature increased. As drought severity increased at each temperature level, the fresh weight decreased accordingly. This result is consistent with the findings of Çokkizgin and Bölek (2015), who determined a significant reduction in cotton seedling fresh weight and demonstrated that priming treatments can prevent this growth retardation.

The measurement of dry weight in plants is a valuable indicator of the plant's overall health, growth potential, and ability to adapt to stressful situations. Changes in dry weight may reflect the physiological and biochemical responses of the plant under stress (Chaves et al., 2003). In the present study, seeds primed with KNO_3 under -0.2 MPa PEG at 15 °C produced the highest seedling dry weight (68.6 mg plant^{-1}), while hydrated seeds under -0.6 MPa PEG at 18 °C produced the lowest dry weight (51.8 mg plant^{-1}). Doddagoudar et al. (2023) reported that the seedling dry weight of rice genotypes was significantly influenced after exposure to low temperatures for 28 days.

4. Conclusions

Seed priming is an effective method for enhancing germination characteristics, particularly under stress conditions like drought and low-temperature stress. It has several advantages, including its straightforwardness and the lack of costly equipment and chemicals. The results of this study indicated that seed priming improved sunflower germination and seedling growth under low temperatures and drought stress. Especially, hydration could alleviate the inhibiting effects of low temperatures and drought on the germination and early growth of sunflower seedlings. Besides, sunflower was more susceptible to drought than to low temperatures during the early growth stages. As a result, hydration could be suggested for improving the germination and seedling growth of sunflowers because it does not require any chemicals or sophisticated equipment.

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