Iranian Journal of Seed Research

Homepage: https://yujs.yu.ac.ir/jisr

ISSN: 2383-1480 (On-Line); 2383-1251 (Print)

Yasouj University

Mepiquat Chloride (Pix) Improves Germination and Biochemical Stability of Sesame (*Sesamum indicum* cv. Darab-1) Seeds under Deterioration

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Article Info

Article type:

Research Article

Article history:

Received 17 December 2025
Received in revised form 16 February 2026
Accepted 27 February 2026
Available online 20 March 2026

Keywords:

α-amylase
Electrolyte leakage
Seed aging
Sesame germination
Vigor index

ABSTRACT

Objective: Seed aging in oilseeds such as sesame is a major storage challenge, reducing germination quality and seedling vigor. The high-oil cultivar Darab-1 is highly sensitive to storage conditions (temperature, moisture, and time). In this study, the effects of different Pix concentrations in interaction with temperature, moisture, and storage duration were investigated on germination and biochemical traits of seeds to determine the possibility of improving seed quality stability during storage.

Methods: The experiment was conducted as a four-factor factorial arrangement in a completely randomized design with three replications. The studied factors were storage temperature (15, 25, and 35°C), seed moisture content (9, 12, and 15%), Pix concentration (0, 3000, and 4500 mg L^{-1}), and storage duration (30, 60, 90, 120, 150, and 180 days). After the storage period, seed physiological traits including germination percentage and rate, root and shoot length, seedling dry weight, vigor index, α-amylase activity, and electrolyte leakage were measured.

Results: Increasing temperature, moisture, and storage duration accelerated seed aging. After 180 days, electrolyte leakage in control seeds increased from 21.47 to 72.72% when storage temperature rose from 15 to 25°C (at 9% moisture), indicating a 54% increase in membrane leakage, while Pix at 3000 mg/L reduced it by 19–80%. α-amylase activity decreased with seed deterioration, but Pix at 3000 mg/L maintained the highest enzyme activity (15.5 vs. 16.3 nmol $seed^{-1} min^{-1}$ after 180 days). Germination percentage and rate, seedling length and dry weight, and vigor index also declined with aging; however, Pix treatment, especially at 3000 mg L^{-1}, significantly moderated these reductions.

Conclusions: Storage at high temperature and moisture accelerated sesame seed deterioration, reducing germination and α-amylase activity while increasing membrane damage. Pix at 3000 mg L^{-1} was the most effective treatment, maintaining seed vigor and enzyme activity and reducing electrolyte leakage. Therefore, seed treatment with 3000 mg L^{-1} Pix before storage, especially at 15°C and 9% moisture content, can be recommended as an effective strategy to extend seed longevity and maintain quality during medium term storage.

Cite this article: Zeilabpour, R., Moradi, A., Balouchi, H., Yadavi, A., & Latifmanesh, H. (2026). Mepiquat chloride (pix) improves germination and biochemical stability of sesame (*Sesamum indicum* cv. darab-1) seeds under deterioration. *Iranian Journal of Seed Research*, *12*(2), 171-199. https://doi.org/10.66224/yujs.12.2.171

Publisher: Yasouj University.
DOI: https://doi.org/10.66224/yujs.12.2.171

Highlights:

- Pix at 3000 mg/L effectively prevented the decline in physiological traits of sesame seeds during storage and maintained germination potential and seed vigor.
- Increased temperature, moisture, and storage duration reduced α-amylase activity and increased electrolyte leakage, indicating accelerated physiological seed aging.
- Pix treatment improved seed quality under warm and humid storage conditions by reducing electrolyte leakage and enhancing membrane stability, suggesting its practical application for extending seed longevity.

Introduction

The global demand for oilseed crops has increased steadily in recent decades due to their importance as major sources of vegetable oils, essential fatty acids, biofuels, and industrial raw materials. Oilseed crops constitute one of the most important agricultural commodities worldwide, with production and consumption continuing to rise in response to growing food, feed, and industrial demands (Bu et al., 2023; OECD-FAO, 2023). One of the most important oilseed crops is sesame (*Sesamum indicum* L.), which is widely cultivated in tropical and subtropical regions of Asia, Africa, and South America due to its high oil content and nutritional value (Zhang et al., 2013; Pathak et al., 2017). It is considered one of the oldest known oilseeds used by humans and has diverse applications. Additionally, it is an annual plant well-adapted to arid and semi-arid climates and is widely grown in the central and southern provinces of Iran (Sepaskhah & Andam, 2001; Adavi, 2025). According to the Food and Agriculture Organization (FAO, 2021), approximately 49,000 hectares of land in Iran were devoted to sesame cultivation in 2020. This cultivated area is projected to expand in response to increasing demand for sesame seed and vegetable oil products. Depending on the region and the variety under cultivation, sesame seeds contain 41-63% oil, 18-25% protein, and approximately 13.5% carbohydrates. One of the primary challenges with sesame is its limited storability, mainly due to the rapid deterioration caused by oil oxidation during storage (Afshari et al., 2014).

Since the advent of agriculture, seed storage has been essential for preserving planting material for subsequent growing seasons. Depending on the species and storage conditions, seeds may be stored from a few months to several years while maintaining their viability and vigor (Solberg et al., 2020; Nadarajan et al., 2023). Seed deterioration is a progressive and inevitable process that reduces seed quality, viability, and vigor through a series of physiological and biochemical alterations, including membrane damage, oxidative stress, and loss of metabolic activity during storage (Zhang et al., 2021; Nadarajan et al., 2023). Several factors influence the rate of deterioration, among which storage temperature, relative humidity, seed moisture content, and biotic agents such as pests and pathogens are considered the most important. Environmental fluctuations during storage further complicate the maintenance of seed viability and vigor over time (Pirredda et al., 2024; Corbineau, 2024). Seed quality during storage largely depends on initial seed quality and the applied storage methods. Seed aging is associated with various cellular, metabolic, and biochemical changes, including lipid peroxidation, membrane degradation, DNA damage, RNA instability, and reduced protein synthesis (Goel et al., 2003). These changes manifest as a decline in germination rate, production of weak seedlings, reduced seed vigor, and eventually seed death. Seed quality is influenced by genetic, physiological, and environmental factors (Bewley et al., 2013; Nadarajan et al., 2023).

Among the environmental factors, storage temperature and humidity are considered the most critical determinants of seed longevity. Variations in these parameters can accelerate seed deterioration processes and significantly reduce seed storage life (Walters, 2015; Nadarajan et al., 2023). For instance, Balouchi et al. (2014) reported that accelerated seed aging negatively affected germination and seedling vigor traits in three rapeseed (*Brassica napus* L.) cultivars. Similarly, Siadat et al. (2012) found a significant reduction in corn (*Zea mays* L.) seed germination under high temperature and humidity. Similar reductions in germination performance under aging conditions have been widely reported in different seed species. Seed deterioration during storage is associated with membrane damage, increased electrolyte leakage, oxidative stress, and reduced germination capacity (Zhang et al., 2021; Nadarajan et al., 2023). Baladi et al. (2016), in an investigation involving two flax (*Linum usitatissimum* L.) cultivars and one *Lallemantia* accession, concluded that increased storage duration significantly decreased germination percentage, germination rate, vigor, and seedling length and dry weight, especially under elevated temperature and humidity.

Assays measuring enzyme activities associated with reserve mobilization or tissue synthesis during germination are considered more sensitive indicators of early seed deterioration. These enzymes include amylases, proteases, glyceraldehyde phosphate dehydrogenases, catalase, and peroxidase (Rao et al., 2006; Xia et al., 2015).

Optimizing storage conditions, particularly by controlling seed moisture content and storage temperature, can effectively slow down seed deterioration processes and extend seed longevity (Corbineau, 2024; Nadarajan et al., 2023). Since aging causes irreversible damage to seeds, using treatments that mitigate deterioration and maintain seed quality is essential. One such treatment is the application of growth regulators such as mepiquat chloride (Pix), which has been widely used as a plant growth regulator to modify physiological processes, improve stress tolerance, and regulate plant development (Wang et al., 2021; Liu et al., 2025). Pix, the commercial name for mepiquat chloride, is a synthetic plant growth regulator composed of 4.2% dimethylpiperidinium chloride and a polyamine complex. It functions by inhibiting gibberellin synthesis, reducing internode elongation, and balancing vegetative and reproductive growth. In sesame, it may help regulate excessive vegetative growth and favor capsule production by reducing plant height (Jost et al., 2006).

Pix has been widely used in modern agriculture as a management tool (Jost et al., 2006). It is odorless, water-soluble, and typically appears as a red crystalline powder. It degrades in soil within approximately two weeks and has no adverse effects on soil microflora when used in recommended dosages (Boquet & Stewart, 2005; Reddy et al., 1990). Mepiquat chloride has been marketed under several trade names, including Pix, Pix Ultra, and Mepex, since its introduction by BASF in the late 1970s and has since become one of the most widely used plant growth regulators in crop production systems (Liu et al., 2025; Stapleton, 2004). It is considered safe for animals and is mainly absorbed by green plant tissues. In crops such as cotton (Muhammad et al., 2007), tomato (Boquet & Stewart, 2005), and sunflower (Polat et al., 2017), Pix application has been shown to enhance growth and yield parameters. While no study has yet investigated the effects of Pix on seed deterioration, seed germination and seedling vigor are known to be crucial factors determining final yield performance.

Seed priming with growth-regulating compounds such as mepiquat chloride (Pix) has been suggested as a potential approach to improve early seedling establishment by enhancing germination performance, seed vigor, and stress tolerance during the early stages of plant development (Wang et al., 2021; Qian et al., 2023). It may improve germination and root development by modulating hormonal activity and altering cell wall properties during early germination stages (Thandapani & Subharayalu, 2000). Niakan et al. (2012) found that Pix-treated seeds exhibited significantly higher germination percentages compared to untreated controls. Given that sesame is an oilseed crop with high susceptibility to deterioration due to its oil-rich nature under various storage conditions, and although the effects of Pix (mepiquat chloride) on plant growth, yield performance, and seedling establishment have been reported in several crops, information regarding its potential role in reducing seed deterioration during storage remains scarce. To the best of our knowledge, no study has specifically investigated the effects of Pix on seed longevity, α-amylase activity, membrane stability, and germination performance of sesame seeds under different storage conditions. Given the high susceptibility of sesame seeds to deterioration due to their elevated oil content, identifying effective treatments to maintain seed quality during storage is of considerable practical importance. Therefore, this study aimed to evaluate the effects of different concentrations of Pix on germination indices, α-amylase activity, and electrolyte leakage of stored sesame seeds under varying storage temperatures, seed moisture contents, and storage durations.

Material and Method

Seeds, cultivar Darab-1, were obtained from the Seed Certification and Registration Institute in Karaj, Iran, to be used in the experiment under various storage conditions. The experiment was arranged in a four-factor factorial based on a completely randomized design (CRD) with three replications at the Agronomy Laboratory, Faculty of Agriculture, Yasouj University. The factors included storage temperature (15, 25, and 35°C), seed moisture content (9%, 12%, and 15%), Pix concentration (0, 1500, 3000, and 4500 mg L^{-1}), and storage duration (0, 30, 60, 90, 120, 150, and 180 days). To determine the initial seed moisture content, three replicates of 5 g of seeds were weighed and dried in an oven at 103 ± 2°C for 17 ± 1 h according to the International Rules for Seed Testing (ISTA, 2024). The moisture content was then calculated on a fresh weight basis, as described by Jorge and Ray (2004). To adjust seed moisture content, the amount of water required was calculated using the following equation (ISTA, 2024):

$$W2 = W1 \frac{A-B}{100-A}$$

Where:

- B is the initial seed moisture content (%),
- A is the target seed moisture content (%),
- W1 is the initial weight of seeds (g),
- W2 is the required amount of Pix solution (g).

To increase the moisture content, Pix solutions at 0, 1500, 3000, and 4500 mg L^{-1} concentrations were prepared. Seeds were placed in aluminum foil pouches, and the appropriate volume of Pix solution (as calculated) was added to the seeds. The pouches were vacuum-sealed using a heat sealer to prevent any moisture exchange with the external environment. These seed packages were then stored in temperature-controlled incubators set at 15, 25, and 35°C.

At one-month intervals, seeds from different storage treatments were removed and subjected to standard germination tests under laboratory-controlled conditions. Germination tests were performed using the "top-of-paper" method in Petri dishes at alternating temperatures of 20/30 °C for 7 days, following the ISTA rules (ISTA, 2009).

Germination indices evaluation

The following parameters were measured during the germination test:

- Germination percentage (Ikić et al., 2012),
- Germination rate (Verma et al., 2003),
- Seedling vigor index (Abdul-Baki and Anderson, 1973),
- Seedling length,
- Seedling dry weight.

Electrolyte leakage and α-amylase enzyme activity

For electrolyte leakage and α-amylase activity assessments, a reduced factorial design was used, still based on a CRD with three replications. The experimental factors were:

- Storage temperature at two levels (15 and 25°C),
- Seed moisture content at two levels (9% and 15%),
- Pix concentration at three levels (0, 3000, and 4500 mg L^{-1}
- Storage duration at three levels (60, 120, and 180 days).

Electrolyte leakage Test

For the electrolyte leakage test, 100 seeds were randomly selected from each treatment. Erlenmeyer flasks containing deionized water were equilibrated at 20°C for 24 hours. Seeds were placed into these flasks and incubated in a germinator at 20°C for another 24 hours. After this initial soaking period, the electrical conductivity of the seed leachate was measured (EC_1).

To release the remaining electrolytes completely, the samples were subjected to a complementary treatment (boiling or autoclaving), after which the final electrical conductivity was recorded (EC_2). The percentage of electrolyte leakage was then calculated according to the following formula:

$EL(\%)=(EC_1)/(EC_2)\times100$ (Dehghan-Shoar et al., 2005).

α-Amylase activity measurement

α-Amylase activity was determined following the protocol of Xiao et al. (2006). Two grams of germinated seeds (at the second germination stage) were homogenized with 5 mL of 60 mM phosphate buffer (pH = 6). The mixture was centrifuged at 12,000 rpm for 10 minutes to extract the enzyme.

For the assay, 0.5 mL of the enzyme extract was incubated at 37°C for 30 minutes. Then, 1 mL of 0.1 N HCl was added to terminate the reaction, followed by 1 mL of iodine reagent. The final volume was adjusted to 10 mL with distilled water. Absorbance was recorded at 620 nm using a spectrophotometer. Enzyme activity was calculated using a starch standard curve and expressed based on the amount of hydrolyzed starch.

Statistical analysis

Statistical analyses were performed using SAS software (version 9.4), and graphical visualizations were generated with Microsoft Excel (2019). The mean comparisons of main effects were conducted using Duncan's multiple range test (DMRT) at the 5% significance level. In cases of significant interactions, the L.S.Means procedure was applied for comparing trait means, also at the 5% probability level.

Results and Discussion

Analysis of variance

The results of the analysis of variance (ANOVA) indicated that the four-way interaction among temperature, seed moisture content, storage duration, and Pix concentration significantly affected electrolyte leakage and α-amylase activity ($P\leq 0.01$) (Table 1). Given the significance of the four-factor interaction on these traits in sesame seeds, a three-factor factorial analysis (moisture × Pix × storage period) was conducted separately for each temperature level. Upon confirmation of significant three-way interactions, data slicing based on moisture levels at each temperature was performed. The sliced analysis also showed that the interaction between Pix concentration and storage duration at each moisture level was highly significant ($p< 0.01$) for both traits (Table 1).

Electrolyte leakage (EL)

The mean comparison of Pix concentration effects on electrolyte leakage at 15 °C and 9% and 15% seed moisture content revealed a significant increase in EL with prolonged storage duration. The highest EL values were observed in the control (untreated) seeds after 180 days, with means of 47.21 and 52.13%, respectively. In contrast, the lowest EL

جدول ۱: مقایسه میانگین اثرات PIX و دوره نگهداری بر نشت الکترولیت و فعالیت آلفا آمیلاز در کنجد (رقم داراب ۱) در دماهای ۱۵ و ۲۵ درجه سلسیوس و درصد رطوبت بذر ۹ و ۱۵درصد.

Table 1: Mean comparison of PIX and storage period effects on electrolyte leakage and α-amylase activity in sesame (Darab 1 cultivar) under 15°C and 25°C, seed moisture content 9% and 15%

غلظت پیکس (میلی‌گرم بر لیتر) PIX concentration (mg/L)	انبارداری (روز) Storage (days)	نشت الکترولیت (درصد) Electrolyte Leakage (%)	آلفا آمیلاز (نانومول بر بذر بر دقیقه) α-Amylase ($nmol.seed^{-1}.min^{-1}$)	نشت الکترولیت (درصد) Electrolyte Leakage (%)	آلفا آمیلاز (نانومول بر بذر بر دقیقه) α-Amylase ($nmol.seed^{-1}.min^{-1}$)
		9%		15%	
		15°C			
Control (0)	60	25.8^{c}	4.68^{bc}	36.5^{f}	3.17^{bc}
	120	39.65^{b}	4.18^{d}	47^{b}	2.68^{d}
	180	47.21^{a}	3.16^{g}	52.13^{a}	1.65^{e}
3000	60	22.71^{d}	5.15^{a}	30.89^{g}	3.47^{a}
	120	37.63^{b}	4.63^{c}	39.55^{e}	2.95^{c}
	180	45.08^{a}	3.47^{e}	44.99^{c}	1.84^{e}
4500	60	24.7^{cd}	4.76^{b}	32.67^{g}	3.24^{ab}
	120	39.86^{b}	4.27^{d}	41.77^{de}	2.73^{cd}
	180	46.87^{a}	3.24^{f}	46.97^{bc}	1.68^{e}
p value (Pix × Storage)		1.56**	2.45**	1.48**	0.33*
		9%		15%	
		25°C			
Control (0)	60	48.06^{f}	3.82^{b}	54.46^{c}	2.55^{b}
	120	65.83^{c}	2.79^{e}	71.49^{b}	1.87^{c}
	180	72.72^{a}	2.03^{h}	81.67^{a}	1.23^{e}
3000	60	42.71^{h}	4.34^{a}	50.69^{d}	2.77^{a}
	120	57.14^{e}	3.28^{c}	66.28^{b}	2.06^{c}
	180	64.11^{cd}	2.32^{f}	71.98^{b}	1.50^{d}
4500	60	46.51^{g}	4.05^{ab}	52.00^{cd}	2.73^{ab}
	120	63.54^{d}	3.08^{d}	68.49^{b}	1.93^{c}
	180	69.01^{b}	2.20^{gh}	78.58^{a}	1.48^{d}
p value (Pix × Storage)		2.13**	2.45**	0.95**	0.33*

* و ** به ترتیب نشان‌دهنده وجود اختلاف معنی‌دار در سطح احتمال پنج درصد و یک درصد هستند. حروف متفاوت در هر ستون نشان دهنده اختلاف معنی‌دار بر اساس آزمون چند دامنه‌ای دانکن در سطح ۵ درصد است.

* and ** indicate a significant difference at the 5% and 1% probability levels, respectively. Different letters in each column indicate a significant difference based on Duncan's multiple range tests at the 5% level.

values were recorded in the 3000 mg L^{-1} Pix treatment after 60 days, with means of 22.71 and 30.89%, respectively (Table 1). Similarly, at 25°C, the highest EL was again observed in the control treatment after 180 days under 9% and 15% moisture, with means of 72.72 and 81.67%, respectively. The lowest EL at this temperature and moisture was also observed in the 3000 mg L^{-1} Pix treatment after 60 days, with values of 42.71 and 50.69%, respectively (Table 1). Electrolyte leakage indirectly reflects the concentration of electrolytes released from seeds during imbibition. An increase in EL has been consistently reported in previous studies as an indicator of seed deterioration (Mosavi Nik et al., 2011; Goel et al., 2003; Mohammadi et al., 2012). However, EL may not be a reliable indicator of seed vigor under low-temperature conditions (Fessel et al., 2010), which aligns with findings from the current research. Numerous studies (Siadat et al., 2012; Alivand, 2010; Mohammadi et al., 2012) have shown that increased seed aging disrupts cell membrane integrity, leading to elevated electrolyte leakage and higher EL values. Seeds exhibiting high EL values are generally associated with low vigor, while seeds with low EL are often of higher physiological quality (Vieira et al., 2004; Ghassemi-Golezani & Hosseinzadeh Mahootchy, 2009). It is widely accepted that increased EC during storage is due to lipid peroxidation and mitochondrial dysfunction, which collectively impair energy production in seeds (McDonald, 1999; Fessel et al., 2006). The increase in electrical leakage observed during storage was accompanied by reductions in α-amylase activity, germination percentage, germination rate, and seedling vigor. This relationship suggests that membrane deterioration is not an isolated event but rather a key component of the overall seed aging process. Damage to membrane systems can impair cellular compartmentalization, enzyme stability, and metabolic efficiency, ultimately reducing germination performance. Therefore, electrolyte leakage may serve as a useful physiological indicator of the biochemical and functional changes occurring during seed deterioration.

α-amylase activity

The comparison of α-amylase activity among Pix treatments at 15°C under 9%, and 15% seed moisture content indicated a significant decrease in enzyme activity with extended storage time. The highest enzyme activity was observed in the 3000 mg L^{-1} Pix treatment after 60 days, with average values of 5.15 and 3.47 nmol $seed^{-1}min^{-1}$, respectively. The lowest activity was recorded in the control treatment after 180 days, at 3.16 and 1.65 nmol $seed^{-1}min^{-1}$, respectively (Table 1). At 25°C, the trend was similar: the maximum α-amylase activity at 9% and 15% moisture was observed in the 3000 mg L^{-1} Pix treatment after 60 days, with mean values of 4.34 and 2.77 nmol $seed^{-1}min^{-1}$, respectively. The minimum activity was again observed in the control group after 180 days, with values of 2.03 and 1.23 nmol $seed^{-1}min^{-1}$, respectively (Table 1). Previous studies have also demonstrated a reduction in α-amylase activity with increasing seed deterioration. This includes studies on wheat (Chauhan et al., 2011), rice (Latifzadeh Shahkhali et al., 2020), bean (Ghanbari et al., 2018), and soybean (Hajabbasi et al., 2021). The strong association between α-amylase activity and germination-related traits observed in this study highlights the importance of reserve mobilization during seed germination. Seeds with higher α-amylase activity generally exhibited higher germination percentages, faster germination rates, and greater seedling vigor. In contrast, declining enzyme activity was accompanied by increased electrolyte leakage, suggesting that membrane deterioration and metabolic dysfunction occur simultaneously during aging. These findings indicate that α-amylase activity can be considered an important biochemical marker of seed physiological quality.

Seed aging effects on α-amylase and germination

McDonald (1999) noted that seed aging leads to DNA degradation, resulting in disrupted transcription processes and impaired synthesis of essential enzymes such as α- and β-amylases, which are vital for the early stages of germination. As aging progresses, the activity of these enzymes diminishes, preventing the hydrolysis of seed reserves and limiting the availability of energy molecules like ATP.

In the present study, the decrease in α-amylase activity across all treatments was aligned with the reduction in germination indices in aged seeds. Similarly, Lee and Kim (2000), and Latifzadeh Shahkhali et al. (2020), reported that reductions in α-amylase activity during seed aging are associated with phospholipid degradation, increased lipid peroxidation, and structural changes in plastid and mitochondrial membranes, alongside damage to DNA, RNA, and proteins. These findings suggest that Pix treatment, by modulating these physiological parameters, may help preserve enzyme activity. The reduction in α-amylase activity observed during storage appears to be directly linked to the decline in germination indices and the increase in electrolyte leakage. α-amylase is a key hydrolytic enzyme responsible for mobilizing starch reserves and supplying soluble sugars required for embryo growth. Therefore, reduced enzyme activity limits energy availability during germination, leading to lower germination percentage, slower germination rate, and reduced seedling vigor. The simultaneous increase in electrolyte leakage further suggests that membrane deterioration may contribute to the loss of enzymatic functionality by disrupting cellular organization and accelerating oxidative damage. The superior performance of seeds treated with 3000 mg L^{-1} Pix, which maintained higher α-amylase activity and lower electrolyte leakage, indicates that preservation of both membrane integrity and reserve mobilization capacity are important mechanisms underlying improved seed storability.

Factors affecting germination indices

The ANOVA results (Table 2) showed that temperature, moisture content, Pix concentration, and storage duration, as well as most of their interactions, had significant effects ($p < 0.01$) on sesame seed germination indices. The temperature × Pix interaction was significant only for seedling length ($p < 0.05$). Due to the significant four-way interaction effects (Table 2), data were first analyzed as a three-factor factorial (moisture × Pix × storage duration) for each temperature, and sliced analyses based on moisture content

جدول ۲ –تجزیه‌واریانس (میانگین مربعات) اثر دما، رطوبت بذر، نگهداری در شرایط PIX و دوره نگهداری بر صفات جوانه‌زنی کنجد رقم (داراب ۱).

Table 2 – Analysis of variance (mean squares) of the effects of temperature, seed moisture content, pix storage, and storage period on germination traits of sesame cultivar 'Darab 1

منابع تغییر Source of variation	درجه آزادی df	درصد جوانه‌زنی Germination percentage	سرعت جوانه‌زنی Germination rate	طول گیاهچه Seedling length	وزن خشک گیاهچه Seedling dry weight	شاخص طولی بنیه گیاهچه Seedling length vigor index	شاخص وزنی بنیه گیاهچهSeedling weight vigor index
دما Temperature (T)	2	65621.8**	3705.2**	236.82**	0.002**	202.79**	0.001**
محتوی رطوبت بذر Seed moisture content (SM)	2	132753.3**	7251.10**	460.07**	0.003**	293.06**	0.002**
پیکس PIX	3	2772.8**	208.40**	13.05**	0.0001**	3.43**	0.00002**
دوره انبارداری Storage Period (SP)	5	16577.5**	3684.34**	228.99**	0.000002**	102.23**	0.0002**
دما × محتوی رطوبت بذر T × SM	4	30803.8**	1691.02**	106.66**	0.00002**	83.39**	0.0005**
دما × پیکس T × PIX	6	113.2^{ns}	15.21**	0.99*	0.00004**	0.05^{ns}	0.0000005**
محتوی رطوبت بذر× دما SM × PIX	6	74.2^{ns}	5.38^{ns}	0.39^{ns}	0.000006**	0.39^{ns}	0.000003**
دما × دوره انبارداری T × SP	10	694.8**	141.59**	8.40**	0.000003**	13.34**	0.00003**
دوره انبارداری× محتوی رطوبت بذر SM × SP	10	1796.7**	286.23**	17.44**	0.00003**	17.07**	0.000004**
دوره انبارداری× پیکس PIX × SP	15	184.7**	30.59**	1.88**	0.000004**	0.29**	0.0000007**
دما × محتوی رطوبت بذر× پیکس T × SM × PIX	12	111.28**	7.50**	0.51**	0.000003**	0.22**	0.000002**
دما × محتوی رطوبت بذر× دوره انبارداری T × SM × SPd	20	1626.31**	112.58**	7.16**	0.000004**	8.85**	0.00004**
دما × پیکس × دوره انبارداری T × PIX × SP	30	75.81**	7.74**	0.51**	0.000002**	0.14**	0.0000007**
محتوی رطوبت بذر× دوره انبارداری× پیکس SMC × SP × PIX	30	111.82**	12.39**	0.81**	0.000003**	0.16**	0.0000005**
دما × محتوی رطوبت بذر× دوره انبارداری T × SM × SP ×PIX	60	63.45**	6.16**	0.39**	0.000002**	0.12**	0.0000004**
خطا Error	430	3.54	0.75	0.05	0.0000001	0.03	0.0000001
ضریب تغییرات (درصد) Coefficient of variation (%)		7.03	12.24	12.94	7.37	16.53	10.99

* و ** به ترتیب نشان‌دهنده اختلاف معنادار در سطوح پنج درصد و یک درصد و ns عدم معنی داری هستند.

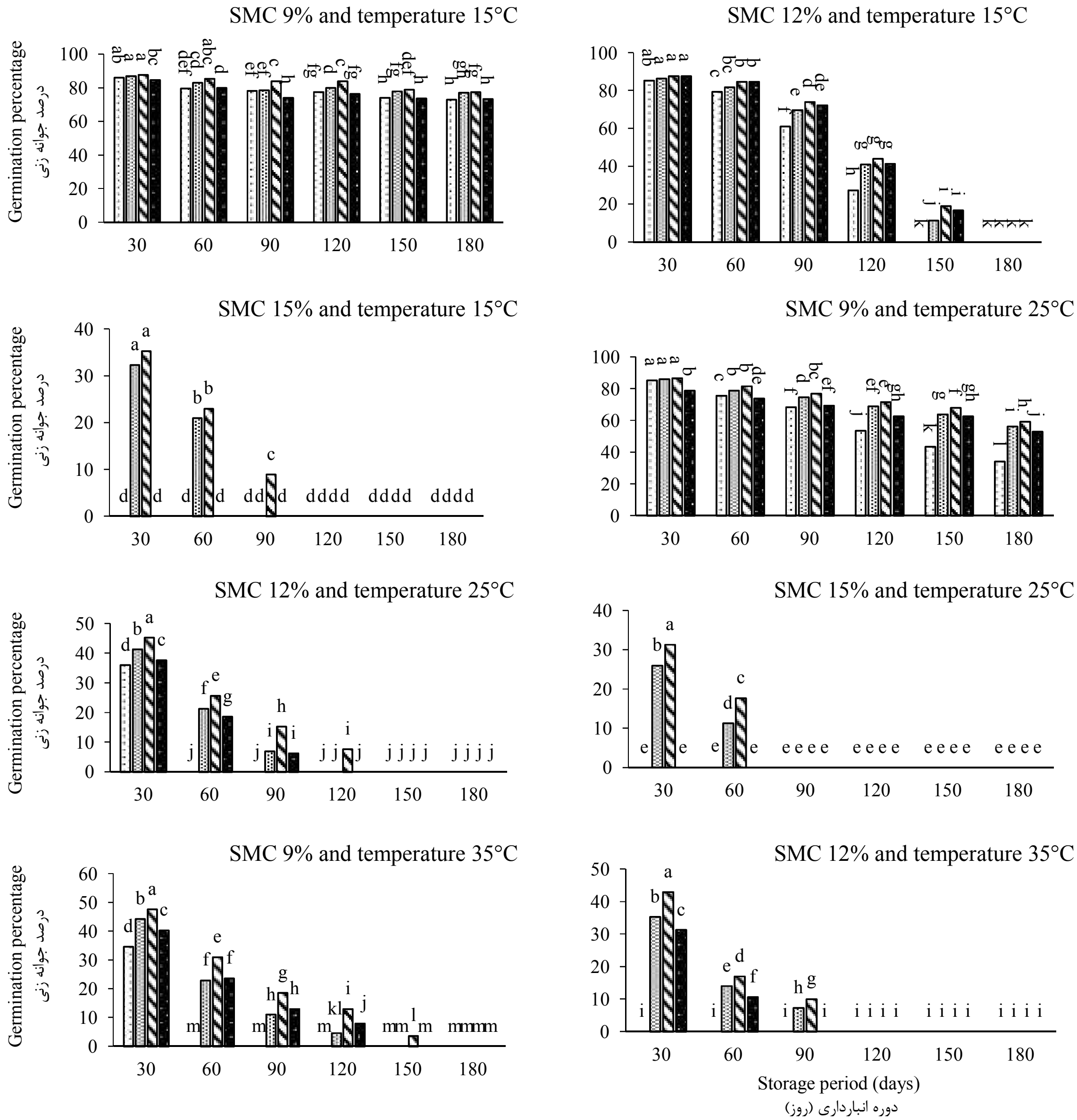
*, ** and ^{ns} indicate a significant difference at the 5% and 1% levels and no significant , respectively.

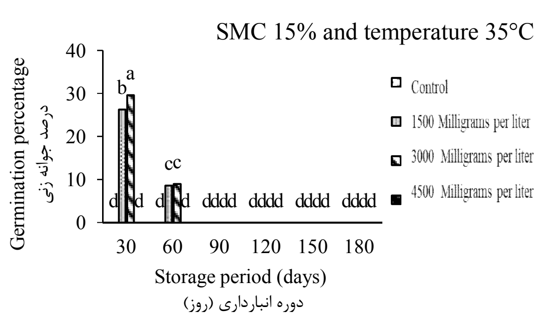
were then conducted. The sliced analysis revealed that the Pix × storage duration interaction was highly significant ($p < 0.01$) for all measured traits at each moisture level.

Germination percentage

The mean comparison of germination percentage under different moisture levels, Pix concentrations, and storage durations at 15, 25, and 35°C showed that germination declined significantly with seed aging in all treatments. However, the reduction was more pronounced in the control seeds (Figure 1). At 15°C and 9% moisture, the highest germination percentages were observed after 30 days of storage, with averages of 87.00%, 87.66%, and 86.00% for 1500, 3000 mg L^{-1} Pix, and control treatments, respectively. The lowest germination (73.00%) was recorded in the control after 180 days of storage, which was not significantly different from the 4500 mg L^{-1} Pix treatment (73.33%) (Figure 1). At 15°C and 12% moisture, the highest germination percentage was again recorded after 30 days of storage across all treatments, with values of 85.33%, 86.33%, 87.67%, and 87.67% for control, 1500, 3000, and 4500 mg L^{-1} Pix, respectively (Figure 1). At 25°C, the highest germination percentages under 9%, 12%, and 15% moisture were 86.67%, 45.33%, and 31.33%, respectively, all recorded for the 3000 mg L^{-1} Pix treatment after 30 days (Figure 1). At 35°C, the highest germination percentages under the same moisture levels were 47.67%, 43.00%, and 29.67%, respectively, again for the 3000 mg L^{-1} Pix treatment after 30 days (Figure 1). In general, germination percentage decreased more rapidly at higher temperatures, and across all temperatures, germination dropped sharply to zero at 15% seed moisture. Notably, only seeds treated with 1500 or 3000 mg L^{-1} Pix retained measurable germination beyond 30 days of storage under high moisture conditions (Figure 1). These findings are consistent with previous studies by Latifzadeh Shahkhali et al. (2020), Baghdadi et al. (2017), Mehrabi Koushki et al. (2022), Bewley et al. (2013), and Ghanbari et al. (2018), all of which reported significant declines in germination percentage with increased seed moisture, temperature, and storage time. The decline in germination under aging stress may be attributed to several factors, including reduced enzymatic activity essential for germination, membrane damage caused by lipid peroxidation, increased accumulation of malondialdehyde (MDA), damage to RNA and DNA, and decreased activity of antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), glutathione reductase (GR), and ascorbate peroxidase (APX) (Kibinza et al., 2006; Brar et al., 2019).

Seed aging is a progressive process associated with a series of physiological and biochemical changes that ultimately reduce seed viability and germination performance. During storage, deterioration processes such as oxidative stress, membrane disruption, increased electrolyte leakage, and impairment of cellular metabolism contribute to the loss of seed quality and vigor (Zhang et al., 2021; Nadarajan et al., 2023). In the present study, control treatments exhibited lower





شکل ۱- اثر پیکس و انبارداری بر درصد جوانه‌زنی کنجد رقم داراب ۱ تحت شرایط دمایی ۱۵، ۲۵ و ۳۵ درجه سلسیوس و رطوبت ۹، ۱۲ و ۱۵ درصد. حروف متفاوت نشان دهنده اختلاف معنی‌دار بر اساس آزمون چند دامنه‌ای دانکن در سطح ۵ درصد است.

Figure 1. The effect of PIX treatment and storage on the germination percentage of Darab 1 sesame variety under temperature conditions of 15, 25, and 35°C and seed moisture content (SMC) of 9%, 12%, and 15%. Different letters indicate a significant difference based on Duncan's multiple range tests at the 5% level.

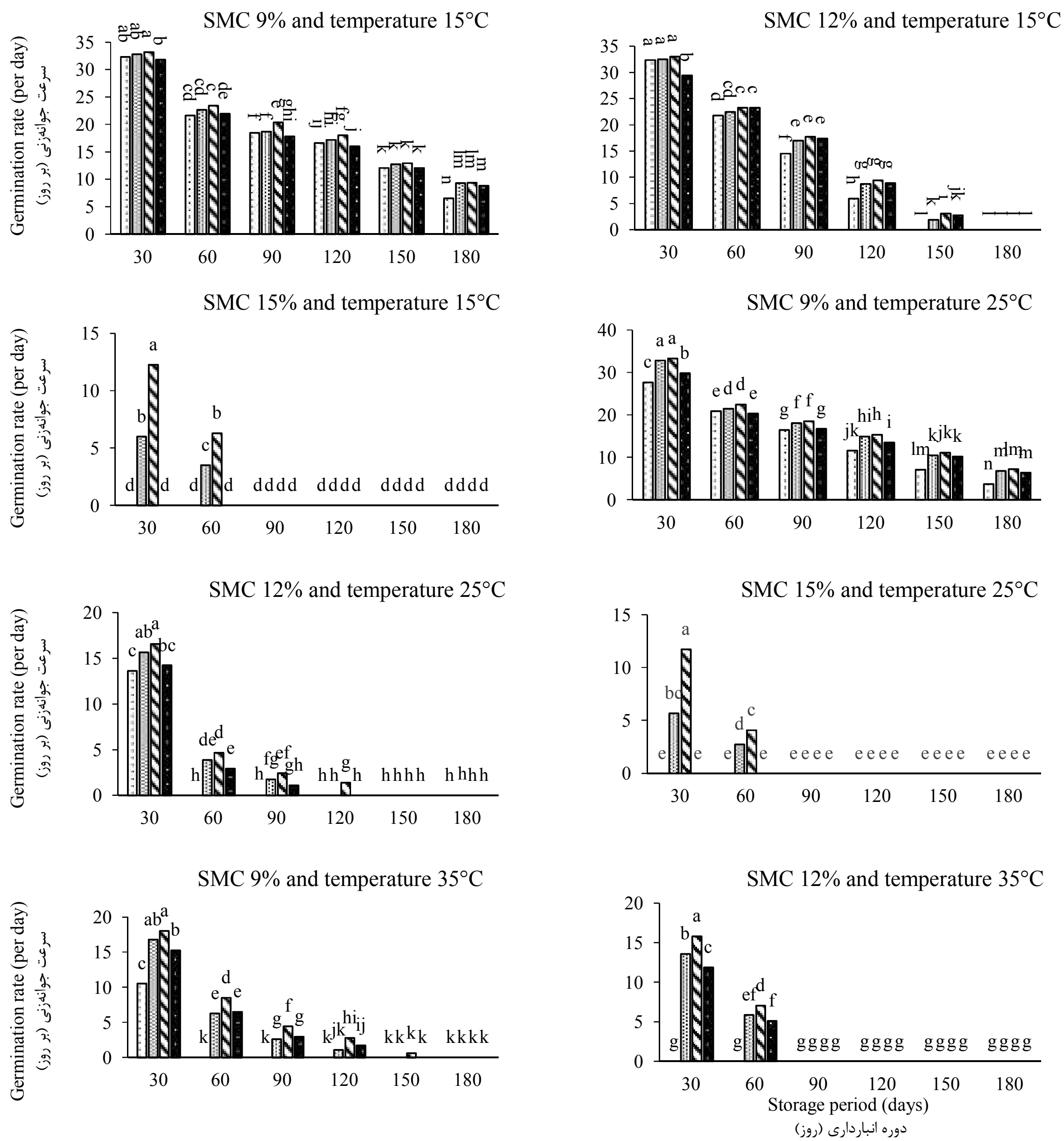
germination percentages than Pix-treated seeds, correlating with reduced α-amylase and peroxidase activity and higher MDA content. Yin et al. (2014) and Latifzadeh Shahkhali et al. (2020) attributed the reduced germination in aged seeds to the accumulation of reactive oxygen species (ROS) due to decreased catalase and peroxidase activity. In contrast, Pix-treated seeds showed higher germination percentages, likely due to a smaller declinein α-amylase and peroxidase activity and lower MDA accumulation. The reduction in germination percentage observed during storage was closely associated with the simultaneous increase in electrolyte leakage and decrease in α-amylase activity. Increased electrolyte leakage indicates membrane deterioration and loss of cellular integrity, while reduced α-amylase activity limits the mobilization of stored reserves required for embryo growth. Therefore, seeds exhibiting lower electrolyte leakage and higher α-amylase activity generally maintained greater germination capacity. These findings suggest that membrane stability and reserve mobilization are key determinants of seed viability during storage.

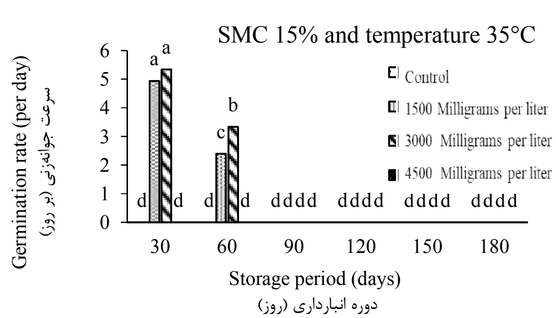
Germination rate

The analysis of mean comparisons for the effects of temperature, moisture content, Pix concentration, and storage duration revealed that germination rate significantly decreased across all treatments as storage duration increased, regardless of temperature and Pix level (Figure 2). At 15°C, the highest germination rates under 9%, 12%, and 15% moisture levels were 16.33, 13.33, and 12.27 seed d^{-1}, respectively. At 25°C, they were 13.33, 6.16, and 11.73 seed d^{-1}, and at 35°C, 18.06, 15.83, and 5.33 seed d^{-1}, respectively (Figure 2). These findings are consistent with reports by Dantas et al. (2019), Latifzadeh Shahkhali et al. (2020), Ansari et al. (2013), Hoseinipoor et al. (2020), and Afrosheh et al. (2018), who also observed significant reductions in germination rate with prolonged storage, increased temperature, and higher seed moisture. The observed decline reflects worsening storage conditions, impeding seed physiological performance. Aging seeds often exhibit delays in the initiation of germination, likely due to the extended time required for repairing damage to cellular membranes and the reactivation of antioxidant defense systems. This leads to longer completion times for germination, thus reducing germination rate and increasing mean germination time (Bewley et al., 2013). Tabatabaei (2013) similarly observed a significant decline in germination rate with extended storage. Lee et al. (2010), in a study on transgenic tobacco seeds, reported higher germination rate associated with overexpression of superoxide dismutase (SOD) genes. In contrast, non-transgenic seeds exhibited higher ionic leakage and more oxidative damage to cell membranes. These findings highlight the crucial role of SOD in enhancing germination and seed longevity.

Latifzadeh Shahkhali et al. (2020) also reported that seeds with higher antioxidant enzyme activity displayed significantly faster germination compared to those with lower enzyme activity. The decline in germination rate under prolonged storage conditions appears to be strongly related to both enzymatic and membrane-related changes occurring during seed aging. Reduced α-amylase activity may delay the conversion of starch reserves into soluble sugars, thereby slowing metabolic activation during germination.

Simultaneously, increased electrolyte leakage reflects membrane damage that can impair water uptake efficiency and cellular metabolism. Consequently,





شکل ۲- اثر پیکس و انبارداری بر سرعت جوانه‌زنی کنجد رقم داراب ۱ تحت شرایط دمایی ۱۵، ۲۵ و ۳۵ درجه سلسیوس و رطوبت ۹، ۱۲ و ۱۵ درصد. حروف متفاوت نشان دهنده اختلاف معنی‌دار بر اساس آزمون چند دامنه‌ای دانکن در سطح ۵ درصد است.

Figure 2. The effect of PIX treatment and storage on the germination rate of Darab 1 sesame variety under temperature conditions of 15, 25, and 35°C and seed moisture content (SMC) of 9%, 12%, and 15%. Different letters indicate a significant difference based on Duncan's multiple range tests at the 5% level.

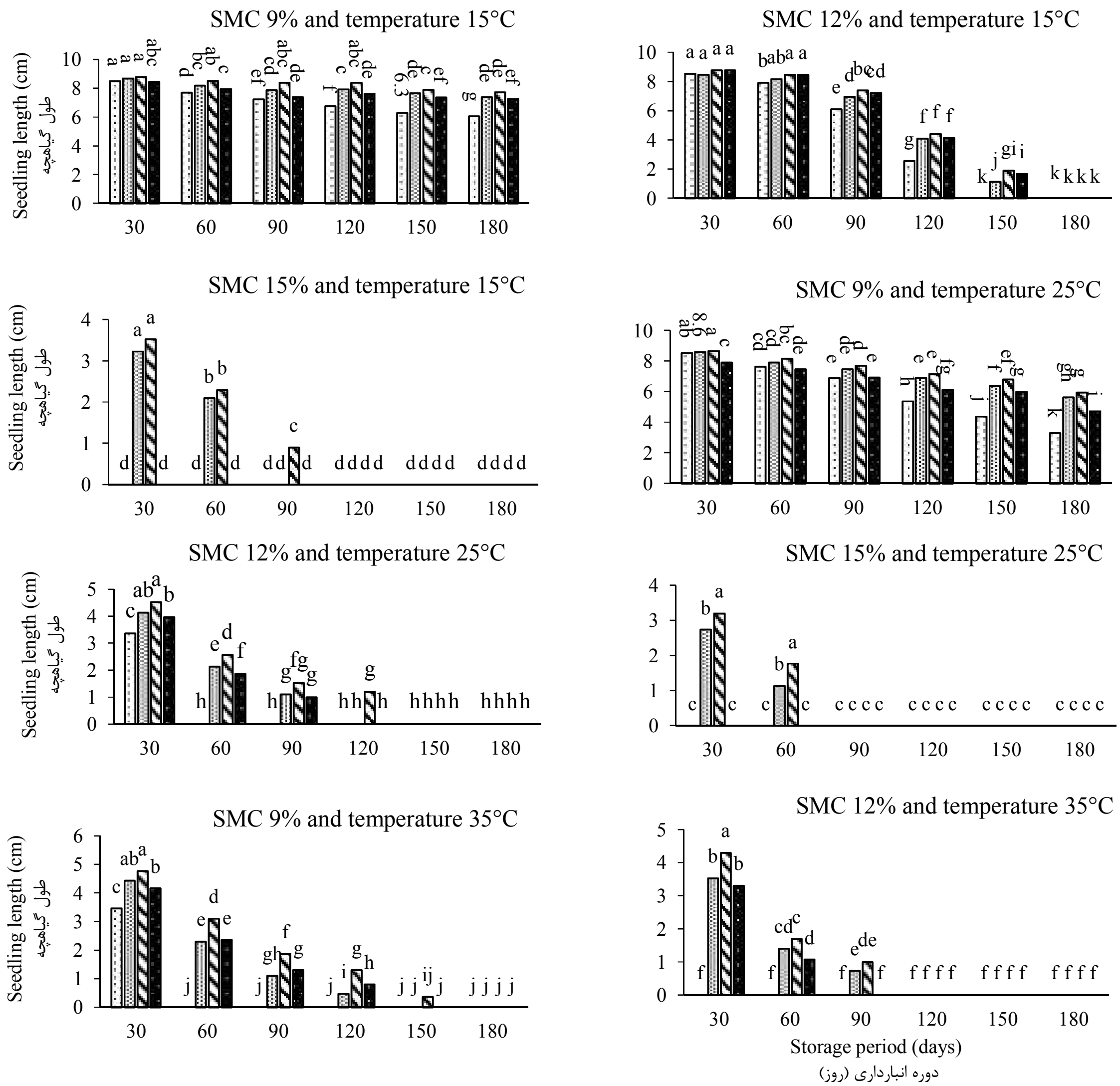
treatments maintaining lower electrolyte leakage and higher α-amylase activity exhibited faster germination, highlighting the physiological interdependence of these traits.

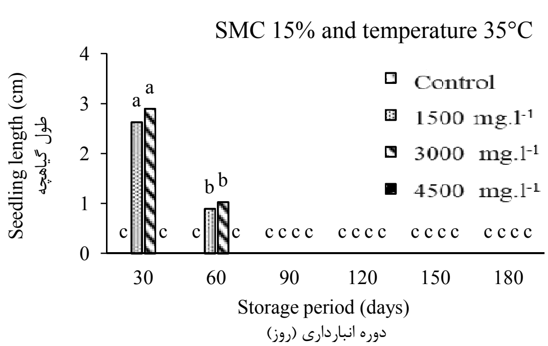
Seedling length

The comparison of mean values under different storage conditions indicated that seedling length decreased significantly with prolonged storage duration. At 15°C, the longest seedlings under 9%, 12%, and 15% moisture conditions were observed in the 3000 mg L^{-1} Pix treatment, with mean lengths of 8.80, 8.76, and 3.53 cm, respectively. In all moisture conditions, the shortest seedlings were recorded in the control treatment (Figure 3). At 25°C, the shortest seedling length was 3.3 cm (control, 9% moisture, 180 days). Seedling length dropped to zero after 60 days (12% moisture) and 30 days (15% moisture) of storage in the control treatment (Figure 3). At 35°C, seedling length reached zero after 60 days at 9% moisture, and after 30 days at 12% and 15% moisture in the control group due to complete germination failure. At 9% moisture after 150 days, only the 3000 mg L^{-1} Pix treatment retained measurable seedling growth (0.36 cm). After 180 days, seedling length was zero in all treatments, and for 15% moisture, no growth was observed beyond 90 days (Figure 3). These results align with findings from Latifzadeh Shahkhali et al. (2020), Alivand (2010), Ansari et al. (2013), and Mehrabi Koushki et al. (2022), who showed that increased storage duration, temperature, and seed moisture significantly reduce seedling length in oilseed and leguminous crops. Seedling growth reduction is generally linked to seed aging and delayed germination, which limits biomass accumulation and elongation (Bewley et al., 2013; Ansari et al., 2013). A reduction in seedling length may reflect declined antioxidant enzyme activity. Chiu et al. (2003) explained that prolonged storage leads to decreased activity of antioxidant enzymes, resulting in increased reactive oxygen species (ROS) that damage seedling development. Additionally, in unfavorable environments, reserve mobilization from seed to seedling becomes inefficient, leading to weaker seedling establishment. Hence, reduced seedling length may be associated with limited utilization of seed reserves. Changes in seedling length were closely associated with alterations in seed vigor-related biochemical characteristics. The maintenance of higher α-amylase activity in Pix-treated seeds likely enhanced reserve mobilization and energy availability for seedling growth. In contrast, increased electrical leakage, indicative of membrane deterioration, was associated with shorter seedlings and weaker seedling establishment. These results suggest that the ability of seedlings to sustain growth after germination depends largely on the preservation of metabolic activity and membrane integrity during storage.

Seedling dry weight

The results of seedling dry weight under varying storage conditions and Pix treatments showed a significant reduction in dry weight with increased storage duration, as well as with elevated moisture content and storage temperature. At 15°C, the highest seedling dry weights under 9%, 12%, and 15% moisture were 0.016, 0.015, and 0.006 g, respectively, in the 3000 mg L^{-1} Pix treatment after 30 days of storage. Beyond this point, seedling dry weight declined significantly in all treatments (Figure 4). At 25°C, the highest seedling dry weight at 9%, 12%, and 15%

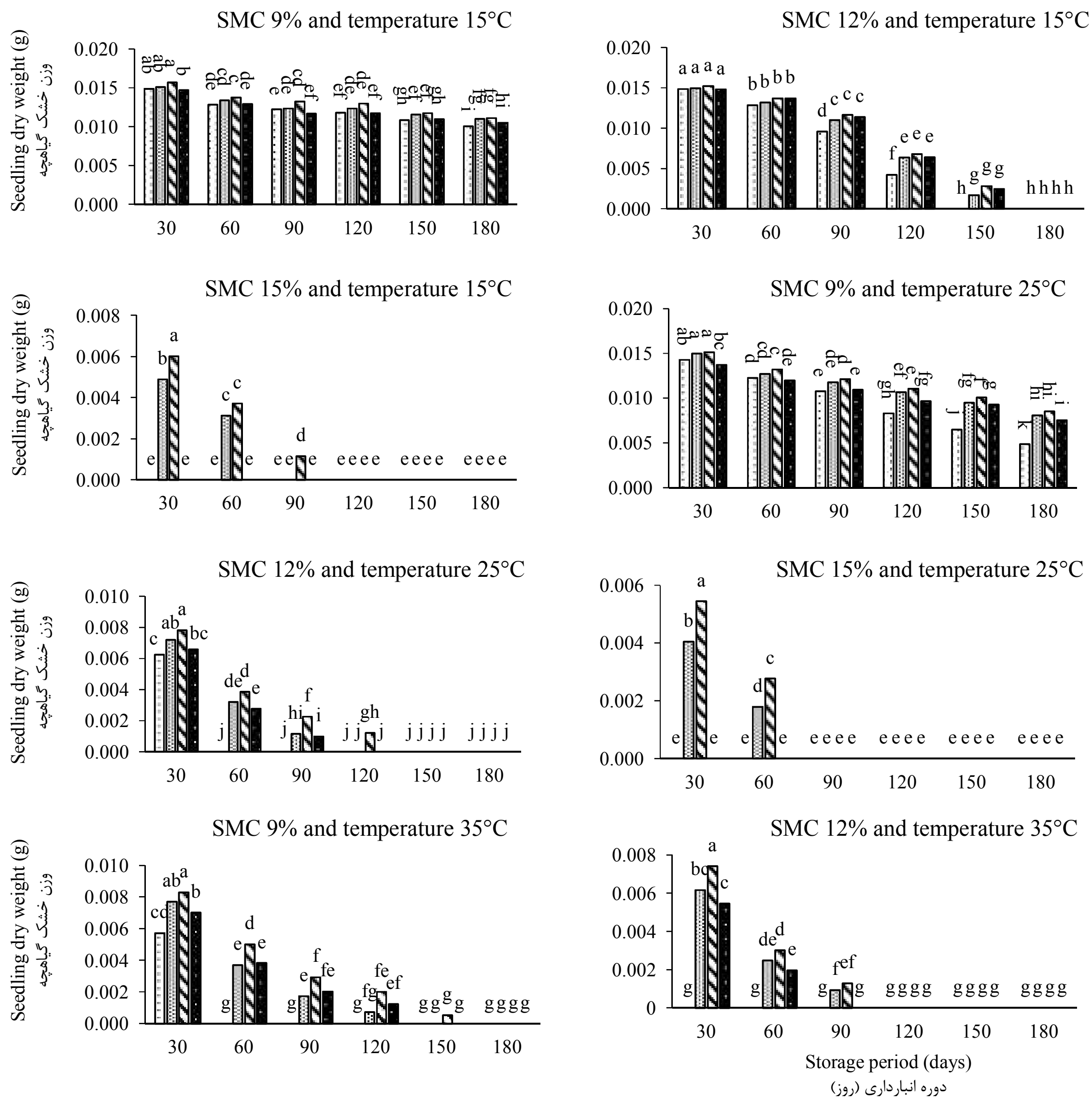


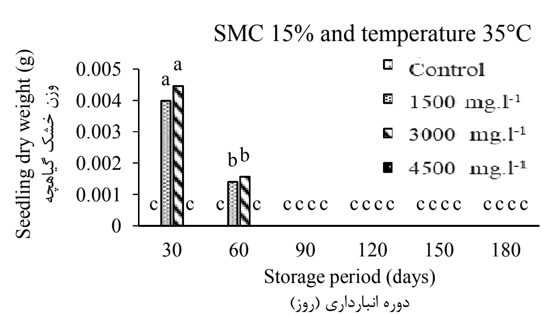


شکل ۳- اثر پیکس و انبارداری بر طول گیاهچه کنجد رقم داراب ۱ تحت شرایط دمایی ۱۵، ۲۵ و ۳۵ درجه سلسیوس و رطوبت ۹، ۱۲ و ۱۵ درصد. حروف متفاوت نشان دهنده اختلاف معنی‌دار بر اساس آزمون چند دامنه‌ای دانکن در سطح ۵ درصد است.

Figure 3. The effect of PIX treatment and storage on the seedling length of Darab 1 sesame variety under temperature conditions of 15, 25, and 35°C and seed moisture content (SMC) of 9%, 12%, and 15%. Different letters indicate a significant difference based on Duncan's multiple range tests at the 5% level.

moisture contents were 0.015, 0.007, and 0.005 g, respectively, in the 3000 mg L^{-1} Pix treatment after 30 days. The lowest value (0.005 g) occurred in the control treatment after 180 days (9% moisture), while the highest dry weight at 180 days





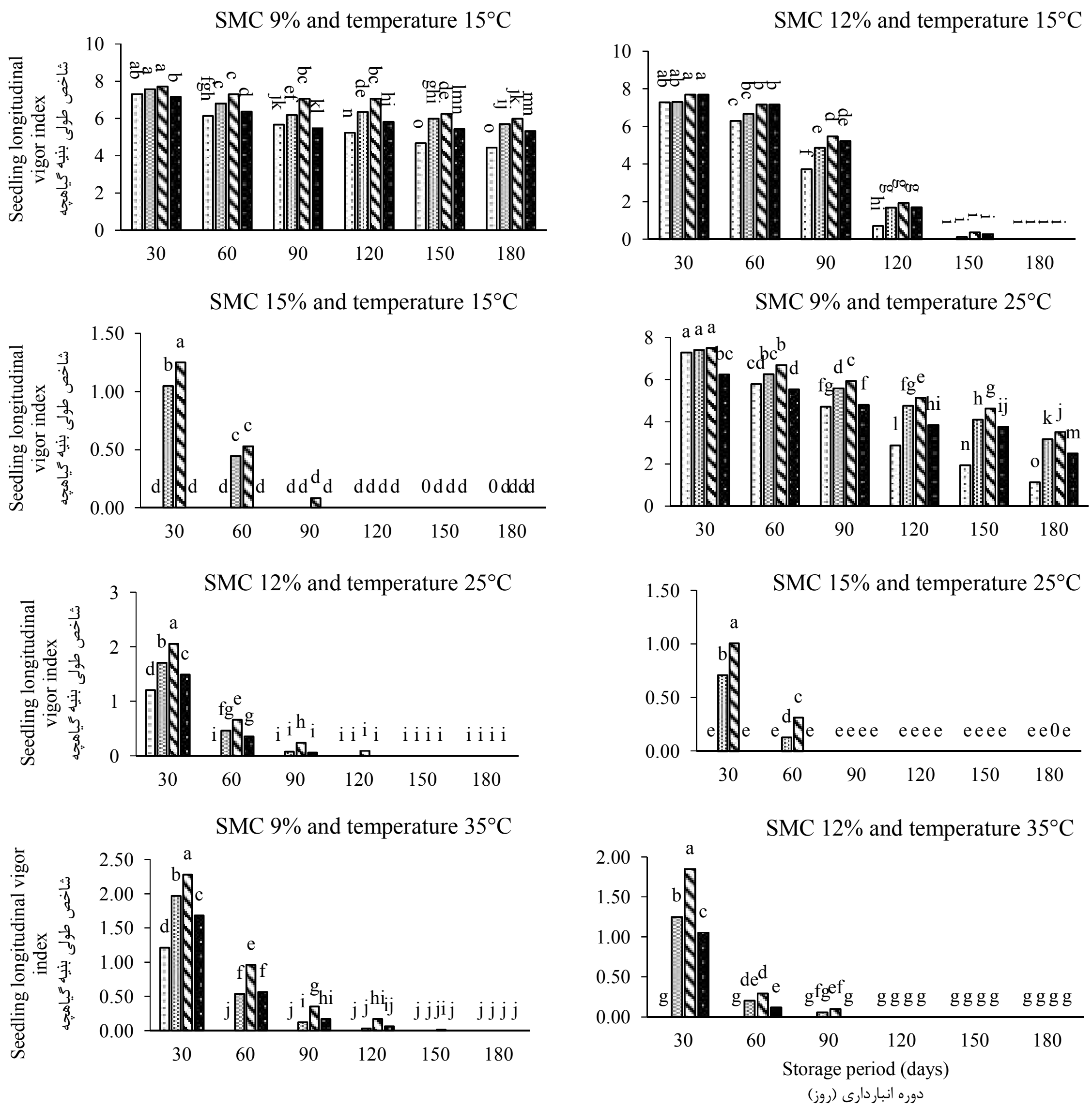
شکل ۴- اثر پیکس و انبارداری بر وزن خشک گیاهچه کنجد رقم داراب ۱ تحت شرایط دمایی ۱۵، ۲۵ و ۳۵ درجه سلسیوس و رطوبت ۹، ۱۲ و ۱۵ درصد. حروف متفاوت نشان دهنده اختلاف معنی‌دار بر اساس آزمون چند دامنه‌ای دانکن در سطح ۵ درصد است.

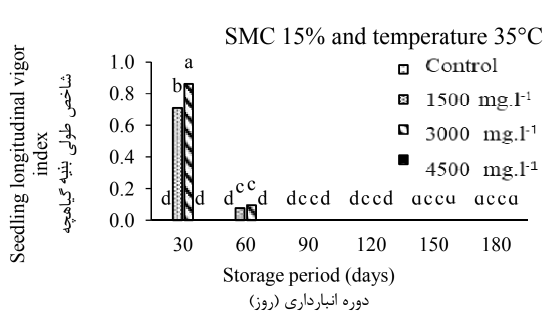
Figure 4. The effect of PIX treatment and storage on the seedling dry weight of Darab 1 sesame variety under temperature conditions of 15, 25, and 35°C and seed moisture content (SMC) of 9%, 12%, and 15%. Different letters indicate a significant difference based on Duncan's multiple range tests at the 5% level.

was still recorded in the 3000 mg L^{-1} Pix treatment (0.009 g) (Figure 4). At 12% and 15% moisture, dry weight in all Pix treatments dropped to zero after 150 and 90 days, respectively. In contrast, dry weight in the control treatment reached zero after 60 and 30 days (Figure 4). At 35°C, the highest seedling dry weights under 9%, 12%, and 15% moisture were 0.008, 0.007, and 0.005 g, respectively, again in the 3000 mg L^{-1} Pix treatment after 30 days (Figure 4). Numerous studies, including those by Alivand (2010), Mehrabi Koushki et al. (2022), and Afrosheh et al. (2018), have confirmed that seedling dry weight decreases significantly with longer storage duration, higher seed moisture, and elevated temperature—findings that align with our results. Latifzadeh Shahkhali et al. (2020) reported that reduced seedling dry weight due to aging was linked to lower germination rate, diminished antioxidant enzyme activity, and elevated malondialdehyde (MDA) levels. In the present study, Pix treatment significantly improved seedling dry weight, which may be attributed to increased seedling length, faster germination, elevated peroxidase activity, and lower MDA levels (data not shown). Given that dry weight is directly related to seedling growth and length, the reduction observed at higher temperature and humidity can be attributed to reduced seedling elongation under adverse conditions. These results support prior findings that impaired seed metabolism and reserve mobilization under aging stress cause a decline in seedling dry weight (Mohammadi et al., 2012).

Seedling vigor index (length-based and weight-based)

The results of seedling vigor indices demonstrated that the highest length-based vigor at 15°C and moisture levels of 9%, 12%, and 15% were 7.71, 7.68, and 1.25, respectively, all in the 3000 mg L^{-1} Pix treatment. The corresponding weight-based vigor values were 0.013, 0.013, and 0.002, respectively. The lowest vigor values were observed in the control at 9% moisture after 180 days, with 4.42 (length) and 0.007 (weight) (Figures 5 and 6). At 25°C, the highest length-based vigor values were 7.51, 2.05, and 1.01 for 9%, 12%, and 15% moisture, respectively, in the 3000 mg L^{-1} Pix treatment. The corresponding weight-based vigor values were 0.013, 0.003, and 0.002 (Figure 5). At 35°C, the highest length-based vigor values for 9%, 12%, and 15% moisture were 2.28, 1.85, and 0.86, respectively, while weight-based vigor values were 0.004, 0.003, and 0.001, all in the 3000 mg L^{-1} Pix treatment (Figures 5 and 6). Since vigor indices are calculated by multiplying germination percentage by seedling length or dry weight, these indices are considered strong indicators of seed vigor. Our study confirms that increased storage duration, higher seed moisture, and elevated temperature significantly reduce both length- and weight-based seedling vigor. These findings are consistent with the results reported by Latifzadeh Shahkhali et al. (2020), Mehrabi Koushki et al. (2022), and Ansari et al. (2013), who linked reduced vigor to increased seed aging. In general, the decline in vigor is closely tied to reduced germination percentage, seedling length, and dry weight. Ghanbari et al. (2018) reported that reduced vigor in aged seeds of bean was associated with declines in all germination indices. Ansari & Sharifzadeh (2012) also stated that seedling vigor showed the strongest

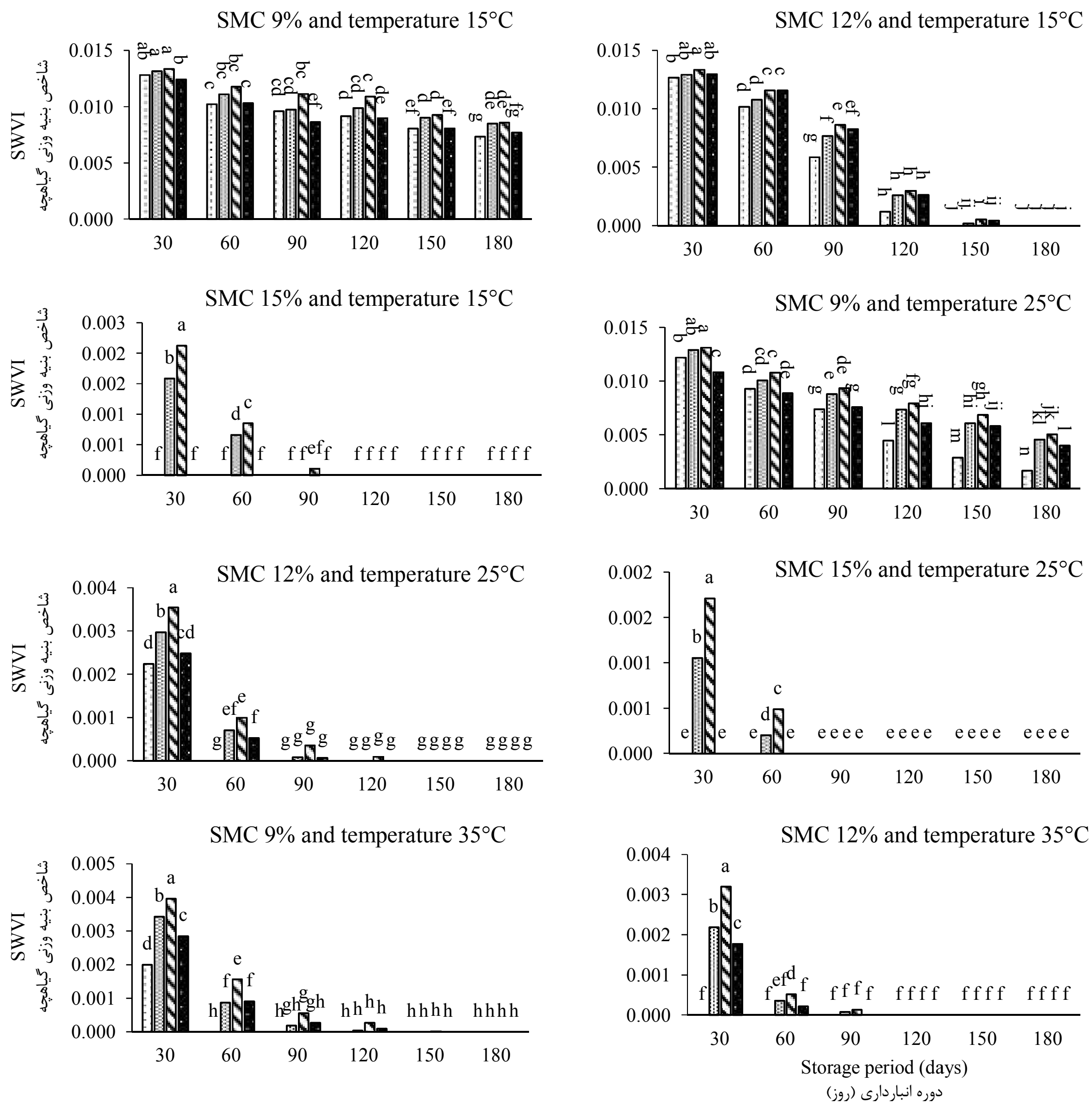


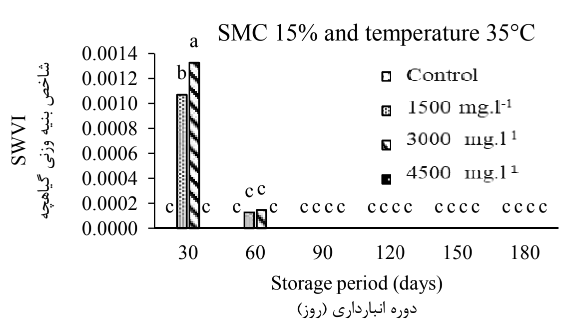


شکل ۵- اثر پیکس و انبارداری بر شاخص طولی بنیه گیاهچه کنجد رقم داراب ۱ تحت شرایط دمایی ۱۵، ۲۵ و ۳۵ درجه سلسیوس و رطوبت ۹، ۱۲ و ۱۵ درصد. حروف متفاوت نشان دهنده اختلاف معنی‌دار بر اساس آزمون چند دامنه‌ای دانکن در سطح ۵ درصد است.

Figure 5. The effect of PIX treatment and storage on the seedling longitudinal vigor index of Darab 1 sesame variety under temperature conditions of 15, 25, and 35°C and seed moisture content (SMC) of 9%, 12%, and 15%. Different letters indicate a significant difference based on Duncan's multiple range tests at the 5% level.

positive correlation with germination percentage, seedling length, and dry weight. This reduction in vigor is due to the deterioration of all its components—a process well documented in studies by Ansari & Sharifzadeh (2012),





شکل ۶- اثر پیکس و انبارداری بر شاخص وزنی بنیه گیاهچه کنجد رقم داراب ۱ تحت شرایط دمایی ۱۵، ۲۵ و ۳۵ درجه سلسیوس و رطوبت ۹، ۱۲ و ۱۵ درصد. حروف متفاوت نشان دهنده اختلاف معنی‌دار بر اساس آزمون چند دامنه‌ای دانکن در سطح ۵ درصد است.

Figure 6. The effect of PIX treatment and storage on the seedling weight vigor index (SWVI) of Darab 1 sesame variety under temperature conditions of 15, 25, and 35°C and seed moisture content (SMC) of 9%, 12%, and 15%. Different letters indicate a significant difference based on Duncan's multiple range tests at the 5% level.

Verma et al. (2003), and Pradidwan (2004). Zamani et al. (2010) found that both natural and accelerated aging in safflower seeds caused severe reductions in vigor due to decreased antioxidant activity, ROS accumulation, lipid peroxidation, and protein and membrane degradation. In a study on transgenic rice, Kaur et al. (2015) found that the overexpression of small heat shock proteins (sHSPs) stabilized protein structure and reduced ROS accumulation, thereby enhancing seed vigor and longevity. Seed vigor index integrates both germination performance and seedling growth and therefore reflects the overall physiological status of seeds. In the present study, higher vigor index values were generally associated with lower electrical leakage and greater α-amylase activity. This relationship indicates that preservation of membrane integrity and efficient reserve mobilization contribute collectively to seed vigor. Conversely, increased membrane leakage and reduced enzymatic activity in aged seeds were accompanied by marked declines in vigor index, emphasizing the interconnected nature of these physiological traits.

Conclusion

The present study demonstrated that sesame seed deterioration accelerated markedly with increasing storage temperature, seed moisture content, and storage duration. Under severe storage conditions (15% seed moisture at 25°C and 35°C), germination declined to zero within 30–90 days, indicating rapid loss of seed viability. In contrast, Pix application, particularly at 3000 mg L^{-1}, substantially alleviated the detrimental effects of seed aging. At 15°C and 9% seed moisture after 180 days of storage, seeds treated with 3000 mg L^{-1} Pix maintained a germination percentage of approximately 80%, whereas germination in untreated seeds declined to about 73%. Pix treatment also reduced electrolyte leakage by up to 52% and maintained higher α-amylase activity throughout storage. Moreover, under several storage conditions, Pix-treated seeds retained measurable germination and seedling growth for 30–60 days longer than untreated seeds. Therefore, application of 3000 mg L^{-1} Pix can be considered an effective strategy for extending sesame seed storability and mitigating physiological deterioration during long-term storage.

Authors' Contributions

Methodology, R.Z., and A.M.; formal analysis, A.M.; investigation, H.L; writing-original draft preparation, R.Z.; writing-review and editing, H.L. and H.B.; supervision, A.M.; project administration, A.M.; All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

Data available on request from the authors.

Acknowledgements

We would like to thank the Department of Agronomy & plant Breeding, Faculty of Agriculture and Natural Resources, Yasouj University for their financial and moral support and sincere cooperation in carrying out this research.

Ethical Considerations

The authors avoided data fabrication, falsification, and plagiarism, and any form of misconduct.

Conflict of Interest

The authors declare no conflict of interest.

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Iranian Journal of Seed Research

Homepage: https://yujs.yu.ac.ir/jisr

ISSN: 2383-1480 (On-Line); 2383-1251 (Print)

Yasouj University

اثر بهبوددهنده مپیکوات کلراید (پیکس) بر جوانه‌زنی و پایداری بیوشیمیایی بذر کنجد (*Sesamum indicum*) رقم داراب ۱ در شرایط زوال

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اطلاعات مقاله

نوع مقاله:

مقاله پژوهشی

تاریخ دریافت: ۱۴۰۴/۰۹/۲۶

تاریخ بازنگری: ۱۴۰۴/۱۱/۲۷

تاریخ پذیرش: ۱۴۰۴/۱۲/۰۸

تاریخ انتشار: ۱۴۰۴/۱۲/۲۹

کلیدواژه‌ها:

آلفا آمیلاز

پیری بذر

جوانه‌زنی کنجد

شاخص بنیه

نشت الکتریکی

چکیده

هدف: پیری بذر در دانه‌های روغنی مانند کنجد، یکی از چالش‌های اصلی انبارداری است که کیفیت جوانه‌زنی و قدرت رویشی را کاهش می‌دهد. رقم داراب-۱ با روغن بالا، به شرایط انبار (دما، رطوبت و زمان) بسیار حساس است. در این پژوهش، اثر غلظت‌های مختلف پیکس در تعامل با دما، رطوبت و مدت نگهداری بر شاخص‌های جوانه‌زنی و بیوشیمیایی بذر بررسی شد تا امکان بهبود پایداری کیفی بذر در انبار مشخص گردد.

روش پژوهش: آزمایش به صورت فاکتوریل چهارعاملی در قالب طرح کاملاً تصادفی با سه تکرار انجام شد. عوامل مورد بررسی عبارت بودند از دمای انبار (۱۵، ۲۵ و ۳۵ درجه سلسیوس)، رطوبت بذر (۹، ۱۲ و ۱۵ درصد)، غلظت پیکس (۰، ۳۰۰۰ و ۴۵۰۰ میلی‌گرم در لیتر) و مدت زمان نگهداری (۳۰، ۶۰، ۹۰، ۱۲۰، ۱۵۰ و ۱۸۰ روز). پس از پایان دوره انبارداری، ویژگی‌های فیزیولوژیکی بذر شامل درصد و سرعت جوانه‌زنی، طول ریشه و ساقه‌چه، وزن خشک نهال، شاخص بنیه گیاهچه، فعالیت آنزیم-α آمیلاز و میزان نشت الکترولیت اندازه‌گیری شد.

یافته‌ها: افزایش دما، رطوبت و مدت نگهداری، زوال بذر را تسریع کرد. پس از ۱۸۰ روز، نشت الکترولیت در شاهد با افزایش دما از ۱۵ به ۲۵ درجه سلسیوس (در رطوبت ۹ درصد) از ۲۱/۴۷ به ۷۲/۷۲ درصد افزایش یافت (۵۴ درصد نشت غشایی)، در حالی که پیکس ۳۰۰۰ میلی‌گرم بر لیتر آن را ۱۹-۸۰ درصد کاهش داد. فعالیت α-آمیلاز با زوال کاهش یافت، اما پیکس ۳۰۰۰ میلی‌گرم بر لیتر بالاترین فعالیت را حفظ کرد (۱۵/۵ در برابر ۱۶/۳ $\mathrm{nmol\ seed^{-1}min^{-1}}$ پس از ۱۸۰ روز). همچنین درصد و سرعت جوانه‌زنی، طول و وزن خشک گیاهچه و شاخص بنیه با پیری افت کردند، اما تیمار پیکس، به‌ویژه در غلظت ۳۰۰۰ میلی‌گرم بر لیتر ، این کاهش‌ها را به‌طور معنی‌داری تعدیل نمود.

نتیجه‌گیری: نگهداری بذر در دما و رطوبت بالا، زوال کنجد را تسریع کرده و موجب کاهش جوانه‌زنی و فعالیت α-آمیلاز و افزایش آسیب غشایی شد. پیکس ۳۰۰۰ میلی‌گرم بر لیتر مؤثرترین تیمار بود که بنیه بذر و فعالیت آنزیمی را حفظ و نشت الکترولیت را کاهش داد. بنابراین، تیمار بذر با ۳۰۰۰ میلی‌گرم بر لیتر پیکس پیش از انبار، به‌ویژه در شرایط ۱۵ درجه سلسیوس و رطوبت ۹ درصد، به‌عنوان راهکاری مؤثر برای افزایش طول عمر و حفظ کیفیت بذر در ذخیره‌سازی میان‌مدت قابل توصیه است.

جنبه‌های نوآوری:

- پیکس ۳۰۰۰ میلی‌گرم بر لیتر به‌طور مؤثری از کاهش صفات فیزیولوژیکی بذر کنجد در طول ذخیره‌سازی جلوگیری کرده و پتانسیل جوانه‌زنی و قدرت بذر را حفظ نمود.
- افزایش دما، رطوبت و مدت نگهداری، فعالیت α-آمیلاز را کاهش و نشت الکترولیت را افزایش داد که نشان‌دهنده تسریع پیری فیزیولوژیکی بذر است.
- تیمار با پیکس کیفیت بذر را در شرایط گرم و مرطوب از طریق کاهش نشت الکترولیت و افزایش پایداری غشا بهبود بخشید، که می‌تواند به‌عنوان راهکاری عملی برای افزایش طول عمر بذر کاربرد داشته باشد.

استناد: زیلاب‌پور، رامین؛ مرادی، علی؛ بلوچی، حمیدرضا؛ یدوی، علیرضا؛ لطیف‌منش، حجت‌اله (۱۴۰۴). اثر بهبوددهنده مپیکوات کلراید (پیکس) بر جوانه‌زنی و پایداری بیوشیمیایی بذرکنجد (*Sesamum indicum*) رقم داراب ۱ در شرایط زوال. *پژوهش‌های بذر ایران*، ۱۲(۲)، ۱۹۹-۱۷۱.

https://doi.org/10.66224/yujs.12.2.171

ناشر: دانشگاه یاسوج.

ملاحظات اخلاقی

پیروی از اصول اخلاق پژوهش

نویسندگان اصول اخلاقی را در انجام و انتشار این پژوهش علمی رعایت نموده‌اند و این موضوع مورد تأیید همه آنهاست.

مشارکت نویسندگان

روش‌شناسی، ر.ز. و ع.م؛ تجزیه و تحلیل رسمی، ع.م؛ تحقیق، ح.ل؛ نگارش پیش‌نویس اولیه، ر.ز؛ بازبینی و ویرایش نگارش، ح.ل و ح.ب؛ نظارت، ع.م؛ مدیریت پروژه، ع.م؛ همه نویسندگان نسخه منتشر شده مقاله را مطالعه کرده و با آن موافقت کرده‌اند.

اظهارنامه در دسترس بودن داده‌ها

داده‌ها از طریق درخواست از نویسندگان در دسترس است.

تعارض منافع

نویسندگان اعلام می‌دارند که هیچ‌گونه تعارض منافع مرتبط با این پژوهش ندارند.

حامی مالی

مقاله حاضر با حمایت مالی معاونت پژوهشی دانشگاه یاسوج انجام شد.

حمایت مالی از این پژوهش از طرف دانشگاه یاسوج، معاونت پژوهشی، دانشکده کشاورزی، گروه زراعت و اصلاح نباتات در قالب پژوهانهٔ طرح نویسنده اول و همچنین پژوهانهٔ برای سایر نویسندگان انجام شده است.

سپاسگزاری

بدینوسیله از گروه زراعت و اصلاح نباتات دانشکده کشاورزی دانشگاه یاسوج به خاطر حمایت مالی/ حمایت معنوی/ همکاری در اجرای پژوهش حاضر تشکر و قدردانی می‌گردد.